Group sessions schedule for GENV0002-1 – Sustainable energy (21-22)

Last update: March 7, 2022
Duration of the presentation : 15 minutes
Check your availability!!
C.8 dead link has been updated.

Gramme

If you have been assigned no groups, please send a mail with two of the height available dates as soon as possible (23/03 am, 28/04 pm, 21/03 am, 26/04 pm, 1/04 am, 29/04 am, 28/03am, 27/04 am).

Session 1

- Supervisors: Manakari Vageesh,
- Date: 21/03
- Time: from 9h00 to 12h30
- Place: 629

Team	Subject
Romain Féron Thomas Frenay Léopold Deliége	The EU Clean Energy Package: present the content of two of the proposals of this package: E-Directive (Directive on common rules for the internal market in electricity (C.1, C.2), and E-Regulation (Regulation on the internal market for electricity (C.3). You can (and probably should) check the following document summarising the content (C.4).
Gilles Boonen Bryan Habsch Benedikt Schroeder	Demand Response as a way of introducing flexibility into the energy sector: what does it entail? How can this be implemented in practice?
Martin Nambaje Olivier Demarche Chloé Dozin	Wholesale markets in Europe: present the organisation of the wholesale markets in Europe: the day-ahead and the intraday markets. Explain how these trading floors operate including examples from at least three different European countries.
Iouri Dupin Cécile Feron Eric Ndjulu	Electricity sector: present the organisation of the electricity sector in Europe, laying stress on the role of TSO and DSO. Explain the role of all actors involved in the delivery of electricity, from its production to its consumption. Include examples from different European countries.
Antoine Larbanois Quentin Strijthagen Hugo Mantion	Balancing markets: present the role of balancing markets in Europe. What are the obligations of BRP, ARP, and BSP? Explain how the balancing markets are integrated in the European Union (e.g. IGCC initiative).
Achille Masset Jonathan Ramkaran	Blockchain technologies in the electricity sector. Search for scientific papers about the topic, explaining how this technology can be implemented and can help the development of the future electricity systems.

Session 2

- Supervisors: Manakari Vageesh,
- Date: 26/04
- Time: from 14h to 17h30
- Place: 419

Team	Subject
Gilles Boonen Iouri Dupin Olivier Demarche	Electricity Interconnectors: what are they? Present the NEMO and ALEGrO links.
Romain Féron Benedikt Schroeder Quentin Strijthagen	EU targets: present and explain the EU 2020 targets, EU 2030 targets, and EU 2050 targets.
Bryan Habsch Martin Nambaje Léopold Deliége	IPCC Special Report Global Warming of 1.5C (C.5): present an overview of the report laying stress on the summary for policy makers, chapter 1, and chapter 5.
Cécile Feron Antoine Larbanois Hugo Mantion	EU Network Codes and guidelines: what are they? Why do they exist? Present an overview of these eight regulations (C.6) laying stress on the the capacity allocation and congestion management guideline (CACM) (C.7). You can resort to this report to help you understand this network code (C.8).
Thomas Frenay Chloé Dozin Eric Ndjulu	Solar photovoltaic (PV) and Electric vehicles: how are these technologies being integrated in the distribution networks? What challenges (technical AND regulatory) do they pose for the distribution networks?
Achille Masset Jonathan Ramkaran	Integrated energy systems: coupling of gas and electricity markets. Explain how this can work, and what benefits it may bring to the European Electricity System. You can use the following reports to guide you (C.9, C.10, C.11, C.12).

Session 3

- Supervisors: Manakari Vageesh,
- Date: 01/04
- Time: from 9h00 to 12h30
- Place: 629

Team	Subject
Alexandre Bruyère Noé Mathonet Maxime Vanstipelen	The EU Clean Energy Package: present the content of two of the proposals of this package: E-Directive (Directive on common rules for the internal market in electricity (C.1, C.2), and E-Regulation (Regulation on the internal market for electricity (C.3). You can (and probably should) check the following document summarising the content (C.4).
Tom Bonjean Théo Castin Hugo Malarme	Demand Response as a way of introducing flexibility into the energy sector: what does it entail? How can this be implemented in practice?
Mathias Debras Émilie Stiernon	Wholesale markets in Europe: present the organisation of the wholesale markets in Europe: the day-ahead and the intraday markets. Explain how these trading floors operate including examples from at least three different European countries.
Ayoub Barzaq Antoine Beaume Olivier Paquot	Integrated energy systems: coupling of gas and electricity markets. Explain how this can work, and what benefits it may bring to the European Electricity System. You can use the following reports to guide you (C.9, C.10, C.11, C.12).
Marc Thonnard Romane Bokiau Anthony Rousseau	Blockchain technologies in the electricity sector. Search for scientific papers about the topic, explaining how this technology can be implemented and can help the development of the future electricity systems.

Session 4

- Supervisors: Manakari Vageesh,
- Date: 29/04
- Time: from 9h00 to 12h30
- Place: 109

Team	Subject
Marc Thonnard Ayoub Barzaq Tom Bonjean	Electricity sector: present the organisation of the electricity sector in Europe, laying stress on the role of TSO and DSO. Explain the role of all actors involved in the delivery of electricity, from its production to its consumption. Include examples from different European countries.
Antoine Beaume Romane Bokiau Théo Castin	Balancing markets: present the role of balancing markets in Europe. What are the obligations of BRP, ARP, and BSP? Explain how the balancing markets are integrated in the European Union (e.g. IGCC initiative).
Mathias Debras Hugo Malarme Noé Mathonet	Electricity Interconnectors: what are they? Present the NEMO and ALEGrO links.
Alexandre Bruyère Olivier Paquot Anthony Rousseau	EU targets: present and explain the EU 2020 targets, EU 2030 targets, and EU 2050 targets.
Émilie Stiernon Maxime Vanstipelen	IPCC Special Report Global Warming of 1.5C (C.5): present an overview of the report laying stress on the summary for policy makers, chapter 1, and chapter 5.

Session 5

- Supervisors: Manakari Vageesh,
- Date: 28/03
- Time: from 9h00 to 12h30
- Place: 629

Team	Subject
Martin Bastin Nicolas Verbauwhede Nicolas Wauters	EU Network Codes and guidelines: what are they? Why do they exist? Present an overview of these eight regulations (C.6) laying stress on the the capacity allocation and congestion management guideline (CACM) (C.7). You can resort to this report to help you understand this network code (C.8).
Quentin Andry Maxime Avenière Maxime Moulin	Solar photovoltaic (PV) and Electric vehicles: how are these technologies being integrated in the distribution networks? What challenges (technical AND regulatory) do they pose for the distribution networks?
Florian Gailly Elie Rixen Martin Szablot	Integrated energy systems: coupling of gas and electricity markets. Explain how this can work, and what benefits it may bring to the European Electricity System. You can use the following reports to guide you (C.9, C.10, C.11, C.12).
Julien Ghuysen Logan Mavaro	Blockchain technologies in the electricity sector. Search for scientific papers about the topic, explaining how this technology can be implemented and can help the development of the future electricity systems.
Tom Wantiez Arthur Bertrand	Electricity Interconnectors: what are they? Present the NEMO and ALEGrO links.

Session 6

- Supervisors: Manakari Vageesh,
- Date: 27/04
- Time: from 9h00 to 12h30
- Place: 324

Team	Subject
Quentin Andry Florian Gailly Tom Wantiez	The EU Clean Energy Package: present the content of two of the proposals of this package: E-Directive (Directive on common rules for the internal market in electricity (C.1, C.2), and E-Regulation (Regulation on the internal market for electricity (C.3). You can (and probably should) check the following document summarising the content (C.4).
Maxime Avenière Logan Mavaro Nicolas Verbauwhede	Demand Response as a way of introducing flexibility into the energy sector: what does it entail? How can this be implemented in practice?
Julien Ghuysen Martin Szablot Nicolas Wauters	Wholesale markets in Europe: present the organisation of the wholesale markets in Europe: the day-ahead and the intraday markets. Explain how these trading floors operate including examples from at least three different European countries.
Martin Bastin Maxime Moulin	Electricity sector: present the organisation of the electricity sector in Europe, laying stress on the role of TSO and DSO. Explain the role of all actors involved in the delivery of electricity, from its production to its consumption. Include examples from different European countries.
Elie Rixen Arthur Bertrand	Balancing markets: present the role of balancing markets in Europe. What are the obligations of BRP, ARP, and BSP? Explain how the balancing markets are integrated in the European Union (e.g. IGCC initiative).

Session 7

- Supervisors: Manakari Vageesh,
- Date: 23/03
- Time: from 9h00 to 12h30
- Place: 206

Team	Subject
Thomas Blaise Méric Bosten Louise Bottenberg	Balancing markets: present the role of balancing markets in Europe. What are the obligations of BRP, ARP, and BSP? Explain how the balancing markets are integrated in the European Union (e.g. IGCC initiative).
Adrien Jamaer Régis Mastrolonardo Florent Mercier	Electricity Interconnectors: what are they? Present the NEMO and ALEGrO links.
Thomas Schols Adrien Stalars Louise Tassin	EU targets: present and explain the EU 2020 targets, EU 2030 targets, and EU 2050 targets.

Session 8

- Supervisors: Manakari Vageesh,
- Date: 28/04
- Time: from 14h to 17h30
- Place: 629

Team	Subject
Louise Bottenberg Régis Mastrolonardo Louise Tassin	IPCC Special Report Global Warming of 1.5C (C.5): present an overview of the report laying stress on the summary for policy makers, chapter 1, and chapter 5.
Thomas Blaise Florent Mercier Adrien Stalars	EU Network Codes and guidelines: what are they? Why do they exist? Present an overview of these eight regulations (C.6) laying stress on the the capacity allocation and congestion management guideline (CACM) (C.7). You can resort to this report to help you understand this network code (C.8).
Méric Bosten Adrien Jamaer Thomas Schols	Solar photovoltaic (PV) and Electric vehicles: how are these technologies being integrated in the distribution networks? What challenges (technical AND regulatory) do they pose for the distribution networks?

ULiège

Session 1

- Supervisors: Reiter Sigrid, Polson Martin
- Date: 14/02
- Time: from 8h30 to 12h30
- Place: B52 (-1/631)

Team	Subject
VOGELS Arthur RENAUD Arnaud BASTIN Sophie	Explain what is "Urban sprawl" and what are their drivers (Reference 1.1 Urban sprawl) (A.1).
BAUMGARTEN Julia GODECHAL Nathan CLOOTS Nicolas	Present the potential energy savings associated with buildings' renovation strategies at the city scale (reference: 1.2 Low energy cities) (A.2).
LEDUC Charline TAMBURRINI Robin QALAJ Puhia	Present and compare key parameters and strategies to improve transport energy consumption (reference : 1.3 transport) (A.3).
PIERRE Jérôme BRANKART Guillaume GUAMGNE SIMO Liliane	Explain the concept of "territorial recomposition" and how it can influence the energy consumption due to transport at a regional scale (reference : 1.4 Territorial recomposition) (A.4).
GILSON Florence RUTTEN Grégoire MAUS Joshua	Explain what is a ZEB (Zero Energy Building) and what are the issues of its definition (reference: 1.5 ZEB & ZEN) (A.5).
TEVOEDJRE Philippe BOUYAKHRICHAN Nabil OOMS Gilles	Explain how the climate and energy mix of a country influence the energy consumption of buildings (references : 1.6 LCA-1 & 1.7 LCA-2) (A.6 and A.7).

Session 2

- Supervisors: Manakari Vageesh, Veronique Doppagne
- Date: 14/02
- Time: from 13h30 to 17h30
- Place: 2.93, B28

Team	Subject
LINOTTE Lucie GECIM Hülya PELZER Hugo	EU targets: present and explain the EU 2020 targets, EU 2030 targets, and EU 2050 targets.
EL FAKIRI Rida ISERENTANT Tanguy DI SIMONE Gaëtan	IPCC Special Report Global Warming of 1.5C (C.5): present an overview of the report laying stress on the summary for policy makers, chapter 1, and chapter 5.
THOMMES Eliott MESSENS Tom GUYSENS Thiébaud	EU Network Codes and guidelines: what are they? Why do they exist? Present an overview of these eight regulations (C.6) laying stress on the the capacity allocation and congestion management guideline (CACM) (C.7). You can resort to this report to help you understand this network code (C.8).
BARET Elisabeth MARTIN Antoine LEJEUNE Célia	Solar photovoltaic (PV) and Electric vehicles: how are these technologies being integrated in the distribution networks? What challenges (technical AND regulatory) do they pose for the distribution networks?
CRUTZEN Théo TROQUAY Julien	Integrated energy systems: coupling of gas and electricity markets. Explain how this can work, and what benefits it may bring to the European Electricity System. You can use the following reports to guide you (C.9, C.10, C.11, C.12).
DROESCH William MARTIN Aurore	Blockchain technologies in the electricity sector. Search for scientific papers about the topic, explaining how this technology can be implemented and can help the development of the future electricity systems.

Session 3

- Supervisors: Job Nathalie, Clara Brereton
- Date: 15/02
- Time: from 13h30 to 17h30
- Place: B7b - A4

Team	Subject
ROMOLI Raphaël GHYSENS François BOULANGER Elyse	Explain how biomass can be transformed into fuel. Discuss the use of biodiesel/diesel blends in vehicle applications, and give an overview of the Belgian regulations.
GREFFE Roland HOUET Florine	Discuss the economic, environmental and ethical issues of biodiesel production.
GELELEENS Emil LE Maureen MESSINA Lucas	Discuss the possibilities of electricity storage by batteries. In particular, give an overview of the limitations of these techniques in terms of material resources.
de LA BRASSINNE BONARDEAUX Maxence DI BARTOLOMEO Katia GODART Antoine	Give an overview of the use of hydrogen as energy carrier (production, limitations, existing networks and end-use).
PAGANO Florian BRACH Mathias JACQUEMIN Gilles	Explain the general principle of fuel cell technology and their advantages/drawbacks vs. thermo-mechanical systems. Discuss the advantages and drawbacks of high temperature fuel cells (MCFC and SOFC) vs. low temperature fuel cells (AFC and PEMFC).
LUKUSA Elio CHARLIER Alexis DUTAILLY Guillaume	Discuss the differences between fuel cell and battery electric vehicles. Give an overview of advantages and drawbacks of both technologies.

Session 4

- Supervisors: Dewallef Pierre, Christine Bouvy
- Date: 16/02
- Time: from 8h30 to 12h30
- Place: 0/36 - B37

Team	Subject
SKA Margaux MOES Tom JACQUET Charles	Status of Concentrated Solar Photovoltaic (CSP) technology for electricity production (See Reference B.1).
BERTHUS Louis LOUVEAU Simon SERVAIS Coline	Status of Solar Tower Power Plant technology for electricity production (See Reference B.2).
DEMEULDRE Lena MOTTARD Alexandre BECKERS Thibault	Status of off-shore wind power technology for electricity production (See Reference B.3).
REBEIX Thomas DELHEZ Jeanne BIRTLES Alixia	Status of biomass combustion power plant technology for electricity production (See Reference B.4).
COLSON Léonore BOULAICH Haytham DUCHESNE Tom	Status of tidal power plant technology for electricity production (See Reference B.5).
DESTEXHE Clara BOUGNET Nicolas DUCHESNE Maxime	Status of ocean thermal energy conversion (OTEC) power plant technology for electricity production (See Reference B.6).

Session 5

- Supervisors: Manakari Vageesh, Polson Martin
- Date: 16/02
- Time: from 13h30 to 17h30
- Place: 2.93, B28

Team	Subject
TYCHON Maxime FLOREA Robert LAMALLE Lili	The EU Clean Energy Package: present the content of two of the proposals of this package: E-Directive (Directive on common rules for the internal market in electricity (C.1, C.2), and E-Regulation (Regulation on the internal market for electricity (C.3). You can (and probably should) check the following document summarising the content (C.4).
WALLON Bertrand DUMORTIER Romain BENOTHMAN Rami	Demand Response as a way of introducing flexibility into the energy sector: what does it entail? How can this be implemented in practice?
DEBAUCHERON Thomas TSHILOLO MUEPU MALAIKA Josémaria DELPORTE Guillaume	Wholesale markets in Europe: present the organisation of the wholesale markets in Europe: the day-ahead and the intraday markets. Explain how these trading floors operate including examples from at least three different European countries.
VERHEYDEN Antoine COLLETTE Florine	Electricity sector: present the organisation of the electricity sector in Europe, laying stress on the role of TSO and DSO. Explain the role of all actors involved in the delivery of electricity, from its production to its consumption. Include examples from different European countries.
DELMOTTE Henri BARZAQ Yasmine T'SERSTEVENS Antoine	Balancing markets: present the role of balancing markets in Europe. What are the obligations of BRP, ARP, and BSP? Explain how the balancing markets are integrated in the European Union (e.g. IGCC initiative).
MELOTTE Théo CHRISTIAENS Juliette BAUDRU Anne-Sophie	Electricity Interconnectors: what are they? Present the NEMO and ALEGrO links.

Session 6

- Supervisors: Reiter Sigrid, Veronique Doppagne
- Date: 17/02
- Time: from 8h30 to 12h30
- Place: B28 (R18)

Team	Subject
PONCELET Antoine FAINGNAERT Théo LEDUC Arnaud	Explain what are the environmental and socio-economic impacts of urban sprawl (reference 1.1 Urban sprawl) (A.1).
GRAINDORGE Pierre SCHUMACKER Cyril HOGGE Louis	Compare strategies to reduce energy consumption of buildings and transport at the city scale (reference: 1.2 Low energy cities) (A.2).
SANDRONT Gaëlle CASTIGLIONE Mattéo DEKINDER Florian	Explain how the built density and urban form influence the energy consumption of districts (reference : 1.8 Built density) (A.8).
WALTREGNY Juliette RASIR Astrid	Explain the potential for energy mutualisation at the urban block scale and how it can help to achieve zero energy communities (reference : 1.5 ZEB & ZEN) (A.5).
HALBACH Quentin GUENFOUDI Ihabe VINDERS Adrien	Explain how energy is taken into account in life-cycle assessment (LCA) of buildings (references : 1.6 LCA-1 & 1.7 LCA-2) (A.6 and A.7).
BOUWERS Nanda WÉRY Victor BROCHARD Adrien	Explain how occupants' behaviours and occupation modes influence the energy consumption of a residential building (reference : 1.9 Occupants) (A.9).

Session 7

- Supervisors: Manakari Vageesh, Christine Bouvy
- Date: 28/02
- Time: from 13h30 to 17h30
- Place: 2.93, B28

Team	Subject
PIRON Romain THOMMES Eliott MICHEL Merlin	EU targets: present and explain the EU 2020 targets, EU 2030 targets, and EU 2050 targets.
LACANNE Laura SCHYNS Léo MICHIELS Sven	IPCC Special Report Global Warming of 1.5C (C.5): present an overview of the report laying stress on the summary for policy makers, chapter 1, and chapter 5.
DELMOTTE Henri CHARLIER Alexis MARTIN Aurore	EU Network Codes and guidelines: what are they? Why do they exist? Present an overview of these eight regulations (C.6) laying stress on the the capacity allocation and congestion management guideline (CACM) (C.7). You can resort to this report to help you understand this network code (C.8).
DENGIS Maël TYCHON Maxime CRUTZEN Théo	Solar photovoltaic (PV) and Electric vehicles: how are these technologies being integrated in the distribution networks? What challenges (technical AND regulatory) do they pose for the distribution networks?
CRON Valentin DARDENNE Denis HAAS Bastien	Integrated energy systems: coupling of gas and electricity markets. Explain how this can work, and what benefits it may bring to the European Electricity System. You can use the following reports to guide you (C.9, C.10, C.11, C.12).
BARET Elisabeth MESSINA Lucas BRIESINGER Zoé	Blockchain technologies in the electricity sector. Search for scientific papers about the topic, explaining how this technology can be implemented and can help the development of the future electricity systems.

Session 8

- Supervisors: Job Nathalie, Polson Martin
- Date: 2/03
- Time: from 8h30 to 12h30
- Place: B6d - R26

Team	Subject
CLOUX Romain SPITS Alexandre THOMEE Corentin	Discuss the concept of ”Clean coal technology”.
PAULY Enya GREFFE Roland LUKUSA Elio	Give an overview of the various carbon capture & storage techniques. Discuss their advantages/drawbacks in terms of economy and environmental issues.
LEJEUNE Célia JACOBS Hugo MAUS Joshua	Explain how to transform solar energy into electricity via steam (Solar Energy Generating Systems). Describe the Mojave Solar Project.
DEPAS Cyrielle GALAN Andrei MATHUES BILGINER Lucie	Describe the ITER project (nuclear energy).
RUWET Emile RENSON Xavier BAUDRU Anne-Sophie	What is coal gasification? Describe the process in the case of (i) classical gasifiers and (ii) underground processes.
HUBERT Martin CLERFAYS Alix AKOGO Ornella	Give an overview of the shale gas extraction technique. Discuss the environmental issues.

Session 9

- Supervisors: Dewallef Pierre, Veronique Doppagne
- Date: 3/03
- Time: from 8h30 to 12h30
- Place: 0/36 - B37

Team	Subject
MARTIN Grégoire RONDIA Arthur FARCAS Maria	Status of Concentrated Solar Photovoltaic (CSP) technology for electricity production (See Reference B.1).
FIRRINCIELI Maxime HALBACH Quentin NAVEZ Tom	Status of Solar Tower Power Plant technology for electricity production (See Reference B.2).
CASTIGLIONE Mattéo MATHY Maxine KADIOGLU Sélim	Status of off-shore wind power technology for electricity production (See Reference B.3).
KEITA Mohamed NDIZEYE ABEWE Elisabeth ARSANOV Ramzan	Status of biomass combustion power plant technology for electricity production (See Reference B.4).
FRANCOIS Constance DESOLEIL Brandon THIEBAUT Martin	Status of Carbon Capture and Storage applied on coal power plants for electricity production (See Reference B.13).
BOUWERS Nanda DALEM Pierre GUENFOUDI Ihabe	Status of Carbon Capture and Storage applied on integrated coal gasification combined cycle (IGCC) power plants for electricity production (See Reference B.14).

Session 10

- Supervisors: Reiter Sigrid, Polson Martin
- Date: 7/03
- Time: from 8h30 to 12h30
- Place: B28 (1.97)

Team	Subject
HOUSSA César LEDUC Charline BAUMGARTEN Julia	Explain what are the environmental and socio-economic impacts of urban sprawl (reference 1.1 Urban sprawl) (A.1).
BRACH Mathias GUAMGNE SIMO Liliane LAMALLE Lili	Compare strategies to reduce energy consumption of buildings and transport at the city scale (reference: 1.2 Low energy cities) (A.2).
GODECHAL Nathan SCHOLZEN Fernand SERET Cédric	Explain how the built density and urban form influence the energy consumption of districts (reference : 1.8 Built density) (A.8).
EL FAKIRI Rida LEHANCE Dylan DUPONT Thibaut	Explain the potential for energy mutualisation at the urban block scale and how it can help to achieve zero energy communities (reference : 1.5 ZEB & ZEN) (A.5).
HAULT Sarah TAMBURRINI Robin LEGRAIN Nathan	Explain how energy is taken into account in life-cycle assessment (LCA) of buildings (references : 1.6 LCA-1 & 1.7 LCA-2) (A.6 and A.7).
CUFFARO Jordan ZALESKI Jules ULITINA Anastasia	Explain how occupants' behaviours and occupation modes influence the energy consumption of a residential building (reference : 1.9 Occupants) (A.9).

Session 11

- Supervisors: Reiter Sigrid, Christine Bouvy
- Date: 9/03
- Time: from 8h30 to 12h30
- Place: B28 (R18)

Team	Subject
ROEMERS Quentin CORMEAU Louis ACHARY Kawthar	Explain what is a ZEB (Zero Energy Building) and what are the issues of its definition (reference: 1.5 ZEB & ZEN) (A.5).
BARZAQ Yasmine SERVAIS Coline HANNACHI Lucas	Explain how the climate and energy mix of a country influence the energy consumption of buildings (references : 1.6 LCA-1 & 1.7 LCA-2) (A.6 and A.7).
PELZER Hugo QALAJ Puhia DARDENNE Alexis	Explain what are the environmental and socio-economic impacts of urban sprawl (reference 1.1 Urban sprawl) (A.1).
DENEFFE Nathan GILLIEAUX Margaux FRANSOLET Lucas	Compare strategies to reduce energy consumption of buildings and transport at the city scale (reference: 1.2 Low energy cities) (A.2).
RENAUD Arnaud BENOTHMAN Rami AERTS Julien	Explain how the built density and urban form influence the energy consumption of districts (reference : 1.8 Built density) (A.8).
DUMORTIER Romain DELPERDANGE Théo JUMPERTZ Sacha	Explain the potential for energy mutualisation at the urban block scale and how it can help to achieve zero energy communities (reference : 1.5 ZEB & ZEN) (A.5).

Session 12

- Supervisors: Dewallef Pierre, Christine Bouvy
- Date: 10/03
- Time: from 8h30 to 12h30
- Place: 0/33 - B37

Team	Subject
QUODBACH Arthur NÉLISSEN Lucie OFFERMANN MARTINS Timóteo	Status of Concentrated Solar Photovoltaic (CSP) technology for electricity production (See Reference B.1).
LECLERC Emilien RUTH Matteo BELLAFQIH Reda	Status of Solar Tower Power Plant technology for electricity production (See Reference B.2).
LOUIS Arthur MOES Tom HOGGE Louis	Status of Natural Gas cogeneration power plant technology for combined heat and electricity production (See Reference B.11).
GASPAR Victor DIFFELS Noé RASIR Astrid	Status of Carbon Capture and Storage applied on natural gas combined cycle power plants for electricity production (See Reference B.12).
VOSKERTCHIAN Gregory MARECHAL Michael VERHEYDEN Antoine	Status of Carbon Capture and Storage applied on coal power plants for electricity production (See Reference B.13).
LOUVIAUX Florence COEN Simon JONLET Lucas	Status of Carbon Capture and Storage applied on integrated coal gasification combined cycle (IGCC) power plants for electricity production (See Reference B.14).

Session 13

- Supervisors: Manakari Vageesh, Clara Brereton
- Date: 11/03
- Time: from 13h30 to 17h30
- Place: 1.97, B28

Team	Subject
LAURENT Célestine LE Maureen BODEN Matthieu	The EU Clean Energy Package: present the content of two of the proposals of this package: E-Directive (Directive on common rules for the internal market in electricity (C.1, C.2), and E-Regulation (Regulation on the internal market for electricity (C.3). You can (and probably should) check the following document summarising the content (C.4).
BATLLE MARI Lucas MITRAKI Rafailia OOMS Gilles	Demand Response as a way of introducing flexibility into the energy sector: what does it entail? How can this be implemented in practice?
TEVOEDJRE Philippe MAGEZA Jules	Wholesale markets in Europe: present the organisation of the wholesale markets in Europe: the day-ahead and the intraday markets. Explain how these trading floors operate including examples from at least three different European countries.
LEFEBVRE Jean CLÉMENS Stéphane	Electricity sector: present the organisation of the electricity sector in Europe, laying stress on the role of TSO and DSO. Explain the role of all actors involved in the delivery of electricity, from its production to its consumption. Include examples from different European countries.
VISEUR Lucas DELHEZ Jeanne DI RENZO JACQUEMIN Antoine	Balancing markets: present the role of balancing markets in Europe. What are the obligations of BRP, ARP, and BSP? Explain how the balancing markets are integrated in the European Union (e.g. IGCC initiative).
REMACLE Colette GHYSENS François ELOUDRHIRI Rayane	Electricity Interconnectors: what are they? Present the NEMO and ALEGrO links.

Session 14

- Supervisors: Reiter Sigrid, Clara Brereton
- Date: 14/03
- Time: from 13h30 to 17h30
- Place: B28 (1.94)

Team	Subject
MAGAIN Pierre LACANNE Laura ISERENTANT Tanguy	Explain what is "Urban sprawl" and what are their drivers (Reference 1.1 Urban sprawl) (A.1).
CLOUX Romain COLSON Léonore TROQUAY Julien	Present the potential energy savings associated with buildings' renovation strategies at the city scale (reference: 1.2 Low energy cities) (A.2).
BOUGNET Nicolas DROESCH William SOW Oumar	Present and compare key parameters and strategies to improve transport energy consumption (reference : 1.3 transport) (A.3).
MARTIN Antoine LERUTH Guillaume WALLON Bertrand	Explain the concept of "territorial recomposition" and how it can influence the energy consumption due to transport at a regional scale (reference : 1.4 Territorial recomposition) (A.4).
ROMOLI Raphaël HEINE Clément LINOTTE Lucie	Explain what is a ZEB (Zero Energy Building) and what are the issues of its definition (reference: 1.5 ZEB & ZEN) (A.5).
VOGELS Arthur GHOSEZ Arthur DI SIMONE Gaëtan	Explain how the climate and energy mix of a country influence the energy consumption of buildings (references : 1.6 LCA-1 & 1.7 LCA-2) (A.6 and A.7).
BRIESINGER Zoé MICHIELS Sven	Explain the potential for energy mutualisation at the urban block scale and how it can help to achieve zero energy communities (reference : 1.5 ZEB & ZEN) (A.5).

Session 15

- Supervisors: Job Nathalie, Clara Brereton
- Date: 18/03
- Time: from 13h30 to 17h30
- Place: B6d - R24

Team	Subject
PAULY Enya BATLLE MARI Lucas BASTIN Sophie	Explain how biomass can be transformed into fuel. Discuss the use of biodiesel/diesel blends in vehicle applications, and give an overview of the Belgian regulations.
VISEUR Lucas DUTAILLY Guillaume SERET Cédric	Discuss the economic, environmental and ethical issues of biodiesel production.
PIERRE Jérôme DI RENZO JACQUEMIN Antoine MOUREAU Gregoire	Discuss the possibilities of electricity storage by batteries. In particular, give an overview of the limitations of these techniques in terms of material resources.
FAINGNAERT Théo DEKINDER Florian SHEBLI Rami	Give an overview of the use of hydrogen as energy carrier (production, limitations, existing networks and end-use).
REMACLE Colette RASIR Juliette MAGEZA Jules	Explain the general principle of fuel cell technology and their advantages/drawbacks vs. thermo-mechanical systems. Discuss the advantages and drawbacks of high temperature fuel cells (MCFC and SOFC) vs. low temperature fuel cells (AFC and PEMFC).
LEFEBVRE Jean ELOUDRHIRI Rayane CORMEAU Louis	Discuss the differences between fuel cell and battery electric vehicles. Give an overview of advantages and drawbacks of both technologies.

Session 16

- Supervisors: Manakari Vageesh, Christine Bouvy
- Date: 21/03
- Time: from 13h30 to 17h30
- Place: 2.93, B28

Team	Subject
CRON Valentin VOSKERTCHIAN Gregory SPITS Alexandre	EU targets: present and explain the EU 2020 targets, EU 2030 targets, and EU 2050 targets.
MARTIN Grégoire RENSON Xavier MICHEL Merlin	IPCC Special Report Global Warming of 1.5C (C.5): present an overview of the report laying stress on the summary for policy makers, chapter 1, and chapter 5.
LAMBERMONT Romain de LA BRASSINNE BONARDEAUX Maxence FRANSOLET Lucas	EU Network Codes and guidelines: what are they? Why do they exist? Present an overview of these eight regulations (C.6) laying stress on the the capacity allocation and congestion management guideline (CACM) (C.7). You can resort to this report to help you understand this network code (C.8).
DESTEXHE Clara CLERFAYS Alix HAAS Bastien	Solar photovoltaic (PV) and Electric vehicles: how are these technologies being integrated in the distribution networks? What challenges (technical AND regulatory) do they pose for the distribution networks?
GECIM Hülya ROEMERS Quentin GUYSENS Thiébaud	Integrated energy systems: coupling of gas and electricity markets. Explain how this can work, and what benefits it may bring to the European Electricity System. You can use the following reports to guide you (C.9, C.10, C.11, C.12).
DENEFFE Nathan BOUYAKHRICHAN Nabil GODART Antoine	Blockchain technologies in the electricity sector. Search for scientific papers about the topic, explaining how this technology can be implemented and can help the development of the future electricity systems.

Session 17

- Supervisors: Dewallef Pierre, Polson Martin
- Date: 23/03
- Time: from 13h30 to 17h30
- Place: 0/36 - B37

Team	Subject
CLÉMENS Stéphane COEN Simon T'SERSTEVENS Antoine	Status of off-shore wind power technology for electricity production (See Reference B.3).
MATHY Maxine BOULANGER Elyse ACHARY Kawthar	Status of biomass combustion power plant technology for electricity production (See Reference B.4).
NDIZEYE ABEWE Elisabeth CUFFARO Jordan CLOOTS Nicolas	Status of tidal power plant technology for electricity production (See Reference B.5).
DEBAUCHERON Thomas LOUVEAU Simon FLOREA Robert	Status of ocean thermal energy conversion (OTEC) power plant technology for electricity production (See Reference B.6).
HUBERT Martin DUPONT Thibaut AKOGO Ornella	Status of Stirling dish power plant technology for electricity production (See Reference B.7).
FRANCOIS Constance ZALESKI Jules BODEN Matthieu	Status of Natural Gas Combined Cycle (NGCC) technology for electricity production (See Reference B.8).

Session 18

- Supervisors: Job Nathalie, Veronique Doppagne
- Date: 24/03
- Time: from 8h30 to 12h30
- Place: B7a - S5

Team	Subject
SANDRONT Gaëlle LOUIS Arthur DIFFELS Noé	Discuss the concept of ”Clean coal technology”.
SCHUMACKER Cyril DALEM Pierre THIEBAUT Martin	Give an overview of the various carbon capture & storage techniques. Discuss their advantages/drawbacks in terms of economy and environmental issues.
GRAINDORGE Pierre DESOLEIL Brandon FARCAS Maria	Explain how to transform solar energy into electricity via steam (Solar Energy Generating Systems). Describe the Mojave Solar Project.
MELOTTE Théo KEITA Mohamed RONDIA Arthur	Describe the ITER project (nuclear energy).
WÉRY Victor LEDUC Arnaud OFFERMANN MARTINS Timóteo	What is coal gasification? Describe the process in the case of (i) classical gasifiers and (ii) underground processes.
MAGAIN Pierre MITRAKI Rafailia VINDERS Adrien	Give an overview of the shale gas extraction technique. Discuss the environmental issues.

Session 19

- Supervisors: Dewallef Pierre, Christine Bouvy
- Date: 30/03
- Time: from 8h30 to 12h30
- Place: 0/36 - B37

Team	Subject
DEMEULDRE Lena JACQUET Charles RUTTEN Grégoire	Status of Nuclear power plant technology for electricity production (See Reference B.9).
MOTTARD Alexandre BRANKART Guillaume RASIR Juliette	Status of Integrated coal Gazeification combined cycle (IGCC) power plant technology for electricity production (See Reference B.10).
ULITINA Anastasia DI BARTOLOMEO Katia SHEBLI Rami	Status of Natural Gas cogeneration power plant technology for combined heat and electricity production (See Reference B.11).
SKA Margaux DEPAS Cyrielle BIRTLES Alixia	Status of Carbon Capture and Storage applied on natural gas combined cycle power plants for electricity production (See Reference B.12).
PIRON Romain THOMEE Corentin MATHUES BILGINER Lucie	Status of Carbon Capture and Storage applied on coal power plants for electricity production (See Reference B.13).
RUWET Emile MOUREAU Gregoire JUMPERTZ Sacha	Status of Carbon Capture and Storage applied on integrated coal gasification combined cycle (IGCC) power plants for electricity production (See Reference B.14).

Session 20

- Supervisors: Manakari Vageesh, Polson Martin
- Date: 30/03
- Time: from 8h30 to 12h30
- Place: R18, B28

Team	Subject
GILLIEAUX Margaux JACOBS Hugo BROCHARD Adrien	The EU Clean Energy Package: present the content of two of the proposals of this package: E-Directive (Directive on common rules for the internal market in electricity (C.1, C.2), and E-Regulation (Regulation on the internal market for electricity (C.3). You can (and probably should) check the following document summarising the content (C.4).
FIRRINCIELI Maxime SCHYNS Léo HEINE Clément	Demand Response as a way of introducing flexibility into the energy sector: what does it entail? How can this be implemented in practice?
GILSON Florence BOULAICH Haytham NAVEZ Tom	Wholesale markets in Europe: present the organisation of the wholesale markets in Europe: the day-ahead and the intraday markets. Explain how these trading floors operate including examples from at least three different European countries.
LECLERC Emilien AERTS Julien DUCHESNE Maxime	Electricity sector: present the organisation of the electricity sector in Europe, laying stress on the role of TSO and DSO. Explain the role of all actors involved in the delivery of electricity, from its production to its consumption. Include examples from different European countries.
LERUTH Guillaume GASPAR Victor GHOSEZ Arthur	Balancing markets: present the role of balancing markets in Europe. What are the obligations of BRP, ARP, and BSP? Explain how the balancing markets are integrated in the European Union (e.g. IGCC initiative).
TSHILOLO MUEPU MALAIKA Josémaria DUCHESNE Tom HOUET Florine	Electricity Interconnectors: what are they? Present the NEMO and ALEGrO links.

Session 21

- Supervisors: Job Nathalie, Clara Brereton
- Date: 30/03
- Time: from 13h30 to 17h30
- Place: B7a - S4

Team	Subject
COLLETTE Florine LEHANCE Dylan SOW Oumar	Discuss the concept of ”Clean coal technology”.
REBEIX Thomas BERTHUS Louis DELPERDANGE Théo	Give an overview of the various carbon capture storage techniques. Discuss their advantages/drawbacks in terms of economy and environmental issues.
DELPORTE Guillaume JONLET Lucas JACQUEMIN Gilles	Give an overview of the shale gas extraction technique. Discuss the environmental issues.
SCHOLZEN Fernand DARDENNE Alexis HAULT Sarah	Explain how to transform solar energy into electricity via steam (Solar Energy Generating Systems). Describe the Mojave Solar Project.
LAURENT Célestine BECKERS Thibault HANNACHI Lucas	Describe the ITER project (nuclear energy).
HOUSSA César MESSENS Tom LEGRAIN Nathan	What is coal gasification? Describe the process in the case of (i) classical gasifiers and (ii) underground processes.

Session 22

- Supervisors: Dewallef Pierre, Veronique Doppagne
- Date: 31/03
- Time: from 8h30 to 12h30
- Place: 0/36 - B37

Team	Subject
LAMBERMONT Romain GELELEENS Emil WALTREGNY Juliette	Status of tidal power plant technology for electricity production (See Reference B.5)
LOUVIAUX Florence RUTH Matteo	Status of ocean thermal energy conversion (OTEC) power plant technology for electricity production (See Reference B.6).
CHRISTIAENS Juliette QUODBACH Arthur ARSANOV Ramzan	Status of Stirling dish power plant technology for electricity production (See Reference B.7).
PAGANO Florian GALAN Andrei NÉLISSEN Lucie	Status of Natural Gas Combined Cycle (NGCC) technology for electricity production (See Reference B.8).
MARECHAL Michael KADIOGLU Sélim BELLAFQIH Reda	Status of Nuclear power plant technology for electricity production (See Reference B.9).
DARDENNE Denis PONCELET Antoine DENGIS Maël	Status of Integrated coal Gazeification combined cycle (IGCC) power plant technology for electricity production (See Reference B.10).

Appendix A: Sigrid Reiter

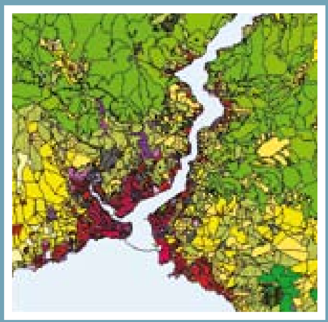
Appendix A.1

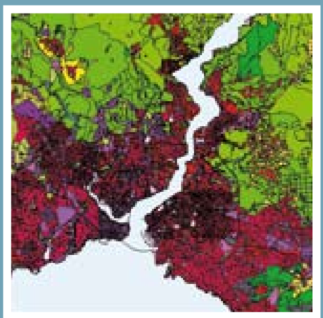
EEA Report | No 10/2006

Urban sprawl in Europe

The ignored challenge

ISSN 1725-9177





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Joint Research Centre

European Environment Agency

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Urban sprawl in Europe

The ignored challenge

EUROPEAN COMMISSION
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Joint Research Centre

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Luxembourg: Office for Official Publications of the European Communities, 2006

ISBN 92-9167-887-2
ISSN 1725-9177

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REG.NO. DK-000244

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Contents

Acknowledgements

The main content of this report is based on the work of EEA Topic Centre on Terrestrial Environment (ETC-TE), in close cooperation with the Joint Research Centre (Ispra) of the European Commission.

The contributors in the project team from the European Topic Centre on Terrestrial Environment were: David Ludlow (lead author, University of the West of England, Bristol), Jaume Fons (task manager), Núria Blanes, Oscar Gómez and Heimo Savolainen, assisted by EEA project officer Agnieszka Romanowicz.

From the JRC, were involved: Marjo Kasanko (task leader), José I. Barredo, Carlo Lavalle, Laura Petrov and Valentina Sagris.

External experts have been consulted throughout the report development. The consultation process included a workshop on the final draft of the report (September 2006). The EEA and JRC wish to acknowledge their valuable input, especially in connection with national, regional and local case studies.

The experts were: Luca Demicheli (APAT — Italian Agency for Environmental Protection and Technical Services), Philippe Doucet (GEPHYRES), Guy Engelen (VITO — Flemish Institute for Technological Research Centre for Integrated Environmental Studies), Andreas Kraemer (Ecologics), Pierre Laconte (Foundation for the Urban Environment; Member of the EEA Scientific Committee) and Henk Ottens (Milieu- en Natuurplanbureau).

This report was conceived, coordinated and edited by Ronan Uhel (EEA).

1 Urban sprawl — a European challenge

1.1 Introduction

Europe is a fascinating and diverse continent, one of the most urbanised on earth. Today, approximately 75 % of the European population live in urban areas, while still enjoying access to extensive natural or semi-natural landscapes. With its stunning urban landscapes, historical cities and cultural treasures, Europe remains one of the world's most desirable and healthy places to live. Moreover, it is the most frequently visited world-travel destination.

The urban future of Europe, however, is a matter of great concern. More than a quarter of the European Union's territory has now been directly affected by urban land use; by 2020, approximately 80 % of Europeans will be living in urban areas, while in seven countries the proportion will be 90 % or more. As a result, the various demands for land in and around cities are becoming increasingly acute. On a daily basis, we all witness rapid, visible and conflicting changes in land use which are shaping landscapes in cities and around them as never before.

Today, society's collective reliance on land and nature for food, raw materials and waste absorption results in a resource demand without precedent in history. In Europe, our consumption patterns are completely different from what they were twenty years ago. Transport, new types of housing, communication, tourism and leisure have emerged as major components of household consumption.

As most of the population live in urban areas, agricultural land uses and their functions in the countryside have consequently evolved. Today, they ensure both the feeding of the city populations and maintenance of a diminishing rural population. Coasts are being urbanised at an accelerating rate, and resident communities are being transformed in order to accommodate these new economies. As a result, our coasts are becoming increasingly intertwined with the hinterland and more dependent on tourism and secondary homes (EEA, 2006).

In this modified landscape, a powerful force is at work: cities are spreading, minimising the time and distances between and in-and-out of the cities. This expansion is occurring in a scattered way throughout Europe's countryside: its name is urban sprawl. Furthermore, it is now rightly regarded as one of the major common challenges facing urban Europe today.

1.2 Why sprawl matters?

Sprawl threatens the very culture of Europe, as it creates environmental, social and economic impacts for both the cities and countryside of Europe. Moreover, it seriously undermines efforts to meet the global challenge of climate change.

Urban sprawl is synonymous with unplanned incremental urban development, characterised by a low density mix of land uses on the urban fringe (Box 1). Classically, urban sprawl is a US phenomenon associated with the rapid low-density outward expansion of US cities, stemming back to the early part of the 20th century. It was fuelled by the rapid growth of private car ownership and the preference for detached houses with gardens.

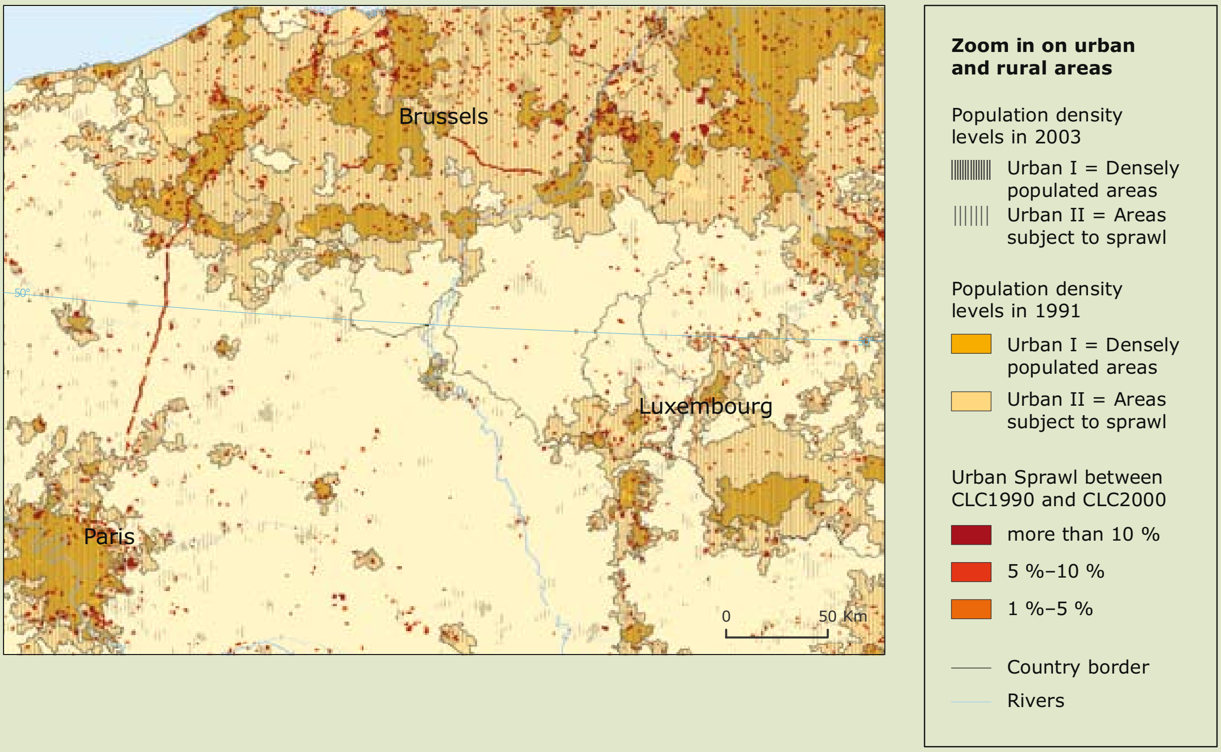
In Europe, cities have traditionally been much more compact, developing a dense historical core shaped before the emergence of modern transport systems. Compared to most American cities, their European counterparts still remain in many cases compact. However, European cities were more compact and less sprawled in the mid 1950s than they are today, and urban sprawl is now a common phenomenon throughout Europe. Moreover, there is no apparent slowing in these trends. The urban areas particularly at risk are in the southern, eastern and central parts of Europe are particularly at risk.

The sprawling nature of Europe's cities is critically important because of the major impacts that are evident in increased energy, land and soil consumption. These impacts threaten both the natural and rural environments, raising greenhouse

Box 1 Urban sprawl — definition

Urban sprawl is commonly used to describe physically expanding urban areas. The European Environment Agency (EEA) has described sprawl as the physical pattern of low-density expansion of large urban areas, under market conditions, mainly into the surrounding agricultural areas. Sprawl is the leading edge of urban growth and implies little planning control of land subdivision. Development is patchy, scattered and strung out, with a tendency for discontinuity. It leap-frogs over areas, leaving agricultural enclaves. Sprawling cities are the opposite of compact cities — full of empty spaces that indicate the inefficiencies in development and highlight the consequences of uncontrolled growth.

The map of northeast France, Belgium, Luxembourg and northwest Germany illustrates the definition of urban sprawl, and shows the urban areas overlaid with population density. It is clear that low density populated areas extend far beyond the centres of cities, with new urban areas spreading along the Paris-Brussels axis adjacent to the TGV high-speed railway (an effect of the 'beetroot' train stations).



Note: Due to changes in the Eurostat methodology the two datasets (1991 and 2003) differ.

Source: EEA (based on EEA and Eurostat data).

gas emissions that cause climate change, and elevated air and noise pollution levels which often exceed the agreed human safety limits. Thus, urban sprawl produces many adverse impacts that have direct effects on the quality of life for people living in cities.

1.3 Why are cities sprawling?

Historically, the growth of cities has been driven by increasing urban population. However, in Europe today, even where there is little or no population pressure, a variety of factors are still driving sprawl. These are rooted in the desire to realise new lifestyles in suburban environments, outside the inner city.

Global socio-economic forces are interacting with more localised environmental and spatial constraints to generate the common characteristics of urban sprawl evident throughout Europe today. At the same time, sprawl has accelerated in response to improved transportation links and enhanced personal mobility. This has made it possible either to live increasingly farther away from city centres, while retaining all the advantages of a city location, or enabled people to live in one city and work in another.

The mix of forces include both micro and macro socio-economic trends such as the means of transportation, the price of land, individual housing preferences, demographic trends, cultural traditions and constraints, the attractiveness of existing urban areas, and, not least, the application of land use planning policies at both local and regional scales.

Overall, evidence suggests that where unplanned, decentralised development dominates, sprawl will occur in a mechanistic way. Conversely, where growth around the periphery of the city is coordinated by strong urban policy, more compact forms of urban development can be secured.

1.4 Links to EU policies

In essence, through the realisation of the 'internal market', Europe's new prosperity and economic development has put pressure on cities. The role and contribution of cities to Europe's economic growth, jobs and competitiveness, while also delivering social and environmental goals, has been addressed extensively by the EU institutions together with the regional and local authorities (European Commission, 2005). Sustainable urban development appears prominently in many European policy commitments, not least EU regional policy.

To this end substantial EU Cohesion and Structural Funds budget transfers to Member States provide powerful drivers of macro-economic change to support EU integration. However, analysis shows that they can also create inadvertent socio-economic effects that have promoted the development of sprawl. The coordination of land use policies and Structural and Cohesion Funds investments remains key to support the containment of urban sprawl, which is complicated by the fact that EU intervention in many other, if not all, policy domains, impact on or are impacted by urban development.

One illustration of the extent of these interrelationships is the EU commitment to sustainable development and policies to tackle climate change: how can we ensure that the growth of urban greenhouse gas emissions due to the dominance of car transport in the EU's sprawling cities does not threaten to undermine EU Kyoto commitments to reduce greenhouse gas emissions by 2020?

Overall, the EU has an obligation in relation to the wide range of environmental, social and economic impacts of urban sprawl to define a clear and substantial responsibility, and a mandate to take an active lead in the development of new initiatives to counter the impacts of sprawl.

1.5 Who should read this report?

This report is targeted at all those actively involved in the management of Europe's urban areas. The aim is to inform about the impacts of urban sprawl in Europe today and that without concerted action by all agencies to address the underlying causes, the economic social and environmental future of our cities and regions can be compromised.

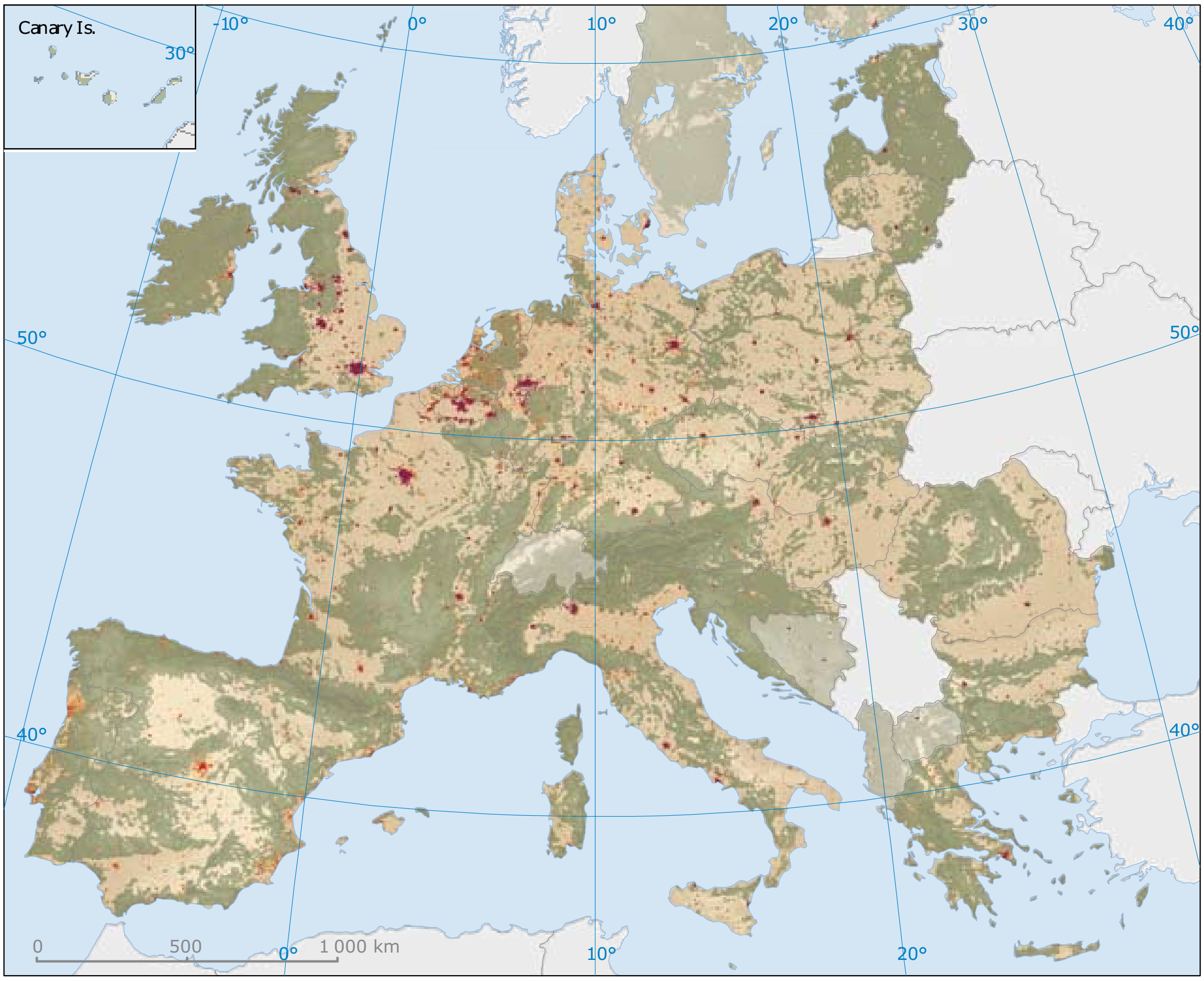
Subsequent chapters of this report describe the patterns of urban sprawl that have emerged throughout Europe during the post war period (Chapter 2), which are related to the global social and economic trends that form the fundamental drivers of sprawl (Chapter 3). Chapter 4 reviews the evidence of the impacts of urban sprawl, and concludes that the sprawling city creates major and severe impacts in relation to a variety of environmental, social and economic issues affecting not only the city and its region but also the surrounding rural areas. Finally, Chapter 5 examines the principles that could underpin the framework for action at EU level to combat urban sprawl. This would include increased policy coherence built around measures to secure policy integration via close coordination between policies in different domains, better cooperation between different levels of administration, as well as policy definition according to the principles of sustainable development.

2 The extent of urban sprawl in Europe

2.1 The European picture

The process of urbanisation in Europe has evolved as a clear cycle of change during the post-war period from urbanisation to suburbanisation to de-urbanisation and, most recently, to re-urbanisation. Historically, the growth of cities was fundamentally linked to increasing population. In contrast, urban sprawl is a more recent phenomenon and is no longer tied to population

Map 1 Urban expansion in Europe (1990–2000)



Urban and infrastructure development
- 1 to 5 %
- 5 to 10 %
- More than 10 %

Urban zones 1990
- More than 50 000 people

Green background index
- 0 to 60 %
- 61 to 100 %

Source: EEA, 2005.

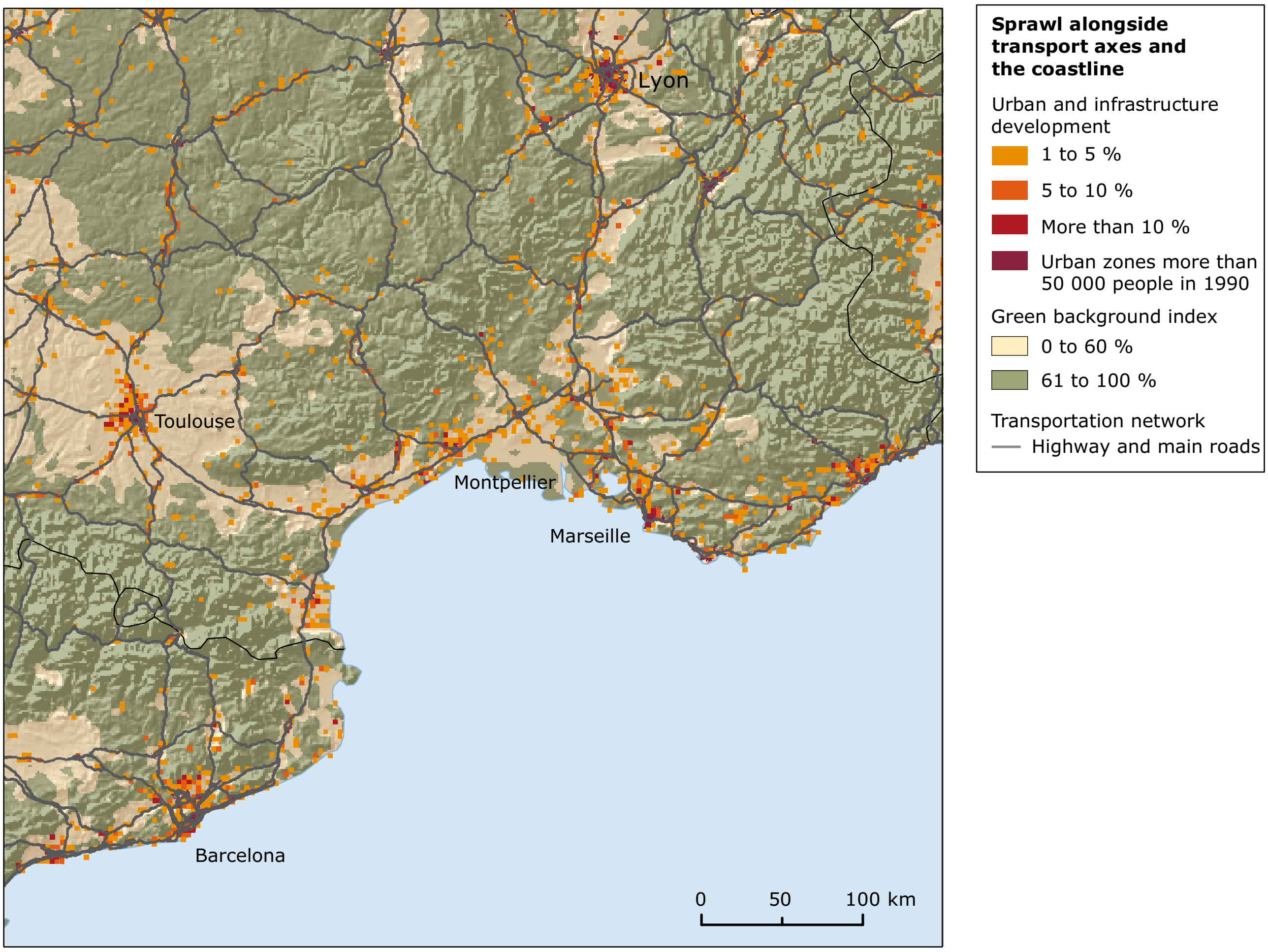
growth as mentioned in Chapter 1. Rather a variety of other powerful factors drive the development of the modern city, including individual housing preferences, increased mobility, commercial investment decisions, and the coherence and effectiveness of land use policies at all levels.

All available evidence demonstrates conclusively that urban sprawl has accompanied the growth of urban areas across Europe over the past 50 years. This is shown from a recent European perspective (Map 1). The areas with the most visible impacts of urban sprawl are in countries or regions with high population density and economic activity (Belgium, the Netherlands, southern and western Germany, northern Italy, the Paris region) and/or rapid economic growth (Ireland, Portugal, eastern Germany, the Madrid region). Sprawl is particularly evident where countries or regions have benefited from EU regional policies. New development patterns can also be observed, around smaller towns or in the countryside, along transportation corridors, and along many parts of the coast usually connected to river valleys. The latter is exemplified by the so-called 'inverse T' of urban sprawl along the Rhône valley down to the Mediterranean coast (Map 2).

Hot spots of urban sprawl are also common along already highly populated coastal strips, such as in the case of Spain where the artificial areas may cover up to 50 % of the total land area (Map 3). This is doubly worrying given the known vulnerability of coastal ecosystems and because the Mediterranean region is classified as one of 34 biodiversity hotspots in the world.

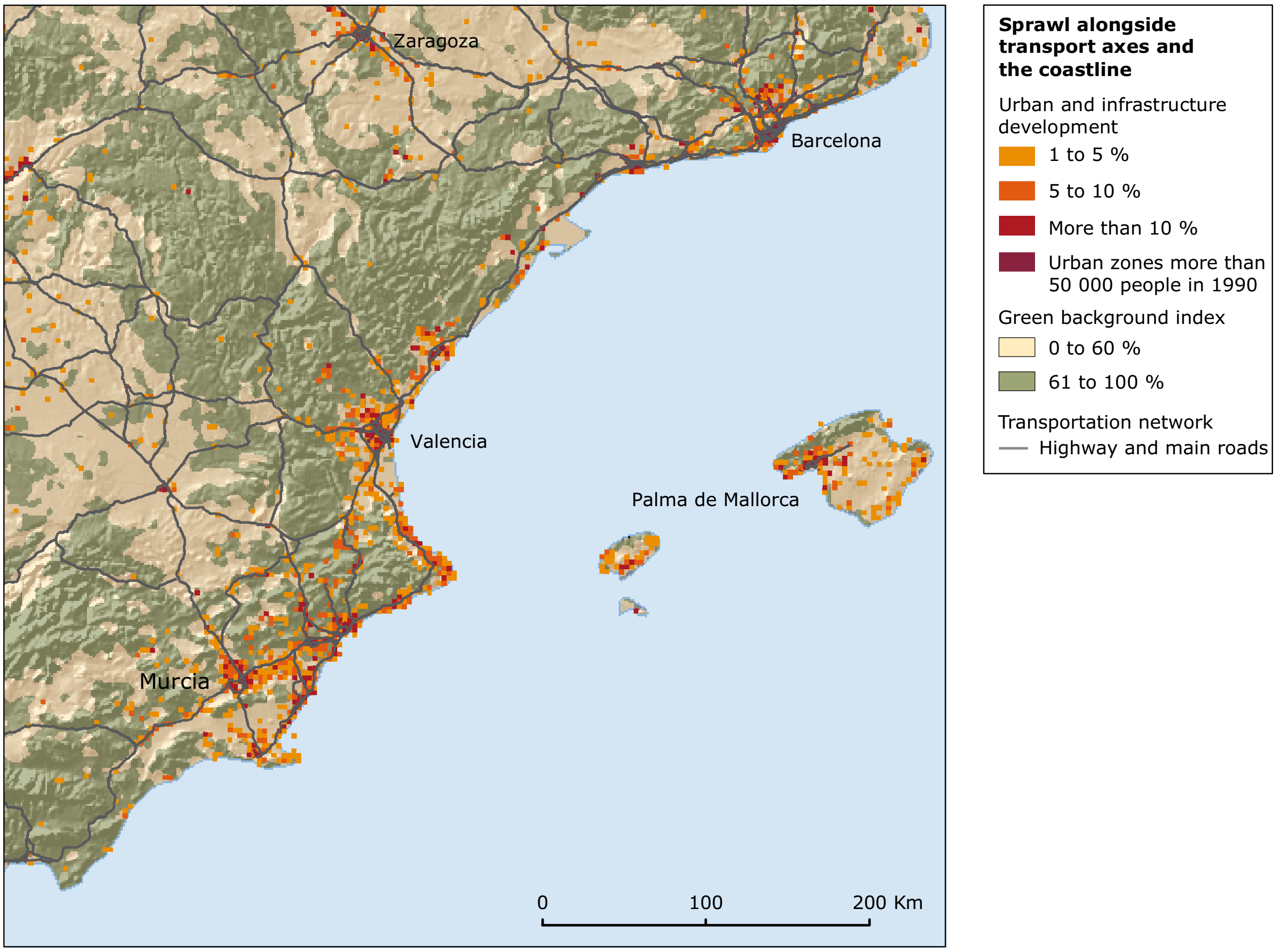
Sprawl may also follow from the expected rapid economic development in many parts of the new Member States, as internal economic dynamism, greater access to EU markets, and Cohesion Fund and Structural Funds investments drive economies. The 2004 accession is too recent to permit full understanding of the potential impacts of urban

Map 2 Urban sprawl along the Rhône corridor: south of France (1990–2000)



Source: EEA.

Map 3 Urban sprawl on the Mediterranean coast: southeast Spain (1990–2000)



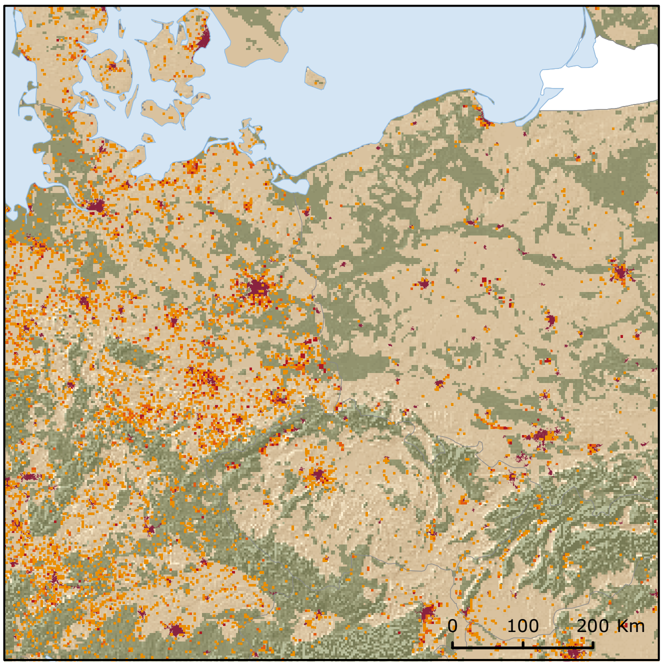
Source: EEA.

sprawl driven by this economic expansion, but some insights can be provided by comparisons between eastern Germany and Poland for the period 1990–2000. East Germany benefited from large monetary transfers from West Germany after unification in 1990, making it one of the most rapidly developing regions in Europe. In contrast, just to the east, in Poland, where EU membership is more recent, there was less development during the period 1990–2000 and the differences in the levels of urban sprawl between Germany and Poland are quite marked (Map 4). This contrast is accentuated by the region history.

As already said, the growth of built-up areas in Europe reached its peak in 1950s–1960s (MOLAND), when the average annual growth rate reached 3.3 % (Figure 1). In subsequent decades the main wave of urban growth has moved farther away from the city centres allowing urban sprawl to extend the urban footprint into the adjacent countryside (Antrop, M., 2004; Sallez & Burgi, 2004; Prud'homme & Nicot, 2004; Couch *et al*., 2005).

Indeed during the ten year period 1990–2000 the growth of urban areas and associated infrastructure throughout Europe consumed more than 8 000 km^2 (a 5.4 % increase during the period), equivalent to complete coverage of the entire territory of the state of Luxembourg. This is equivalent to the consumption of 0.25 % of the combined area of agriculture, forest and natural land. These changes may seem small. However, urban sprawl is concentrated in particular areas which tend to be where the rate of urban growth was already high during the 1970s and 1980s. Moreover, they run alongside the emerging problems of rural depopulation. On a straight extrapolation, a 0.6 % annual increase in urban areas, although apparently small, would lead to a doubling of the amount of urban area in little over a century (EEA, 2005). This needs careful consideration as

Map 4 Urban sprawl in Germany, Poland and Czech Republic (1990–2000)



Time lags and uneven development

Urban and infrastructure development

- 1 to 5 %
- 5 to 10 %
- More than 10 %

Urban zones 1990

- More than 50 000 people

Green background index

- 0 to 60 %
- 61 to 100 %
- No data

Source: EEA, 2005.

we look ahead to the type of Europe we would like to see in the next 50–100 years, taking into account possible climate change and the many impacts and adaptation challenges it would pose (see Chapter 4, Section 4.1.4).

Historical trends, since the mid-1950s, show that European cities have expanded on average by 78 %, whereas the population has grown by only 33 %. A major consequence of this trend is that European cities have become much less compact. The dense enclosed quarters of the compact city have been replaced by free standing apartment blocks, semi-detached and detached houses. In half of the urban areas studied in the Moland project, more than 90 % of all residential areas built after the mid-1950s were low density areas, with less than 80 % of the land surface covered by buildings, roads and other structures (Figure 2). Only in 5 of the 24 cities, all in southern or central parts of Europe, were more than 50 % of new housing areas (built since the mid-1950s) densely built-up.

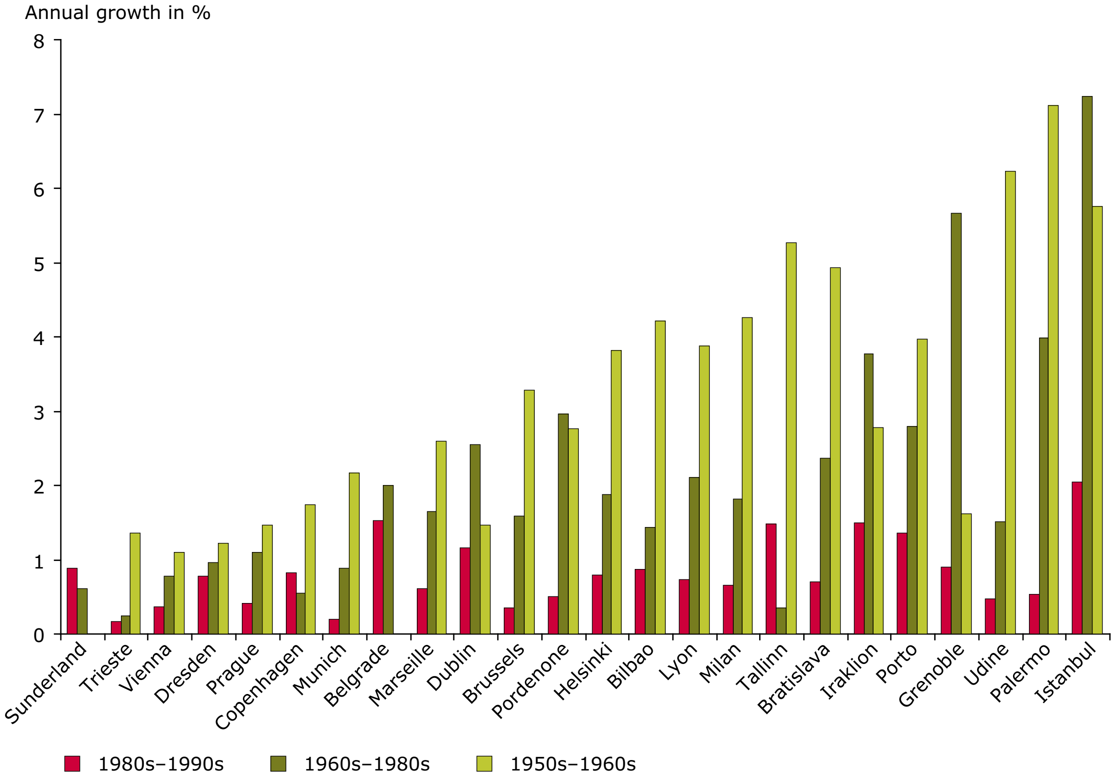
Trends towards new low density environments are also evident in the space consumed per person in the cities of Europe during the past 50 years which has more than doubled. In particular, over the past 20 years the extent of built-up areas in many western and eastern European countries has increased by 20 % while the population has increased by only 6 % (Figure 3).

Sprawl is greater, and in many cases significantly greater, than would be expected on the basis of population growth alone (MOLAND). Only in Munich and Bilbao has population grown more rapidly than in the built-up area. Palermo with 50 % growth in population generated more than 200 % growth in the built-up area (Figure 4).

Although the population is decreasing in many regions of Europe (Map 5 — blue tone), urban areas are still growing in those areas, notably Spain, Portugal and some parts of Italy (Map 5 — dark blue tone). Conversely, moderate increases of population accompanied by a large expansion of urban areas can be observed in Spain, Portugal, Ireland and the Netherlands. Major gains of population (> 10 %, through immigration) can only be observed in western Germany, where the average annual expansion of built-up areas is 47 000 ha/year, growth equivalent over 5 years to the area of Greater Copenhagen.

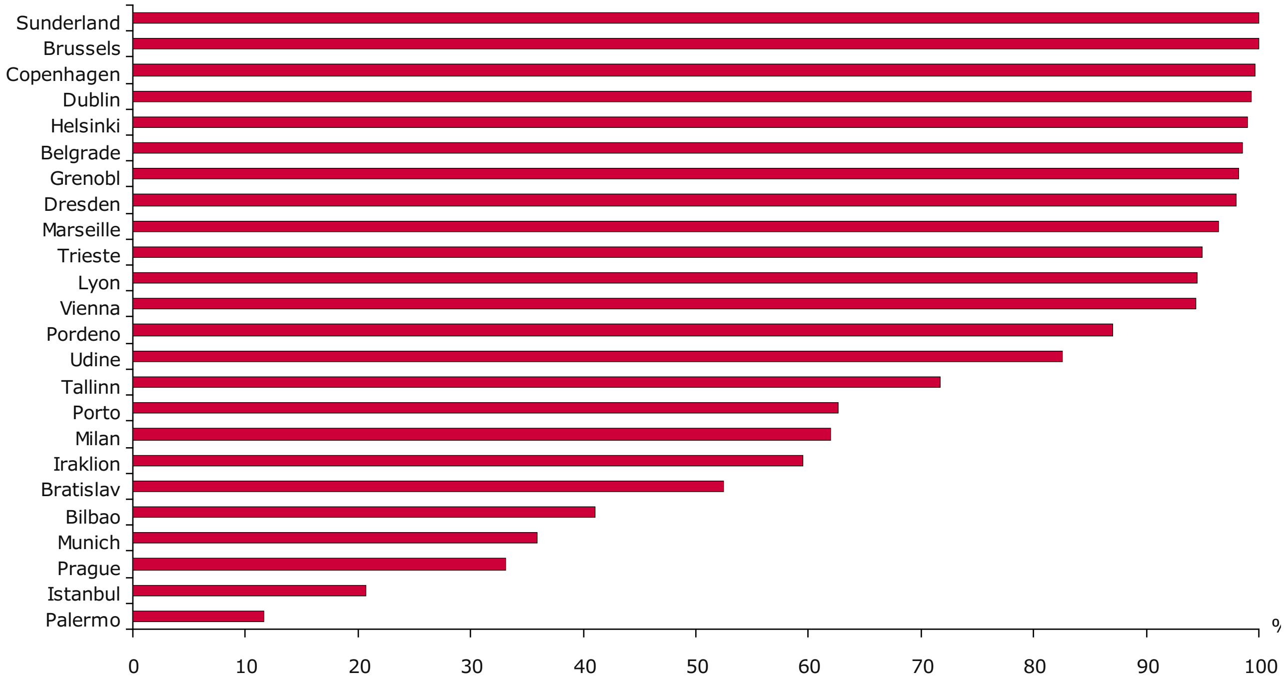
European cites are also remarkably diverse in respect of urban residential densities (Figure 5). Generally, there is a tendency for residential densities to fall towards the north and west of Europe, and the five urban areas with residential densities of at least 10 000 inhabitants/km^2 are all located in southern or southeastern Europe. There is no tendency, however, for urban sprawl to vary with the density of cities, as irrespective of urban

Figure 1 Annual growth of built-up areas from the mid-1950s to the late 1990s, selected European cities



Source: MOLAND (JRC) and Kasanko *et al.*, 2006.

Figure 2 Low density residential areas as a proportion of all residential areas built after the mid-1950s, selected European cities



Source: MOLAND (JRC) and Kasanko *et al.*, 2006.

residential density, sprawl is equally evident in the vast majority of the cities examined.

2.2 Regional clusters of sprawling and compact cities

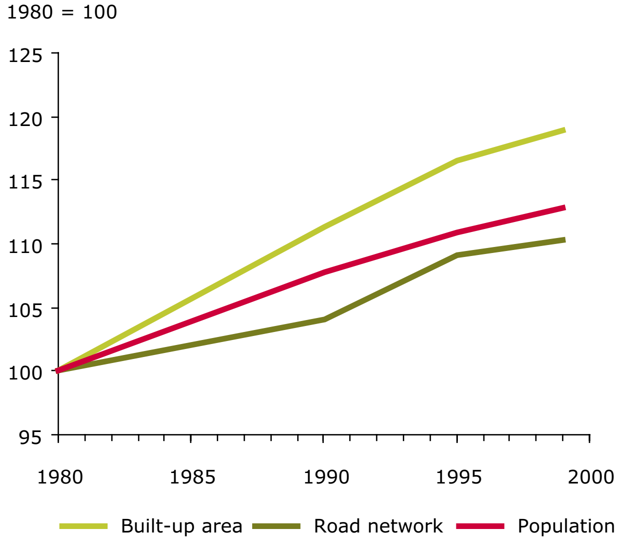
An assessment of the most sprawled and most compact urban areas in Europe can be realised based on the following indicators:

- Growth of built-up areas (1950s–1990s)
- Share of dense residential areas of all residential areas (1990s)
- Share of low density residential areas of all new residential areas (mid-1950s onwards)
- Residential density (1990s)
- The change in growth rates for population and built-up areas (1950s–1990s)
- Available built-up area per person (1990s).

Such indicator analysis for selected cities in Europe, undertaken as part of the MOLAND project, shows the most compact city, Bilbao, is three times denser than the most sprawled city, Udine. Generally the analysis demonstrates certain clustering of cities according to the degree of sprawl or compactness that appear to be more pronounced in certain regions of Europe rather than others (Table 1).

Southern European cities have a long urban tradition in which the urbanisation process has been slower, with fewer periods of rapid growth and the cities have been very compact. In recent decades, however, urban sprawl has started to develop at unprecedented rates, and it is most probable that unless land use planning and zoning restrictions are

Figure 3 Built-up area, road network and population increases, selected EEA countries



Note: Countries covered are: Belgium, Czech Republic, Denmark, France, Germany, Latvia, Lithuania, the Netherlands, Poland, Slovakia and Spain.

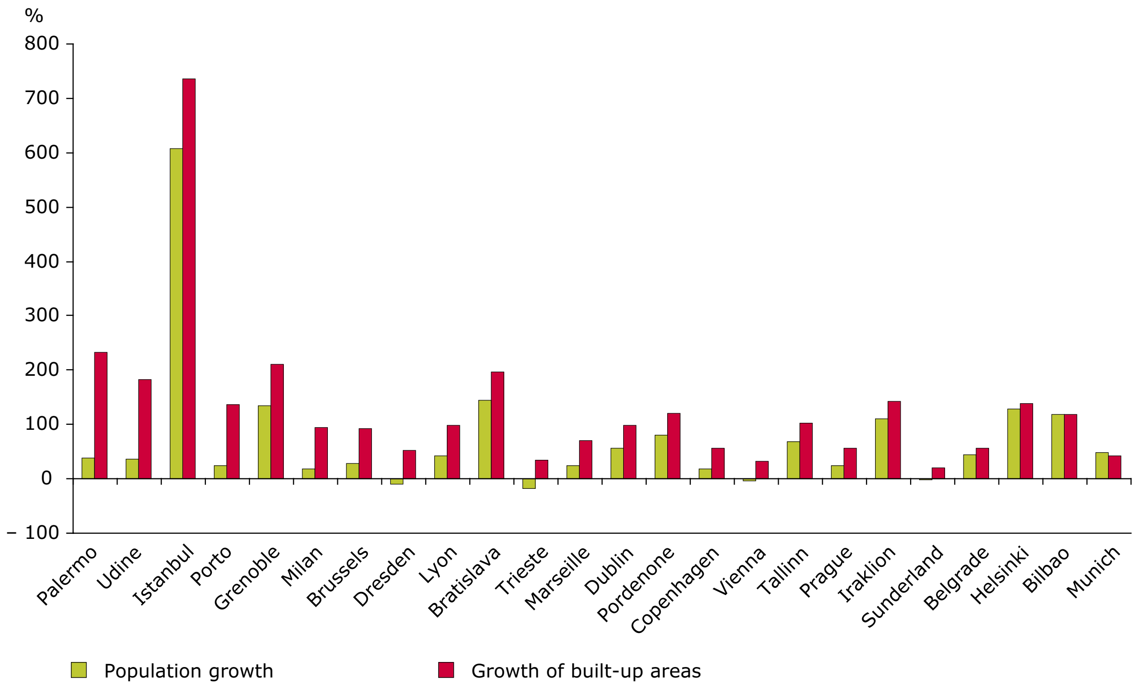
Source: EEA, 2002.

Table 1 Distribution of Europe's sprawling and compact cities

	Southern European cities	Eastern and central European cities	Northern and western European cities
Sprawled		Udine	
		Pordenone	
		Dresden	Helsinki
			Copenhagen
			Dublin
			Brussels
			Grenoble
	Marseille	Trieste	Sunderland
	Porto	Vienna	Lyon
		Bratislava	Tallinn
		Belgrade	
	Iraklion	Prague	
	Palermo	Munich	
	Milan		
	Bilbao		
Compact			

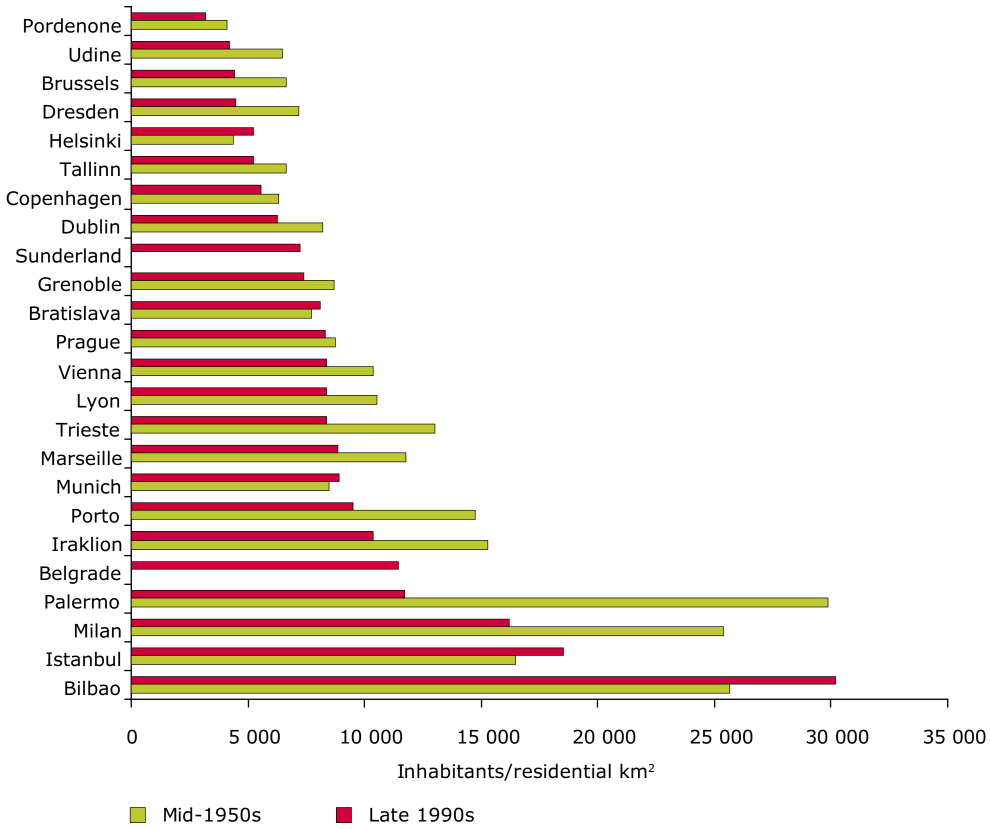
Source: MOLAND (JRC) and Kasanko *et al.*, 2006.

Figure 4 Population growth and the growth of built-up areas (mid-1950s to late 1990s), selected European cities



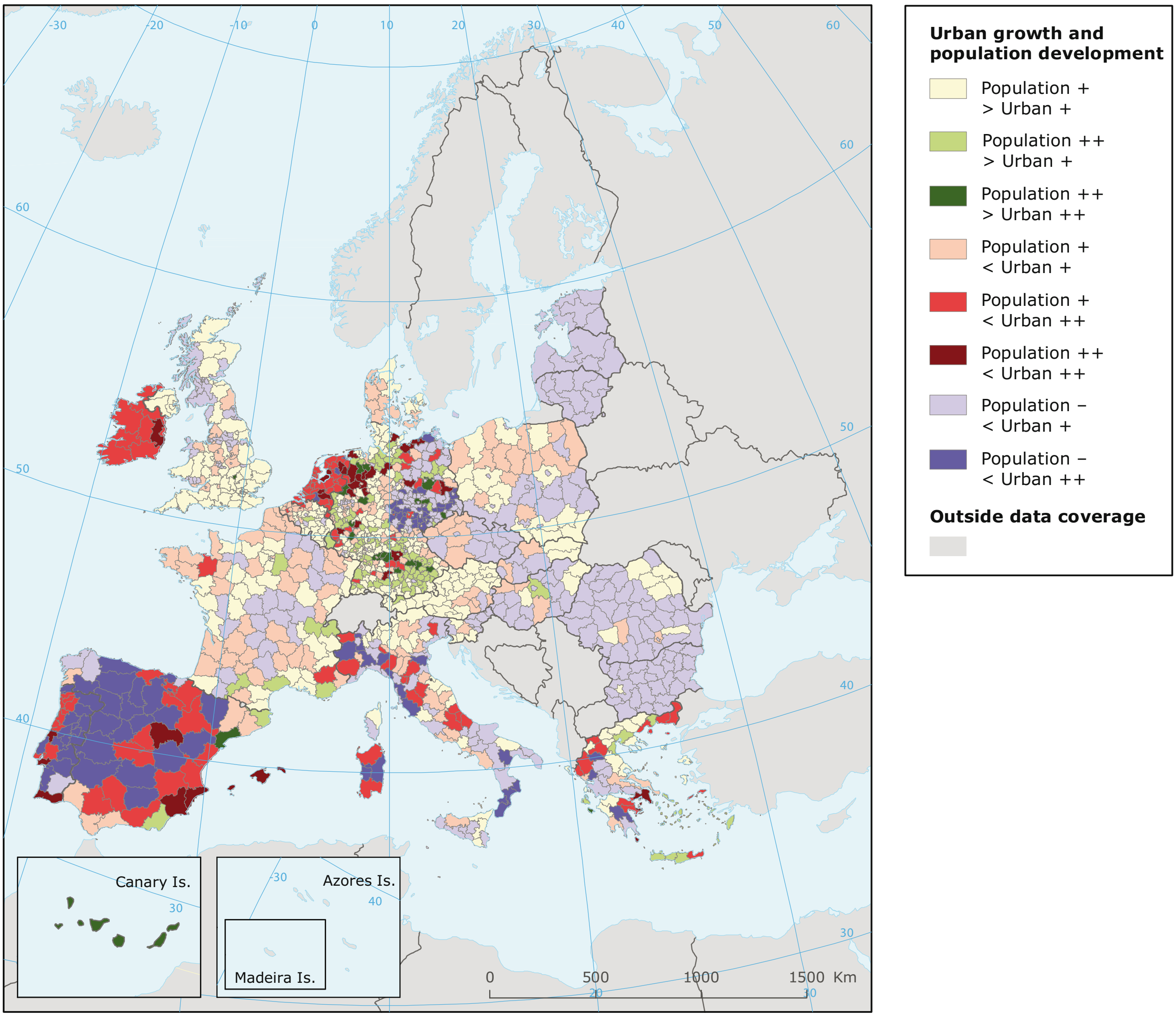
Source: MOLAND (JRC) and Kasanko *et al.*, 2006.

Figure 5 Residential density in mid-1950s and late 1990s (measured by inhabitants/ residential km²), selected European cities



Source: MOLAND (JRC) and Kasanko *et al.*, 2006.

Map 5 Urban growth and population development in Europe (1990–2000)



Source: By courtesy of ESPON, 2006; GeoVille Information Systems (based on EEA and Eurostat data).

more rigorously applied the gap between northern and southern cities will rapidly narrow (Blue Plan, 2005; Munoz, 2003; Dura-Guimera, 2003). Bilbao lies in a class of its own in respect of density and compactness, much of which can be attributed to its location, adjacent to the sea and bordered on two sides by mountains. Nonetheless it is apparent that physical constraints cannot provide the entire explanation of its success, and credit should also be given to the active local planning regime and its well developed transport system.

Clusters of compact cities are also evident in the former socialist countries of central and eastern Europe. The compact urban form and high densities mainly reflect the strong centralised planning regimes and substantial reliance on public transport that prevailed during the communist era (Ott, 2001; Nuissl and Rink, 2005). Today, these cities are facing the same threats of rapid urban sprawl as the southern European cities as the land market is liberated, housing preferences evolve, improving economic prospects create new pressures for low density urban expansion, and less restrictive planning controls prevail. Dresden is an exception amongst ex-socialist cities with a much less compact structure due to the unique circumstances of its wartime experience and subsequent reconstruction.

In northern Italy, small and medium sized cities are also special cases as the whole region has experienced very strong urban sprawl in the past decades and the process continues. The most sprawled cities in the study, Udine and Pordenone, are relatively small cities in the Venezia-Friuli-Giulia region. In smaller cities, in general, densities are lower as the population pressure is lower and in many cases the planning regulations are more permissive allowing more low density building than in large cities.

In general cities in northern and western Europe have less of an urban tradition, and have been more strongly influenced by traditions in which the planning ideal has supported spacious, less compact, garden suburbs (Hall, 2002). This has resulted in much lower densities and more suburban development, particularly as individual housing preferences in north and west European cities have also favoured semi-detached and detached houses.

Along the coastal regions of Europe major population growth is accommodated by continuous sprawling development. During the period 1990–2000, urbanisation of the coast grew approximately 30 % faster than inland areas, with the highest rates of increase (20–35 %) in the coastal zones of Portugal, Ireland and Spain. Many of the mountainous regions of Europe are also under threat from urban impacts, especially where transport routes provide good communications with adjacent lowland regional centres.

All the evidence presented in this section demonstrates that throughout Europe urban areas have expanded considerably more rapidly than the growth of population during the post-war decades. There is no apparent slowing down in these trends. Particularly at risk are the urban areas of the southern, eastern and central parts of Europe where the urban structure has historically been very compact but which in the past few decades have started to grow rapidly outwards.

For these reasons, it is apparent that new policies and tools are necessary to control and channel urban expansion so that urban areas can develop in a more sustainable manner. However, in order to define which sustainable urban planning strategies should be adopted, it is essential in the first place to fully understand the socio-economic drivers that provide the motors of sprawl. This is the focus of the next chapter.

3 The drivers of urban sprawl

3.1 Clusters of drivers

Sustainable urban planning strategies to combat urban sprawl can only be effectively specified when the forces driving urban sprawl are fully understood. Further general analysis shows that residential sprawl and the development of economic activities, in turn linked to the development of transport networks, are intrinsic causes of expanding cities. This is largely a consequence of increasing passenger and freight transport demand throughout Europe, as well as relatively high increases in the price of already urbanised land. The attractiveness of living in the centre of cities has fallen, while the quality of life associated with more 'rural areas' including city suburbs, being closer to nature, has increased. These factors present a planning challenge for small municipalities attempting to maintain their populations and attract small and medium-sized enterprises.

The extremely low price of agricultural land (in most cases good agricultural land) compared to already urbanised land (e.g. brownfield sites) or former industrial sites, is also an important factor underlying urban sprawl. In many development projects, the cost of agricultural land acquisition is relatively low. Thus, it enables greater profits to be made compared to those from already urban land or former industrial waste land, even in cases where no remediation is needed (non-polluted sites). This factor is particularly important in the economic heart of Europe stretching from the United Kingdom down through the Benelux countries, Germany and France (also known as the Pentagon zone). The trend of good agricultural land being deliberately and artificially maintained at a low value is reinforced by the broad use of expropriation tools. A direct side effect of these combined tools — low value, future use not taken into account, and expropriation — is clearly demonstrated by the development of villages near cities for residential or business purposes.

3.1.1 Macro-economic factors

Global economic growth is one of the most powerful drivers of urban sprawl. Globalisation of the economy is today fundamentally interrelated with the development of information and communication technologies (ICT). Both phenomena are beginning to have profound impacts on the spatial distribution of population and employment. Overall, it is likely that ICT will drive urban development towards an even more sprawled future (Audriac, 2005).

Drivers of urban sprawl

Macro-economic factors
- Economic growth
- Globalisation
- European integration

Micro-economic factors
- Rising living standards
- Price of land
- Availability of cheap agricultural land
- Competition between municipalities

Demographic factors
- Population growth
- Increase in household formation

Housing preferences
- More space per person
- Housing preferences

Inner city problems
- Poor air quality
- Noise
- Small apartments
- Unsafe environments
- Social problems
- Lack of green open space
- Poor quality of schools

Transportation
- Private car ownership
- Availability of roads
- Low cost of fuel
- Poor public transport

Regulatory frameworks
- Weak land use planning
- Poor enforcement of existing plans
- Lack of horizontal and vertical coordination and collaboration

EU integration also has far-reaching impacts upon the economies of European cities. In this context, barriers to trade between Member States have been substantially removed and an important feature of this trend is the emergence of the 'super regions' which transcend national boundaries. Furthermore, integration tends to support the development of capital cities, and erode the competitive position of smaller cities and towns. All regions of the EU are intended to benefit from economic growth generated in the new integrated Europe; however, the reality is that new patterns of economic advantage and disadvantage are emerging, as EU action is only one factor amongst many influencing trends in local economies.

EU integration supports investment in longer-distance transport networks to facilitate improved accessibility and mobility. The proposed Trans-European Transport Networks (TEN-T) will greatly influence the future spatial development of urban areas across Europe especially in the EU-10 where natural areas are more prevalent than in the EU-15. In particular, the TEN transportation network is designed to solve some of the existing accessibility problems between EU-15 and the new Member States. However, given the powerful influence that new transport links have in generating development it is vital that current TEN plans fully address all possible impacts of the new infrastructure provision on urban sprawl and on the natural environment.

EU Structural and Cohesion Funds investments throughout Europe can either drive sprawl or support its containment. Investment in new motorways and other road connections readily attracts new development along the line of the improved transport links, frequently exacerbating urban sprawl, as will be seen later in the case study of Dresden-Prague. Alternatively, Structural Funds interventions can be channelled to the redevelopment of deteriorating inner cities making them more attractive for housing and other public and private investments, thereby assisting in the development of more compact cities.

Global competition is also driving efforts to secure economies of scale in the distribution and consumption of goods that have driven changes in the retail sector over the past decades. In the 1950s, most shops were small and located in the middle of residential areas, and the majority of the population did their shopping on foot. Today, major out-of-town shopping centres are the dominant form of retail provision, which together with the surrounding parking areas occupy vast areas of land only accessible by car.

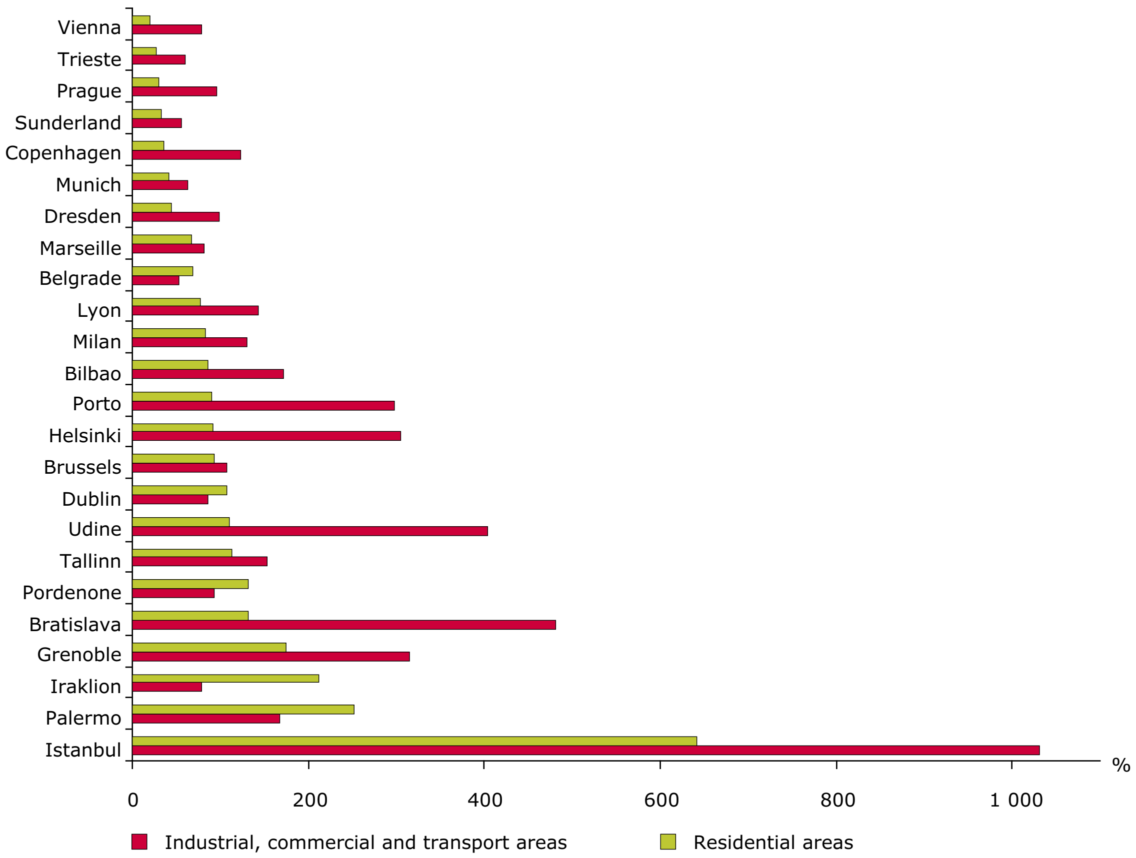
The inter-linkages between residential and industrial/commercial/transport areas in urban development are also critical to the promotion of sprawl. In some cases residential areas promote the development of associated commercial areas. More often new transport links and nodes, and commercial and industrial development facilitate the development of new residential areas in their vicinity. Whatever the relationship it is notable that in most cities industrial, commercial and transport areas are prime motors of sprawl that have outpaced the growth rates of residential areas with on average, growth rates of 100 % above those of residential areas.

The rapid development of transport networks over the past 45 years has impacted particularly strongly outside the historic city centres and these new networks today occupy significantly more space than previous networks. Furthermore, industrial, commercial and transport areas occupy between 25 % and 50 % of all built-up land, and on average one third of urban land is used for these purposes (Figure 6).

In distributional terms, analysis of these land uses shows that in the core of cities the growth of housing and commercial areas are of similar magnitudes, whereas in the immediate vicinity outside the core, the pressures for housing development are generally greater (Figure 7). For all land uses, new development predominantly takes the form of diffuse sprawl, and most new services, other than commercial, and recreation activities are developed outside the core of the city.

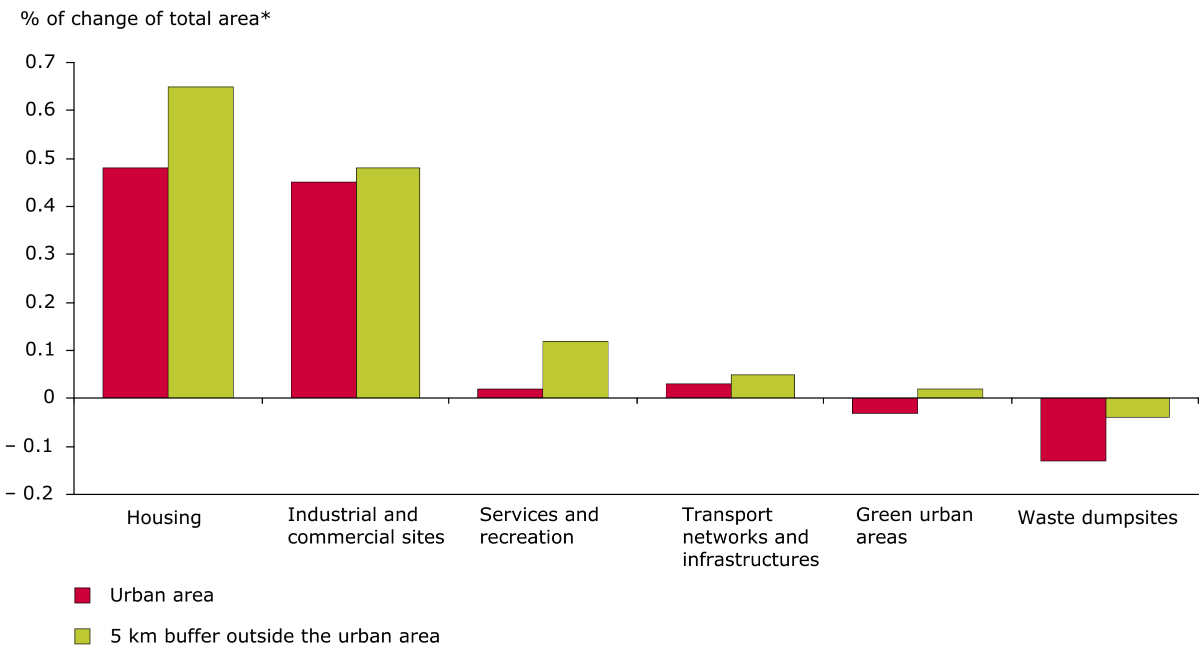
New transport investment, in particular motorway construction, can be a powerful stimulant for new development and sprawl, including shopping centres and residential areas. Land use and transport are inter-dependent in complex ways as development influences mobility patterns. New suburban development without adequate public transportation typically increases the demand for private car use. In contrast the construction of new light rail systems has a tendency to increase housing densities around access points (Handy, 2005). Households make choices between residential areas taking into account the price of housing and the price of commuting between the work place and home. When travel costs fall below a certain threshold and income reaches a certain level the rate of sprawl quickens, and unsurprisingly sprawl is more common in regions where incomes are high and commuting costs are low (Wu, 2006).

Figure 6 Growth rates of residential areas and industrial, commercial and transport areas from the mid-1950s to the end 1990s), selected European cities



Source: MOLAND (JRC) and Kasanko *et al.*, 2006

Figure 7 Functional changes for urban areas greater than 50 000 inhabitants (1990–2000)



Note: * EU-25 except Cyprus, Finland, Malta and Sweden, but with Bulgaria and Romania.

Source: EEA.

3.1.2 Micro-economic factors

From the perspective of land economics, high land prices in the core of the city force developers to seek lower prices in the more peripheral areas. The price of agricultural land is universally much lower than the price of land zoned for housing or the development of services. Agricultural land therefore becomes a highly attractive target for investors and developers. Although planning permission for non-agricultural development increases the value of agricultural land substantially, its price still remains at much lower levels than land in the core urban areas.

Municipalities and public development agencies have a crucial role in the process of conversion of agricultural or natural land to space for housing or commercial development. Throughout the EU, countries they have the responsibility for land use zoning. Competition among municipalities for new income generating jobs and services is great, and many municipalities can be tempted to relax controls on the development of agricultural land and even offer tax benefits to commercial and industrial enterprises to invest in the municipality. Competition of this nature between municipalities fuels urban sprawl.

3.1.3 Social factors

As the evidence presented in Chapter 2 indicates, population growth no longer determines the outward expansion of built-up areas.

Other demographic factors may however increasingly have impacts on urban sprawl. Families with small children are most likely to move to suburban areas and to rural areas outside the city. In contrast the elderly and single are least likely to move out of cities. As the trend towards an increasingly ageing population and smaller households continues, it may be anticipated that some slowing down of the movement from cities to suburbs will occur in the coming decades (Couch & Karecha, 2006).

More and more people in Europe regard a new house, ideally a semi-detached or detached house in the suburban/rural areas outside the city, as the prime investment to be made in their lifetimes. Many wealthier households also actively seek a good investment opportunity. Properties on the peripheries of cities are considered to be better investments because land prices are generally lower than in the core, and the value of property is expected to rise more rapidly outside the urban core (Couch & Karecha, 2006; Wu, 2006). Similar considerations apply in respect of the purchase of second homes, which are not only seen as good investments but also provide additional opportunities for recreation outside the city. The persistence of the suburban ideal underpins the apparently ever increasing demand for houses in the sprawled suburbs and peripheral urban areas, and forms a vital stimulus to urban sprawl.

In contrast to the apparent attractions of the suburbs, the many negative aspects of the inner city cores, including poor environment, social problems and safety issues, create powerful drivers of urban sprawl. City cores are perceived by many as more polluted, noisy and unsafe than the suburbs. The built-up environment is also considered unattractive because of poor urban planning, with areas lacking green open space and sports facilities. Unemployment, poverty, single parent households, drug abuse and minorities with integration problems are also often identified with inner-city areas. These negative environmental factors drive many families with small children out of the city.

As families move out of the city, social segregation begins to intensify. Municipal tax revenues are lowered, and can become insufficient to maintain services such as schools and hospitals. The quality of schools plays a crucial role as parents try to secure the best education for their children. In the inner city a downward cycle of deprivation can readily become established as more and more of the population attempt to move out, reinforcing the problems of those that must remain (Burton, 2000; Couch and Karecha, 2006).

3.2 Pathways to urban sprawl

Deeper understanding of the relationships between the trends that drive urban sprawl, and the specific national, regional and local considerations that fashion the development of the cities and regions of Europe, is essential to redress the adverse effects of sprawl. The prime aim of the following case studies is to permit an assessment of the relative importance and impact of the various forces driving sprawl set against the range of contrasting development outcomes described.

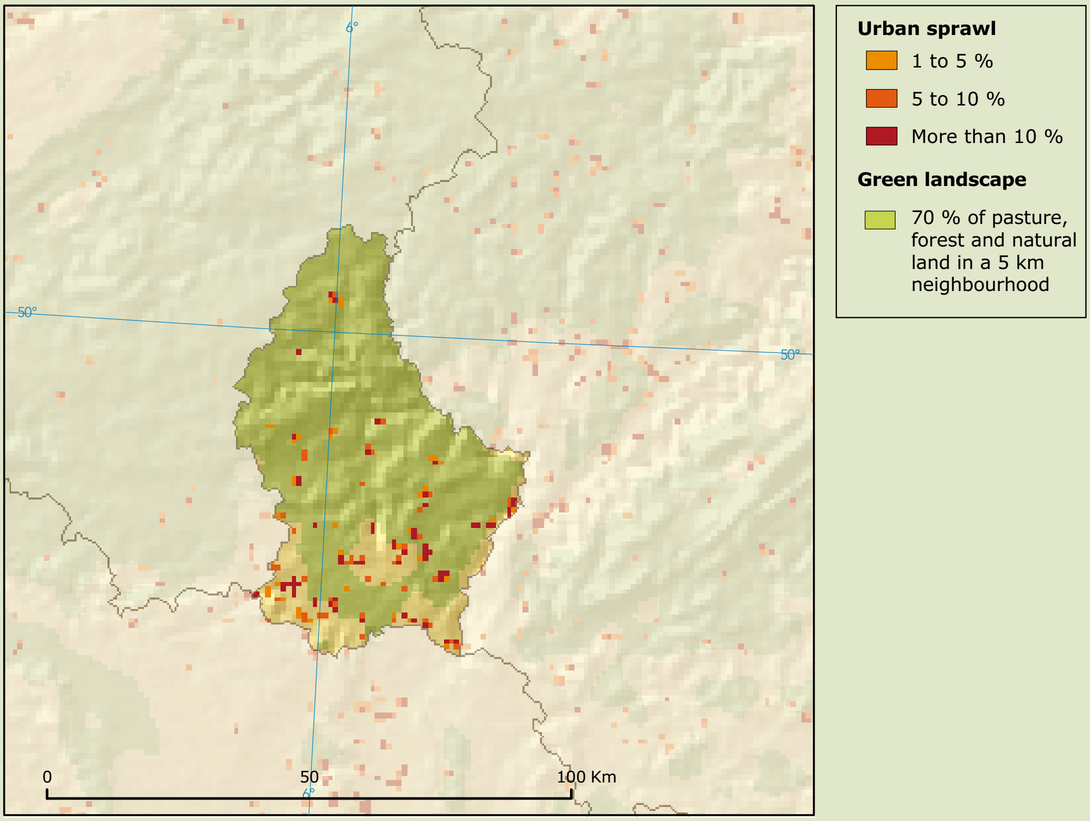
The case studies consistently emphasise the commonality of the key drivers of urban development in terms of economic development, allied in some cases with population growth. Urban development is characterised in terms of a low density space extensive mix of residential, commercial, transport and associated land uses in the urban fringe. However, the case studies also clearly demonstrate city sprawls, the extent to which effective planning strategies control development and how they are applied influence the degree of urban sprawl. Where unplanned, decentralised development dominates, sprawl will occur. Conversely, where growth around the periphery of the city is coordinated by strong urban policy perspectives, more compact forms of urban development will be secured.

The next chapter reviews the multiple, severe and interconnected impacts of urban sprawl in order to fully understand the impacts of sprawl and why it is important for cities not to sprawl. The full range of impacts of sprawl are considered including impacts in respect of environmental resources, natural and protected areas, rural environments, the quality of urban life and health, as well as socio-economic impacts.

Box 2 Luxembourg: new urban traditions, high income and immigration

The expansion of urban areas is the most important land use change in Luxembourg. These changes are mainly concentrated around the existing urban centres of the city of Luxembourg and the old industrial southwest. In both cases the main contributor to this trend is the development of new service industries including financial and EU institutions. The pressure for new residential growth reflects efforts made to attract new inhabitants from the countries bordering Luxembourg and the influx of a growing working population with their families. It also reflects the high income levels in Luxembourg which makes it possible for most inhabitants to live in detached houses. Furthermore, short distances and a relatively small population make commuting a feasible option without excessive congestion.

Map Urban sprawl in Luxembourg driven by socio-economic changes (1990–2000)



Source: EEA.

Box 3 Dublin metropolitan area: rapidly growing economy and population

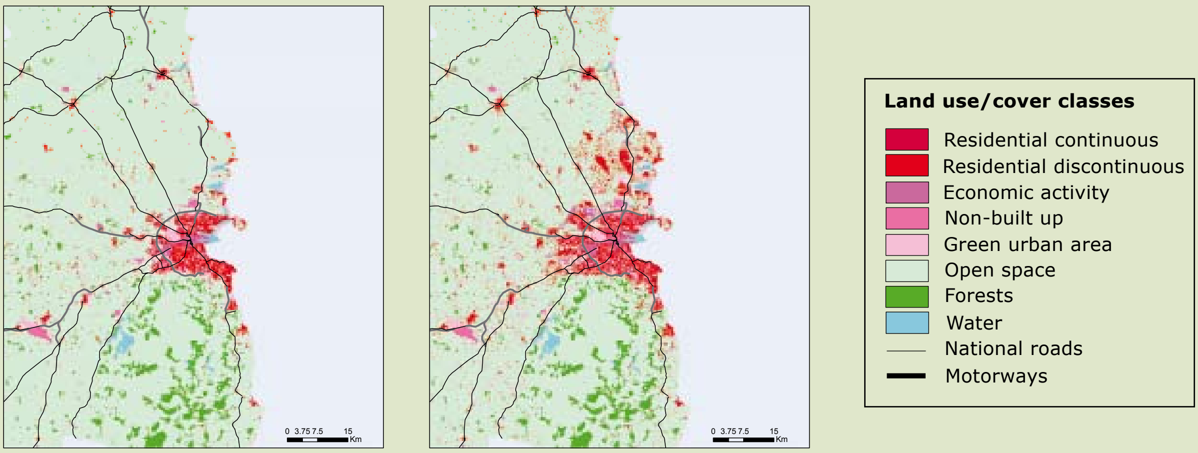
Dublin is a relatively small city by European and international standards. However, it dominates the urban pattern of Ireland in terms of demography, employment and enterprise (Bannon, 2000). The Greater Dublin metropolitan area population was 1 535 000 in 2002, 40 % of the total Irish population. The National Spatial Strategy (2002) suggests that by 2020 the Greater Dublin area population will be in the range of 1.9–2.2 million. The strong growth of the Greater Dublin is a result of the region's role both within Ireland and as a European capital city. Consequently, the Greater Dublin area will need to accommodate 403 000–480 000 additional inhabitants by the year 2020.

Population growth and economic development, as well as house type and price, are predicted to be the main drivers of land use change in the Greater Dublin area during the coming decades. High house prices in Dublin are a significant push factor driving the population towards the rural fringes of the city where it is cheaper to buy or build a house. Another push factor is the small size of apartments in the city centre, forcing families with children needing more space to move out of the city where houses prices are lower and housing more affordable. Personal housing preferences also play an important role as rural living is the Irish housing ideal (Michell, 2004). This preference is realised in single-family houses in open countryside with the benefits of the proximity to the capital or other urban areas. The realisation of this ideal is greatly facilitated by the planning regime which imposes few constraints on the conversion of agricultural areas to low-density housing areas.

Urban–rural migration in the Greater Dublin area has led to the growth of rural towns and villages at the expense of the City of Dublin. The growth of residential areas appears to follow the line of road and rail transport, suggesting a preference for rural living but with the benefits of proximity to urban areas including employment. Another push factor is the transport system in Dublin. Commuting times are long and the lack of orbital roads and rail networks means that to get from one side of the city to the other necessitates a journey through the centre. Often it is quicker to commute from outside Dublin to the centre rather than from one side to the other (Gkartzios and Scott, 2005).

The regional MOLAND model was applied to the Greater Dublin metropolitan region consisting of the following 9 counties: Dublin Co., Kildare, Laois, Longford, Lough, Meath, Offaly, West Meath and Wicklow. According to the 2025 scenario, the outward expansion of residential areas in the Greater Dublin area is estimated to increase by 110 % over the forecast period. In the same period commercial areas will more than double while industrial areas will grow slightly more modestly. The main development axis is to the north from the Greater Dublin area along the seashore as well as inland. To the south little new residential, or industrial or commercial development will take place because of the physical constraints of upland areas. The 2025 scenario also suggests the development of Dublin City to the northwest along the line of the Dublin-Belfast corridor. This development will encourage Dublin City to develop from a mono-centric to poly-centric relationship with the neighbouring cities of Dundalk, Newry and Drogheda. The Greater Dublin Metropolitan area needs land use guidance and zoning as well as new infrastructure if it is going to achieve a more sustainable form of development over the period to 2025.

Map Dublin 1990 and modelled scenario for 2025



Source: MOLAND (JRC).

Box 4 Portugal and Spain: threats to the coasts of Europe

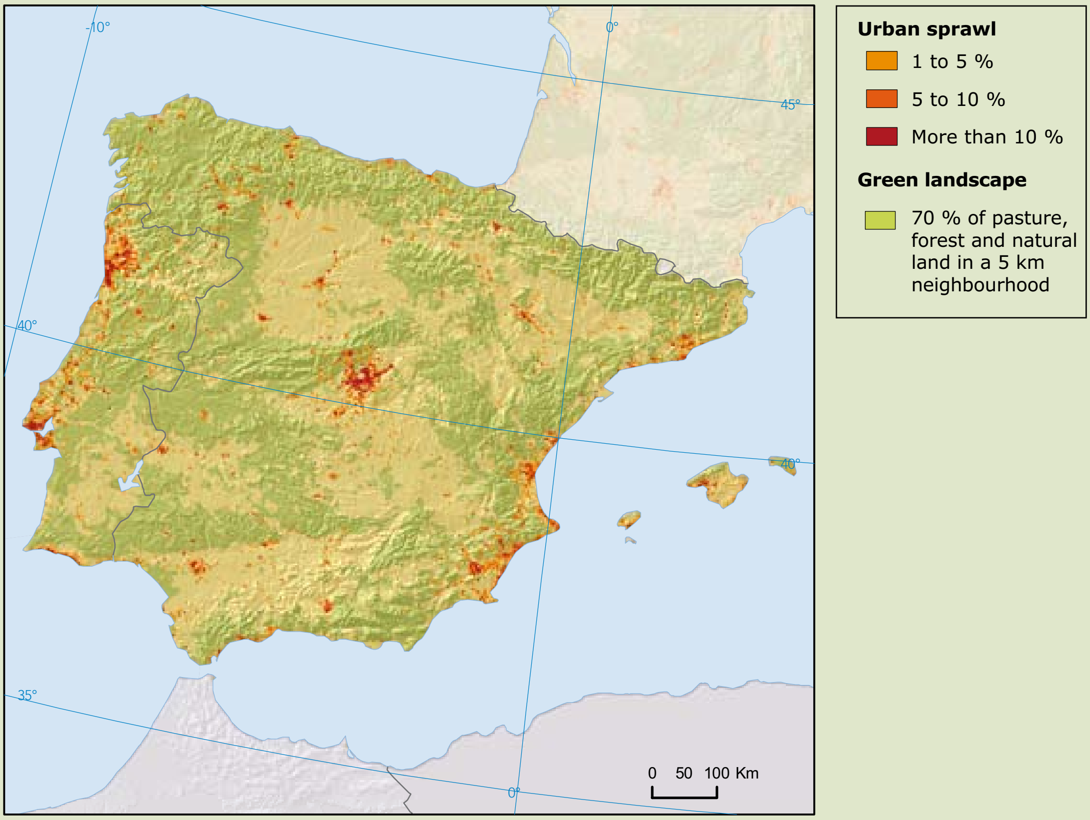
Coastal urbanisation and urban sprawl in coastal zones is no longer necessarily induced and supported by the main coastal cities. By its nature, urban land use along the coasts has become suburban. This new phenomenon, which challenges the state of the environment and sustainability of the coastal areas, is recognised by coastal managers across Europe (CPMR, 2005).

The predominant pattern of residential urbanisation is diffuse settlements adjacent to or disconnected from concentrated urban centres. Residential sprawl is on average responsible for more than 45 % of coastal zone land transformation into artificial surfaces. There is an increasing demand for investment in coastal residences due to tourism and leisure from northern Europe. In addition, there is also domestic demand from the inland population, e.g. the retired. In the past 10 years residential expansion has spread to the coasts of other regional seas, for example the Atlantic coast of Portugal.

Portugal has experienced some of the most rapid increases in urban development in the EU, focused around major cities and the coast. Portugal's urban development is concentrated around the two metropolitan areas of Lisbon and Porto, along the coastline from Lisbon/Setubal to Porto/Viana do Castelo, and more recently along the Algarve coast. In 2000, 50 % of continental Portugal's urban areas were located within 13 km of the coastline, an area which accounts for only 13 % of the total land area. Given the persistently high urban pressures along the coastline, these zones are subject to special development and legal measures.

In Spain, economic growth and tourism has resulted in an increased number of households and second homes particularly along the Mediterranean coast. Illustrative of this phenomenon are the Costa del Sol and Costa Brava which developed significantly during the 1950s and 1960s due to the demand for high quality holidays. This led to the combined development of accommodation, infrastructure and leisure facilities, such as golf courses and marinas. This development is still very intensive today.

Map Polarised urban sprawl around major cities and the coast of Portugal and Spain (1990–2000)



Source: EEA.

Box 5 Madrid region: rapidly growing economy and weak planning framework

The Madrid region is considered to be one of the EU hotspots in urban development in the EU (EEA, 2005). Urbanised land in Madrid grew by 50 % in the 1990s, compared with a national rate of 25 %, and an EU Figure of 5.4 % (Fernández-Galiano, 2006; EEA, 2005). The extraordinary urban development in Madrid region is the result of a number of drivers other than population growth, as the population of the Madrid Autonomous Community had a growth rate of only 5.16 % during the period. There is no single explanation for the intense growth of Madrid in the last few years, rather a number of inter-linked socio-economic factors have produced enormous pressures. The first factor is demand for first and second homes. 513 000 new houses were built in the region in the 1990s (López de Lucio, 2003) even though the population increase for the same period was only 240 000. This housing demand is supported by the current favourable economic situation in Spain combined with low mortgage interest rates across the Euro-zone. Other factors driving the decentralisation process include increased mobility based on a substantially improved transport network, including new toll motorways, three motorway rings around the city, and new and improved metropolitan and train connections. Today both Guadalajara and Toledo can be considered an integral part of the Madrid region due to improved accessibility in the Madrid region, Conversely, in the new low-density residential areas on the periphery of the city new mobility needs are being generated and transport improvements are a priority. The overall effect of the above is a tremendous increase in house prices. More and more people must go further out from the centre to find affordable housing, forcing an ever-growing number of people to commute by car. These socio-economic drivers have promoted an intense decentralisation process in the Madrid region involving both population and economic activity, with a number of territorial impacts, population and employment redistribution, very high rates of housing growth, and the appearance of new urban hubs served by large, decentralised shopping and entertainment malls (López de Lucio, 2003). Today Madrid is a sprawled region, a process that has occurred within the context of a weak spatial planning framework (Munoz, 2003; López de Lucio, 2003; Fernández-Galiano, 2006). The problem of planning is common to a large number of European urban regions, in which the regulatory capacity of municipalities cannot match the enormous forces reshaping the territory (Fernández-Galiano, 2006).

Future development paths: scenarios

Three land use scenarios identified for the region of Madrid describe alternative development paths that form the basis for decisions facing the city planners in delivering a more sustainable Madrid. The alternatives include urban regional development paths based on the idea of competitiveness and free market forces (business-as-usual and scattered scenarios), contrasting with a development path where competitiveness is sought in a more environmentally and socially sustainable way through integrated planning and engagement with stakeholders (compact development scenario). These scenarios are represented as follows:

Business-as-usual: This scenario represents a continuation of very rapid economic growth with low to moderate population growth. The scenario extrapolates the same characteristics and trends identified in the 10 year period 1990–2000.

Compact development: This is an environmental scenario, and is based on an assumption of a 40 % decrease in demand for urban land as compared with the 'business-as-usual' scenario. In this case a more compact development style prevails, representing a departure for current trends. It is probably the least realistic scenario of the three identified.

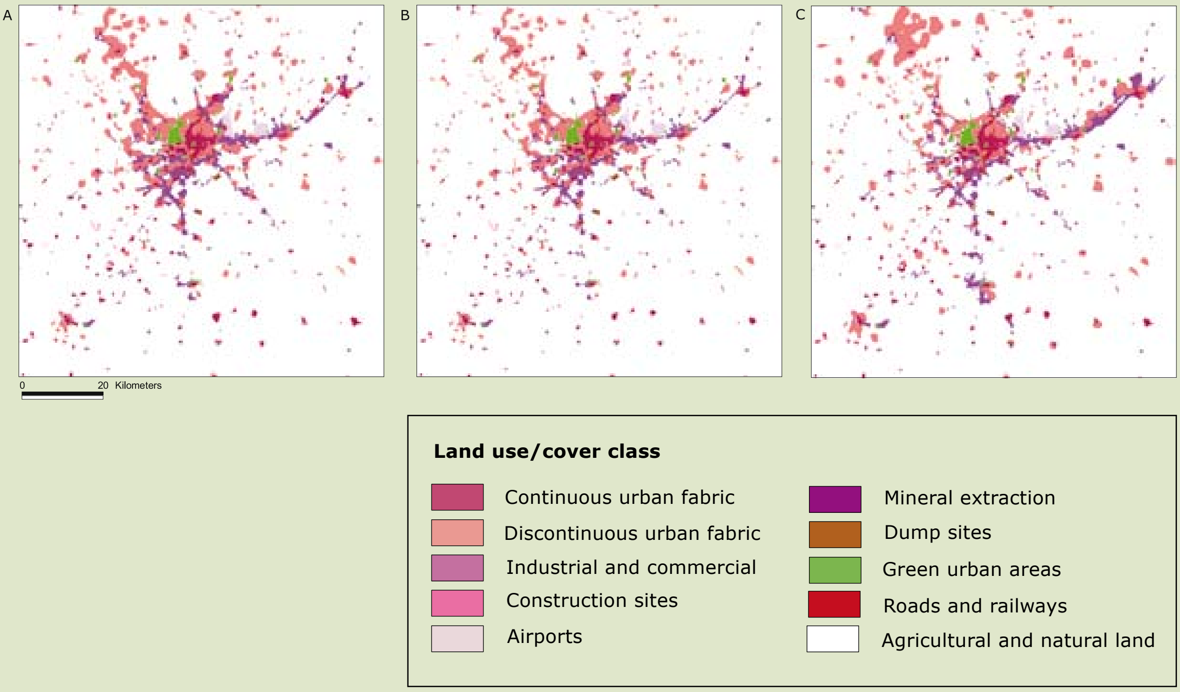
Scattered development: This is a market-led development scenario with greater environmental impacts than the 'business-as-usual' scenario. The scenario is based on more rapid population growth than the business-as-usual case, and assumes a 10 % increase in demand for urban land compared to the 'business-as-usual' scenario. Growth is mainly concentrated in a number of peripheral nodes and the city moves towards a sprawled development style.

The three scenarios show divergent patterns of land use for 2020. However, the business-as-usual scenario shares some common features with the scattered development scenario, as both create severe impacts in terms of additional land consumption and the generation of new commuter movements relying on the private car, as well as other environmental impacts. Overall, urban sprawl is profoundly modifying Madrid in an unsustainable way, and it is clear that the sustainable development of the Madrid region can only be attained by the compact development scenario provided spatial regulation measures are implemented in the short to medium term.

Box 5 (cont.)

Map Development scenarios for the Madrid region 2020

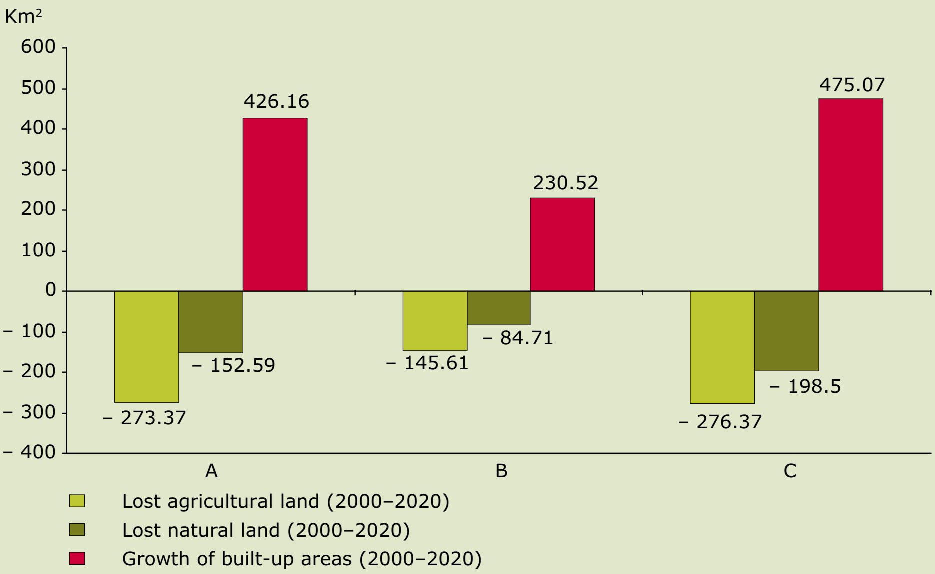
A: Business-as-usual B: Compact development C: Scattered development



Source: MOLAND (JRC) and Kasanko *et al.*, 2006.

Figure Land use changes for the Madrid region 2020

A: Business-as-usual B: Compact development C: Scattered development



Source: MOLAND (JRC).

Box 6 Istanbul: European megacity on two continents

Istanbul is a large city at the very edge of Europe, and has a long and turbulent history at the crossroads of European and Asian cultures. Istanbul has always been among the largest cities in the world. At the turn of the 21st century there were approximately 10 million people living in Istanbul, 15 % of the Turkish population. This figure is estimated to grow by 2.5 million people by 2015 based on high birth rates and continuing migration from the countryside. In the past 50 years the growth of Istanbul has been stunning. The built-up area has expanded by 600 % and the population has grown even more, from approximately 1 million to 10 million. Istanbul has always been and still is a very densely populated city. The fact that it is divided by the Straits of Bosporus has created very specific land use development dynamics.

Rapid growth has created numerous problems, such as traffic congestion, pollution (both air and water), unemployment and other social problems, large areas of unregulated housing (50–70 % according to Blue Plan, 2005) and squatter settlements, infrastructure which is lagging behind both the expansion of the city and increasingly restrictive environmental standards (Çağdaş & Berköz, 1996; Erkip, 2000).

What will Istanbul physically look like in 2020? Population growth will remain a key driving force shaping the Istanbul of 2020. Growth of 25 % means 2.5 million new inhabitants, equivalent to the total population of Rome. It is also likely that with the modernisation of the economy and the changes brought by preparations for EU membership, the general standard of living will rise. The improved economic situation will lead to changing housing preferences, with increasing movement out of the city centre to the peripheral parts. (Ergun, 2004; Dökmeci *et al.*, 1996). The new suburbs are typically more spacious, with dominance of larger detached and semi-detached houses, gardens etc. which particularly attract families (Dökmeci & Berköz, 2000). Even the phenomenon of gated cities, which are inhabited by the richest strata and guarded 24 hours a day with full commercial and recreational services have spread to the environs of Istanbul. There are almost 300 gated cities in the immediate vicinity of Istanbul metropolitan municipality (Blue plan, 2005). As a consequence of these developments the population density has dropped. The future of the squatter settlements is an unknown factor, although it is likely that rising living standards (Türkoğlu, 1997) and pressures from the EU will push the authorities to provide proper housing and services to the squatter settlements. The provision of improved housing for these areas will require the accommodation of the same number of people in apartments with at least double or triple the land take.

Residential housing occupies only a part of urban space. Approximately one third is used for commerce, industries and transport purposes. These land use classes tend to grow at a much quicker pace than residential areas when the economy is expanding (Kasanko *et al.*, 2006). As Istanbul will remain the engine of the Turkish economy and will inevitably attract a lot of foreign investment after joining the EU, it is certain that commercial and service related areas will grow very rapidly (Çağdaş & Berköz, 1996) and that new business and office areas will be built to accommodate the growth. The globalisation of the economy and rapid technological development will also create pressures for increases in commercial land. Attempts to alleviate major problems of traffic and congestion will require further space for new transport infrastructure. The Marmaray project linking the European and Asian parts of Istanbul via an underwater railway tunnel and linked to 76 km of combined tube and railway along the coastline will have a drastic impact on future land use in Istanbul.

Future development paths: scenarios

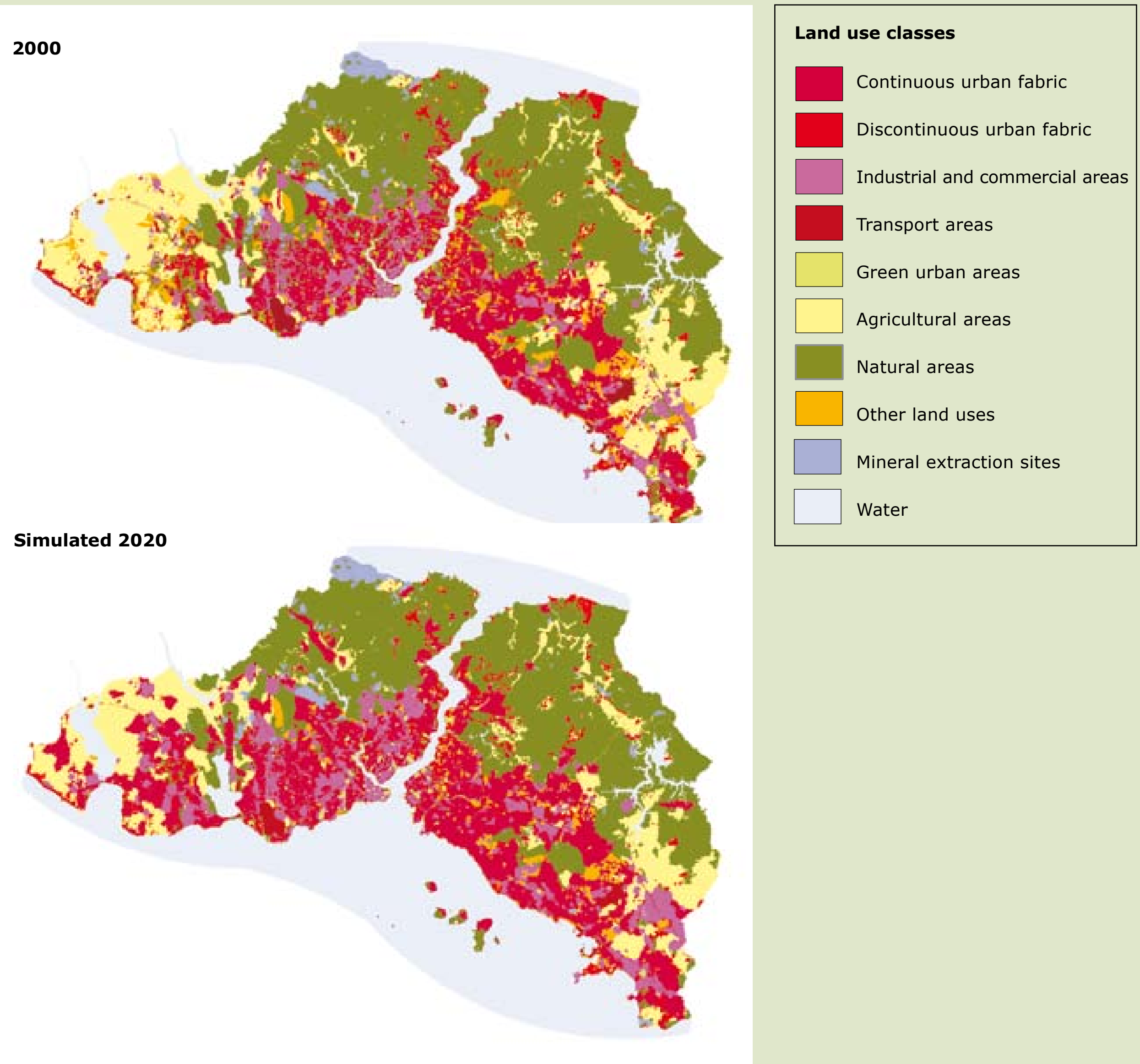
The land use scenario for the year 2020 follows the main trends from 1988 to 2000 with slightly smaller growth expectations. The estimated population growth of 2.5 million inhabitants is comparable to the growth from 1988 to 2000. The simulation was made using the MOLAND model (Barredo *et al.*, 2003; Barredo *et al.*, 2004).

Three clear development tendencies are evident (see Map). First, the filling in of available land within previously built-up areas on both the European and Anatolian sides of Istanbul. Second, the growth along the coastline both westwards and eastwards. This is particularly noticeable on the western side of the European part of Istanbul where large new residential areas are built in the Bükükçekmece area between the two lakes near the coastline. The future Marmaray rail link on the Anatolian side will support the development of the areas close to the coast on the eastern part of the study area. Third, the conservation of the forest area north of Istanbul where there is relatively little new residential development occurring.

Box 6 (cont.)

From an environmental point of view the future developments presented in these simulations are acceptable. Making the urban structure denser and channelling growth along the major transport axes reduces environmental impact, and retains large parts of the natural and agricultural areas in the vicinity of Istanbul. However, it should be emphasised that there are many drivers including housing preferences and land price, which are exerting pressure for less dense future development. Achieving more compact urban development and controlled growth necessitates political agreement on planning and zoning objectives and means of implementing them as well as the control of unauthorised developments.

Map Istanbul 2000 and 2020



Source: MOLAND (JRC) and Kasanko *et al.*, 2006.

4 The impacts of urban sprawl

'Four out of five European citizens live in urban areas and their quality of life is directly influenced by the state of the urban environment' (European Commission, 2006).

Urban development has impacts far beyond the land consumed directly by construction and infrastructure and its immediate surroundings. Economic development and the marginalisation of land by consequent urban development generates the need for new transport infrastructures to link them together, which in turn produces more congestion, and additional costs to society (SACTRA, 1995).

These developments, supported in part by EU budget transfers, have given a powerful economic boost to many disadvantaged regions or regions undergoing restructuring throughout Europe. Some of the most visible impacts, evident in urban sprawl, are apparent in countries or regions with rapid economic growth (Ireland, Portugal, eastern Germany, the Madrid region), regions that have also benefited most from EU regional policies.

New Member States, where little urban sprawl has been detected, may follow the same path of urban development in the coming decades. The environmental impacts will be greater as these areas still possess large amounts of natural landscape. In particular, transport needs are set to grow rapidly in the context of the enlarged EU and the new EU neighbourhood policy. Preliminary analysis indicates that these developments will impact directly on valuable areas of natural landscape.

Experience shows, moreover, that many environmental problems generated by the expansion of our cities create economic and social implications for the city. Urban sprawl and the demise of local shopping and social infrastructures affect many cities with negative effects on the urban economy, as mentioned earlier. Furthermore, environmentally degraded urban areas are less likely to attract new enterprise and services, posing a significant impediment to further local investment. This in turn causes reallocation and the further exacerbation of urban sprawl. Environmental degradation also tends to reduce house prices in the urban core leading to concentrations of socially underprivileged groups, aggravating social exclusion (Austrian EU Presidency, 2006).

The drivers of sprawl and their impacts are fully interconnected and essential to the concept of sustainable development and the associated ecosystems view of the functioning of the city and its surrounding areas. Both concepts inform the analysis of the impacts of urban sprawl in this chapter of the report. The interconnectedness of impacts poses some of the greatest challenges for the design of effective policy solutions to combat the problems of sprawl. However, active urban renewal and redevelopment policies in many urban areas are successfully reversing the deconcentration of urban centres and the decay of central city districts (Working group, 2004).

4.1 Environmental impacts

4.1.1 Natural resources and energy

Urban development involves the substantial consumption of numerous natural resources. The consumption of land and soil are of particular concern as they are mostly non-renewable resources. In contrast to changes in agricultural land use, the development of farmland for new housing or roads tends to be permanent and reversible only at very high costs.

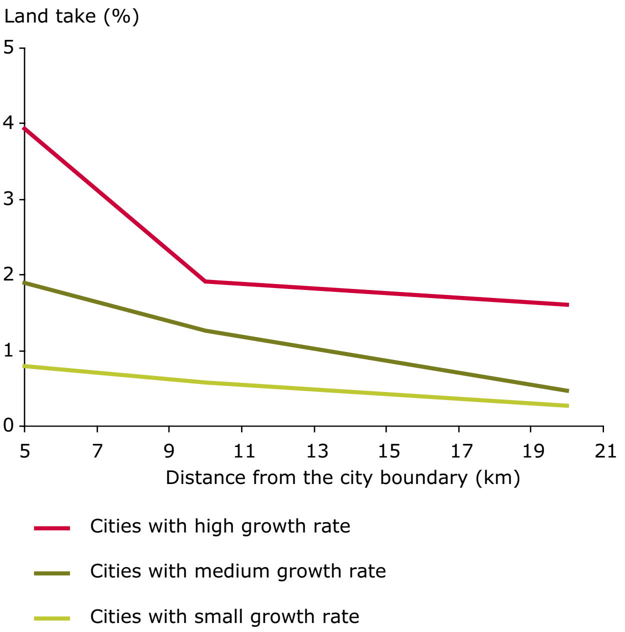
Over the past 20 years, as described in Chapter 2, low density suburban development in the periphery of Europe's cities has become the norm, and the expansion of urban areas in many eastern and western European countries has increased by over three times the growth of population (see Chapter 2, Figures 3 and 4). The problem of the rapid consumption of scarce land resources is graphically illustrated in the widespread sprawl of cities well beyond their boundaries (Figure 8).

Urban sprawl has also produced increased demands for raw materials typically produced in remote locations and requiring transportation. The consumption of concrete in Spain, for example, has increased by 120 % since 1996, reaching a level of 51.5 million tons in 2005. This increased demand reflects major expansion of construction activity in Spain, mainly along the coast and around major cities, where urban sprawl has become endemic. Associated environmental conflicts include the expansion of quarries adjacent to nature reserves and the over-extraction of gravel from river beds.

Urban sprawl and the development of urban land also dramatically transform the properties of soil, reducing its capacity to perform its essential functions. These impacts are evident in the extent of compaction of soil leading to impairment of soil functions; loss of water permeability (soil sealing) which dramatically decreases; loss of soil biodiversity, and reductions of the capacity for the soil to act as a carbon sink. In Germany, for example, it is estimated that 52 % of the soil in built-up areas is sealed (or the equivalent of 15 m^2 per second over a decade). Regions such as Mediterranean coastal areas have experienced 10 % increase in soil sealing during the 1990s. In addition, rainwater which falls on sealed areas is heavily polluted by tire abrasion, dust and high concentrations of heavy metals, which when washed into rivers degrade the hydrological system.

Land use change also alters water/land-surface characteristics which, in turn, modify surface and

Figure 8 Growth of built-up areas outside urban areas (1990–2000)



Source: EEA (CLC 2000, UMZ 2000).

groundwater interactions (discharge/recharge points), to the point that a majority of the small watersheds affected by urban sprawl show hydrological impairment. If the capacity of certain territories to maintain the ecological and human benefits from ground water diminishes, this could lead to conflicts due to competition for the resource. These conditions generally generate strong migratory flows of people looking for places offering a better quality of life (Delgado, J., 2004). Areas in the southern part of Europe, where desertification processes are at work, are particularly sensitive to such a situation. Reducing groundwater recharge might in addition negatively impact on the hydrological dynamics of wetlands that surround sprawled cities (Salama *et al*., 1999).

Changes in lifestyle associated with urban sprawl contribute as well to increases in resource use. As mentioned in Chapter 3, people are living increasingly in individual households, which tend to be less efficient, requiring more resources per capita than larger households. For instance, a two-person household uses 300 litres of water per day, two single households use 210 litres each. A two-person household will use 20 % less energy than two single person households. The number of households grew by 11 % between 1990 and 2000, a trend that increases land use and acts as a driver for expansion of urban areas. The general trend is for greater consumption of resources per capita with an associated growth in environmental impact. This adds pressure to the fact that about 60 % of large European cities are already over-exploiting their groundwater resources and water availability.

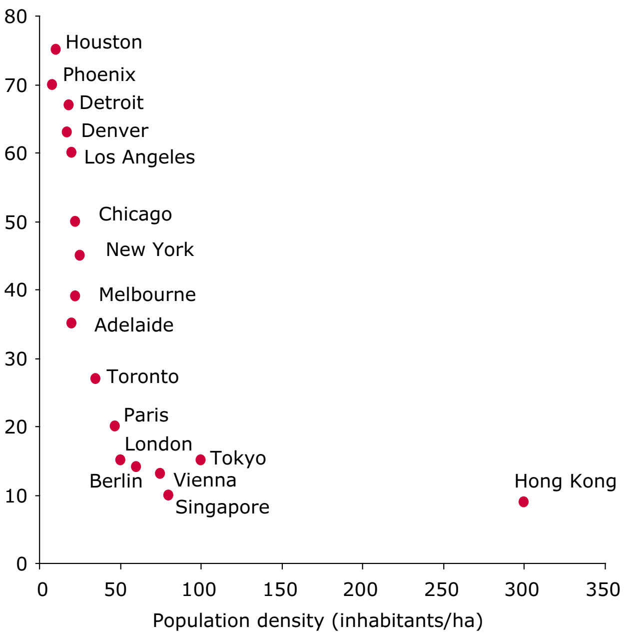
A further consequence of the increasing consumption of land and reductions in population densities as cities sprawl is the growing consumption of energy. Generally, compact urban developments with higher population densities are more energy efficient. Evidence from 17 cities around the world (Figure 9) shows a consistent link between population density and energy consumption, and in particular high energy consumption rates that are associated with lower population densities, characteristic of sprawling environments, dependent on lengthy distribution systems that undermine efficient energy use.

Transport related energy consumption in cities depends on a variety of factors including the nature of the rail and road networks, the extent of the development of mass transportation systems, and the modal split between public and private transport. Evidence shows (Table 2) that there is a significant increase in travel related energy consumption in cities as densities fall. Essentially, the sprawling city is dominated by relatively energy inefficient car use, as the car is frequently the only practical alternative to more energy efficient, but typically inadequate, relatively and increasingly expensive public transportation systems.

Increased transport related energy consumption is in turn leading to an increase in the emission of CO_2 to the atmosphere. The relationship between population densities and CO_2 emissions (Figure 10) is apparent as emissions increase progressively with falling urban densities. Although there are several factors that may explain differentials in CO_2 emissions between cities, including the level of industrial activity and local climatic conditions, the predominance of car borne transportation in sprawling cities is clearly a major factor in the growth of urban green house gas emissions. Urban sprawl therefore poses significant threats to the EU Kyoto commitments to reduce greenhouse gas emissions by 2020.

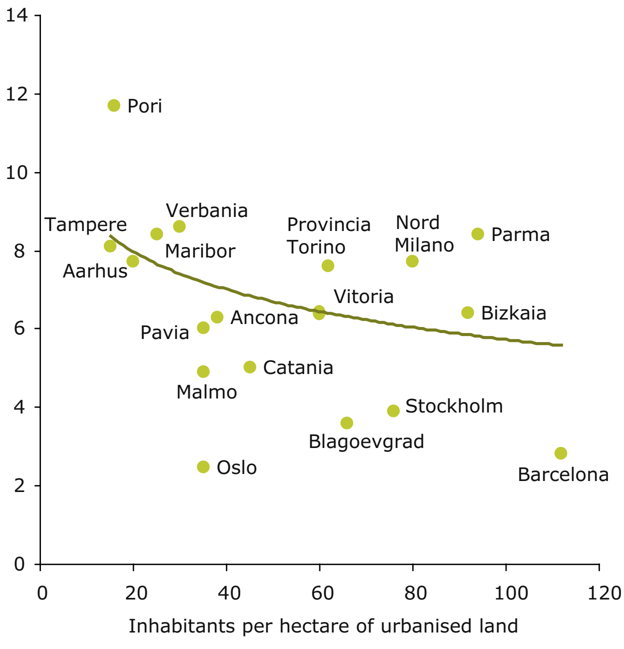
Sprawl also increases the length of trips required to collect municipal waste for processing at increasingly distant waste treatment plants and this is expected to continue as household waste grows 3–4 % annually. The material cycle is becoming geographically decoupled with increasing transport demands, impacting on transport related energy consumption and pollution emissions.

Figure 9 Population density and energy consumption, selected World cities



Source: Adopted from Newman, P. and Kenworthy, J., 1999.

Figure 10 Population density and CO_2 emissions, selected European cities



Source: Adopted from Ambiente Italia, 2003.

Table 2 Population density, energy consumption and cost of transport

Density (population + jobs per hectare)	Annual energy consumption for travel (mega joules per inhabitant)	Cost of transport (% of GDP)
< 25	55 000	12.4
25 to 50	20 200	11.1
50 to 100	13 700	8.6
> 100	12 200	5.7

Source: Adopted from Newman, P. and Kenworthy, J., 1999.

4.1.2 Natural and protected areas

The impacts of sprawl on natural areas are significant. Land sustains a number of ecosystems functions including the production of food, habitat for natural species, recreation, water retention and storage that are interconnected with adjacent land uses. The considerable impact of urban sprawl on natural and protected areas is exacerbated by the increased proximity and accessibility of urban activities to natural areas, imposing stress on ecosystems and species through noise and air pollution.

But even where the direct advance of urban land on natural and protected areas is minimised, the indirect fragmentation impacts of transport and other urban-related infrastructure developments create barrier effects that degrade the ecological functions of natural habitats. Immediate impacts such as the loss of agricultural and natural land or the fragmentation of forests, wetlands and other habitats are well known direct and irreversible impacts.

Urban land fragmentation, with the disruption of migration corridors for wildlife species, isolates these populations and can reduce natural habitats to such an extent that the minimum area required for the viability of species populations is no longer maintained. This process of degradation of ecological networks clearly threatens to undermine the important nature conservation efforts of initiatives such as Natura 2000 (see Box 7).

The environmental impacts of sprawl are evident in a number of ecologically sensitive areas located in coastal zones and mountain areas. Along the European coastal regions urban sprawl is endemic, Moreover, there is little prospect of relief over the next two decades, especially with a predicted increase in population of around 35 million people.

The development related impacts on coastal ecosystems, and their habitats and services, have produced major changes in these coastal zones. The Mediterranean coast, one of the world's 34 biodiversity hotspots, is particularly affected, and the increased demand for water for urban use, competes with irrigation water for agricultural land. This problem has been exacerbated by the increased development of golf courses in Spain, where the over-extraction of groundwater has led to salt water intrusion into the groundwater. Clearly all of this questions the sustainability of, in the long run, the economic development based on tourism that largely fuels this population explosion and urban sprawl.

The mountain ranges of Europe are universally recognised as both the 'water tanks of Europe' and sensitive ecosystems. Currently, they are under severe threat from urban impacts. New transport infrastructures facilitate commuting to the many urban agglomerations with populations over 250 000 inhabitants that lie close to the mountain regions, encouraging urbanisation in the mountain zones. Increased transit and tourist traffic, particularly day tourism from the big cities, also adds to the exploitation of the mountain areas as a natural resource for 'urban consumption' by the lowland populations. More balance is needed in the urban-mountain relationship if the unique ecosystems of these regions are to be conserved.

4.1.3 Rural environments

The growth of European cities in recent years has primarily occurred on former agricultural land (Figure 11). Typically, urban development and agriculture are competing for the same land, as agricultural lands adjacent to existing urban areas are also ideal for urban expansion.

The motivations of farmers in this process are clear as they can secure substantial financial benefits for the sale of farmland for new housing or other urban developments. In Poland, for example, between 2004 and 2006 the price of agricultural land increased on average by 40 %. Around the main cities and new highway developments, increases in price are often much higher (Figure 12).

Soils need to be conserved. They are non-renewable resources and the loss of agricultural land has major impacts on biodiversity with the loss of valuable biotopes for many animals, and particularly birds. Sprawling cities also threaten to consume the best agricultural lands, displacing agricultural activity to both less productive areas (requiring higher inputs of water and fertilisers) and more remote upland locations (with increased risk of soil erosion). In addition, the quality of the agricultural land that is not urbanised but in the vicinity of sprawling cities has also been reduced (Figure 13).

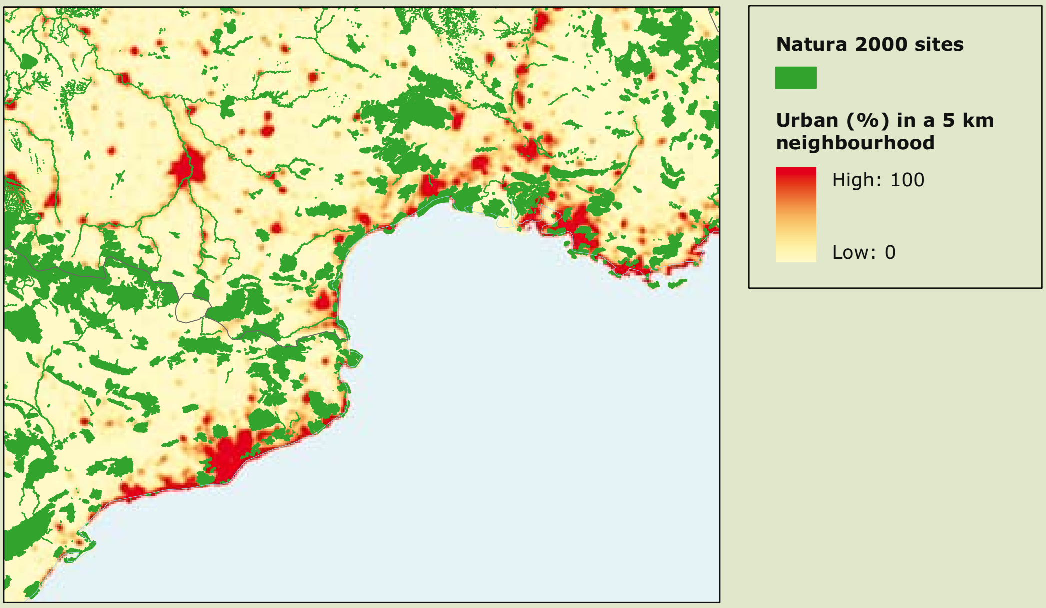
All these characteristic impacts of urban sprawl are well illustrated by the Mediterranean coast. Throughout the region 3 % of farmland was urbanised in the 1990s, and 60 % of this land was of good agriculture quality.

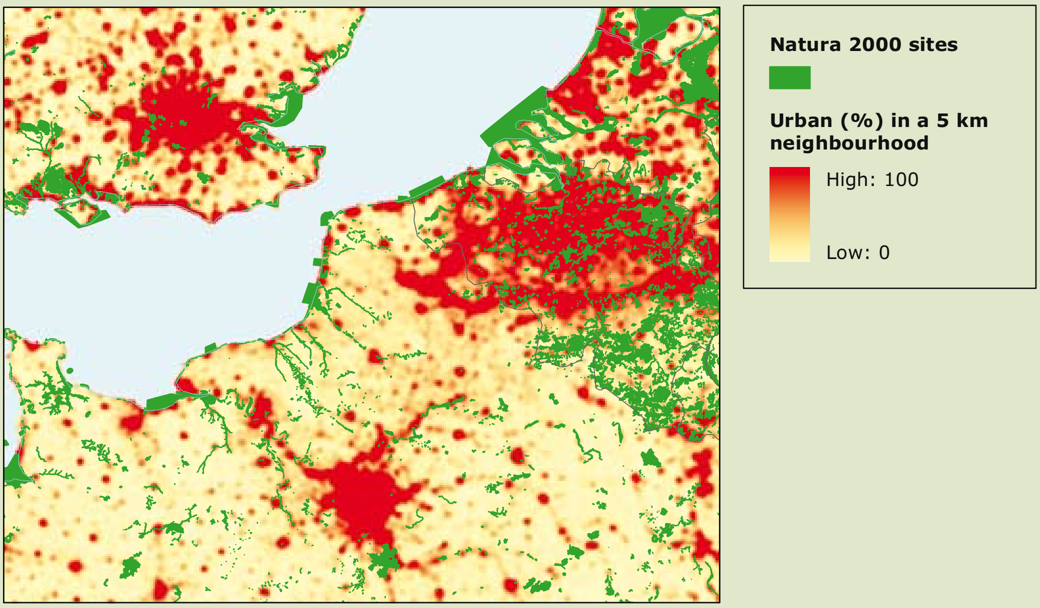
Box 7 Urban pressure on Natura 2000 sites

Pressures on natural areas are derived not only from new land use change but equally from the cumulative effects of land uses in the past. Impacts are generated not only from major urban areas but also from the combined impacts of several small sources that can have equally severe effects.

The map below shows the distribution of urban areas around Natura 2000 sites in the London metropolitan area, northern Belgium, the Netherlands and northern France. To the northeast of Paris, the urban fabric runs along the river Seine, adjacent to Natura 2000 sites. The strong interconnections between urban and natural areas are visible, with 10 % of forests in Belgium and 15 % in Netherlands within 5km of major cities with population in excess of 100,000. In the most extreme cases Natura 2000 sites are completely integrated within the urban areas, and so suffer major pressure from air pollution, noise and human disruption.

Map Urban pressure on Natura 2000 sites in the coastal areas of the English Channel and western Mediterranean





Source: EEA (based on Corine land cover 2000 and Natura 2000 data).

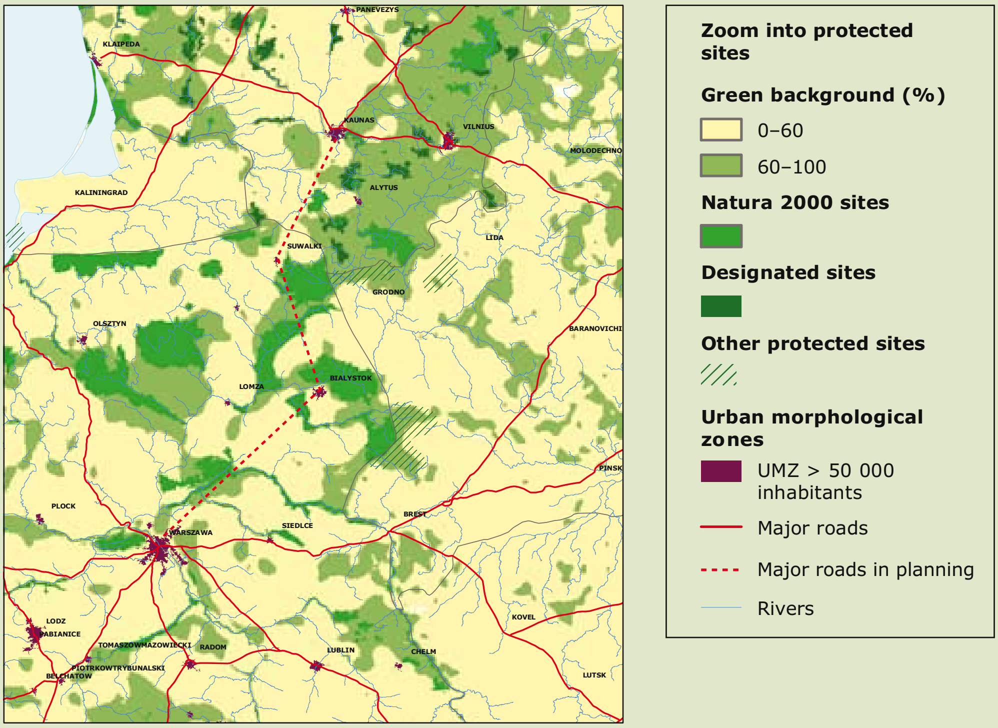
Box 7 (cont.)

Pressures on urban areas are also great on coastal zones, particularly in the western Mediterranean. The map below shows a clear contrast between the expansion of urban areas on the coast and inland. In the case of Barcelona geographic constraints are driving sprawl to the coast, and as a consequence Natura 2000 sites on the coast are becoming more isolated. Elsewhere new urban development is encroaching on inland protected areas. In some localities urbanisation is occurring within Natura 2000 sites.

Impact of transport infrastructure on protected sites: Via Baltica road development, southern part in Lithuania and North-Eastern Poland

Via Baltica is one of the routes planned within the TEN networks to connect the Baltic states and Finland with the rest of the EU. The route commences in Helsinki passing through the Baltic states to Warsaw and beyond. Via Baltica crosses the most important environmental zone in Poland. Unique in Europe, it consists of four very important natural forest and marshland sites (see map sites of environmental interest at regional, national, and European level). The marshes of Biebrza are the only natural wetlands remaining in the whole of Europe, and their protection is a key environmental priority for Poland.

Map Transboundary Environmental Protection Zone: Lithuanian-Polish border



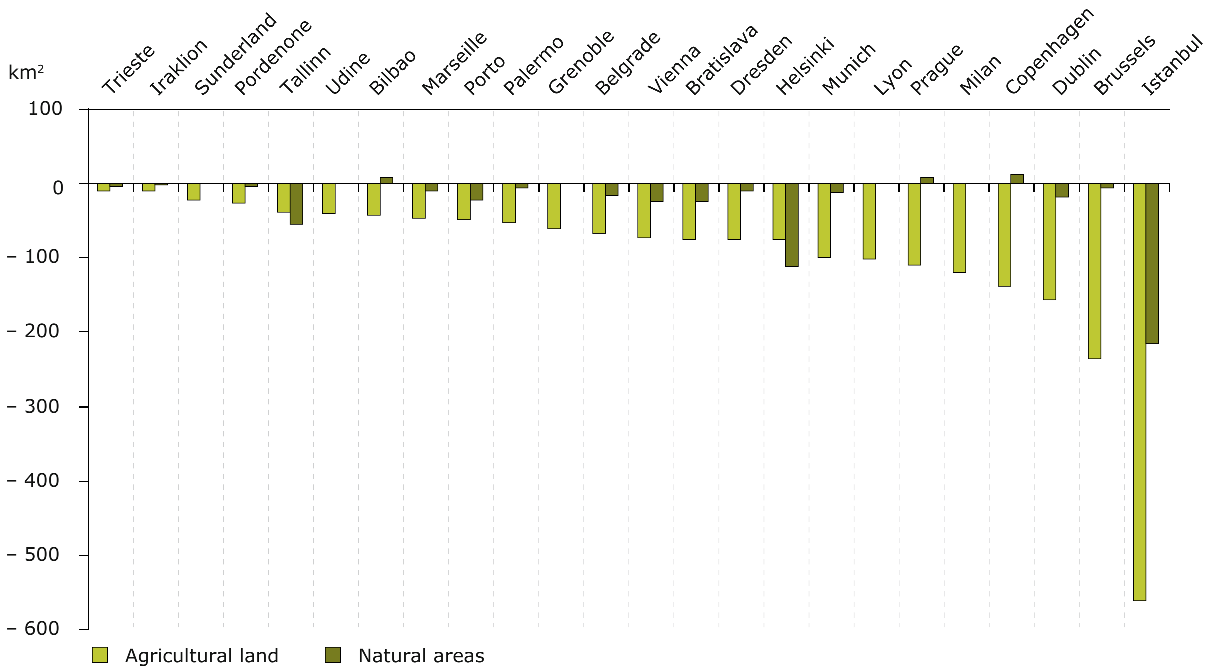
Note: The line indicating major roads in planning is an estimate only.

Source: EEA (based on multiple source data).

The EU funds have now provided financial aid for the Polish government to commit to the construction of this part of the TEN networks, and despite major protests from ecological groups, as well as questions raised at the EU level, most of the plans for the Via Baltica have been accepted.

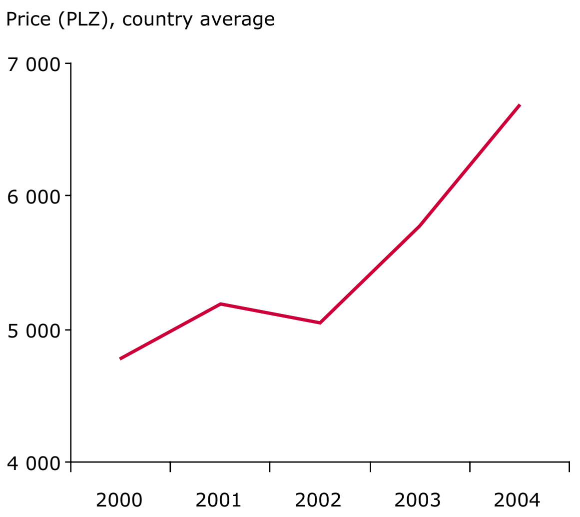
The proposal is to build a dual carriageway that connects the border zone with the main cities of the region as an extension to the existing national road. The proposal routes part of the road close to the borders of the Biebrza National Park, and part of the route is directed through one of the Natura 2000 sites. To minimise environmental damage the route will be limited to a dual carriageway, instead of a motorway, and elsewhere the route will be tunneled or constructed on raised embankments. Clearly, there are many questions raised regarding the environmental impacts of this section of Via Baltica on the Transboundary Environmental Protection Zone.

Figure 11 Sprawl impacts on agricultural land and natural areas, selected European cities



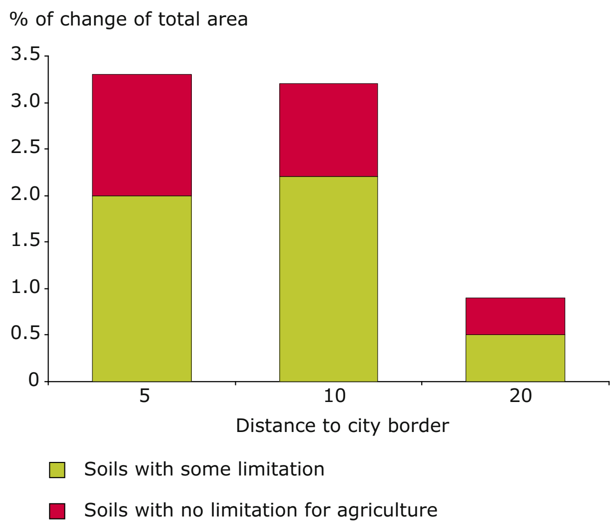
Source: MOLAND (JRC).

Figure 12 Trends in Polish agricultural prices 2000–2004 (Polish Zloty)



Source: Polish Central Statistical Office.

Figure 13 Loss of agricultural land outside urban areas



Source: EEA (CLC 2000, UMZ 2000).

4.1.4 Urban quality of life, hazards and health

As noted earlier, urban sprawl produces many adverse environmental impacts that have direct impacts on the quality of life and human health in cities, such as poor air quality and high noise levels that often exceed the agreed human safety limits.

In the period 1996–2002 significant proportions of the urban population were exposed to air pollutant concentrations in excess of the EU limit values (25–50 % of the urban population for different pollutants). It is estimated that approximately 20 million Europeans suffer from respiratory problems linked to air pollution. In particular, the societal cost of asthma has been estimated at 3 billion euro/year. Although current legislation restricts the emission of harmful substances, certain extreme events facilitated by climatic conditions, or even accidents, are of concern given the large number of people potentially exposed to these threats. Moreover, the impact of air pollution is becoming a global problem as a consequence of long-distance transportation of bio-accumulative substances.

The level of air pollution exposure in the densely developed centres of cities may often be at higher levels than the suburbs due to the greater concentrations and slower movement of traffic. However, the noise produced by all vehicles, and the rapid growth in transport, particularly air and road transport, is more ubiquitous and has resulted in well over 120 million people throughout the EU being exposed to noise levels affecting their well-being.

Sprawl related growth of urban transport and greenhouse gas emissions have major implications for global warming and climate change, with the expectation of increasingly severe weather events in the coming years and increased incidences of river and coastal flooding. The risks from the continued development of these areas in the context of a changing climate is evident in the recent major floods in Europe that have affected large urban populations. The floods in central Europe in August 2002 caused 112 casualties and over 400 000 people were evacuated from their homes. These expected transformations pose major challenges for urban planning that are clearly focussed on the growth of urban sprawl along the coastal fringes throughout Europe, as well as development of sprawling extensions across greenfield sites in the river valleys and lowlands of Europe.

The more general permanent flooding of the coastal regions of Europe due to rising sea levels and climate change is particularly worrying considering the concentration of urban populations along the coasts and the importance of these areas for tourism. The countries of Europe most vulnerable to coastal flooding include the Netherlands and Belgium, where more than 85 % of the coast is under 5 m elevation. Other countries at risk include Germany and Romania where 50 % of the coastline is below 5 m, Poland (30 %) and Denmark (22 %), as well as France, the United Kingdom and Estonia where lowlands cover 10–15 % of the country.

Overall, 9 % of all European coastal zones lie below 5 m elevation. Even with conservative estimates of predictions for sea level rise, a substantial part of the population of Europe living in the coastal regions are highly vulnerable to sea level rise and flooding. It is clear that this is not a specific issue generated by urban sprawl, however, the management of these risks and planning for adaptation will be made more complicated if urban sprawl is not controlled.

Furthermore, the majority of coastal lowlands have ageing defense systems and considerable resources are needed to maintain and improve these systems in order to provide the capacity to withstand the predicted rise in sea levels. In addition and just as important is the fundamental need for new visions for urban and regional planning policy that respond to these challenges. These visions must recognise that continued sprawl in the coastal regions of Europe is fundamentally unsustainable.

Finally, a further emerging issue is worth reporting: urban areas and their hinterlands are becoming increasingly vulnerable to geo-problems controlled by geological processes. The total cost of these problems to society ranges from major hazards (such as volcanic eruptions, earthquakes, floods, land subsidence, landslides) to minor hazards (such as local swelling or shrinking of clays in foundations). Reworking and removal of the soil surface by construction can unbalance watersheds and landscapes, contributing to the loss of biological diversity, ecosystem integrity and productivity, as well as to land degradation and erosion.

4.2 Socio-economic impacts

From a social perspective urban sprawl generates greater segregation of residential development according to income, as mentioned in Chapter 3. Consequently, it can exacerbate urban social and economic divisions. The socio-economic character of suburban and peripheral areas is typified by middle and upper income families with children, who have the necessary mobility and lifestyle to enable them to function effectively in these localities. However, the suburban experience for other groups, including the young and old, who lack mobility and resources can be very different and can reduce social interaction. Furthermore, large segments of urban society are excluded from living in such areas.

Social polarisation associated with urban sprawl is in some cities so apparent that the concept of the 'divided' or 'dual' city has been applied to describe the divisions between the inner city core and the suburban outskirts. In the inner city, poor quality neighbourhoods often house a mix of unemployed people, the elderly poor, single young people and minority ethnic groups, often suffering from the impacts of the selective nature of migration and employment loss.

These socio-economic problems are not, however, unique to city centres. In many cities similar social and economic problems have increasingly developed in the more peripheral areas where post war re-housing schemes are today home to some of the most disadvantaged urban groups and the location of the lowest quality environments.

From an economic perspective urban sprawl is at the very least a more costly form of urban development due to:

- increased household spending on commuting from home to work over longer and longer distances;
- the cost to business of the congestion in sprawled urban areas with inefficient transportation systems;
- the additional costs of the extension of urban infrastructures including utilities and related services, across the urban region.

Urban sprawl inhibits the development of public transport and solutions based on the development of mass transportation systems, and the provision of alternative choices in transportation that are essential to ensure the efficient working of urban environments. These conclusions are reinforced by experience from both Munich and Stockholm where the efficient control of urban sprawl and resulting increase in population densities fosters the use of public transport and reduces the growth of car use (Lyons, 2003; Cameron *et al.*, 2004).

Economic inefficiency is also associated with the market orientated planning regimes that frequently generate sprawling urban areas. Market orientated land use allocations driving urban expansion and the transformation of economic activity often result in the abandonment of former industrial areas. As a result, there are many derelict or underused former industrial zones throughout Europe. In Spain about 50 % of sites contaminated from past industrial activities are located in urban areas (1999), and in Austria it is estimated that abandoned industrial sites cover about 2 % of all urban areas (2004).

Generally, the efficiency savings of more compact city development as compared with market driven suburbanisation can be as high as 20–45 % in land resources, 15–-25 % in the construction of local roads and 7–15 % savings in the provision of water and sewage facilities (Burchell *et al.*, 1992).

EU enlargement and the accession of new Member States have in some instances generated economic effects with associated impacts on the development of cities. In Tallinn, for example, over the past 2–3 years the price of apartments has risen considerably during a period of widespread increases in real estate and land market transactions (Box 8). Generally, increased land prices throughout western Europe, as a consequence of urban sprawl and speculation, is attracting investors to new markets in the new Member States. The input of external capital distorts internal markets, particularly in small countries like Estonia which has a small property market and a population of just 1.3 million.

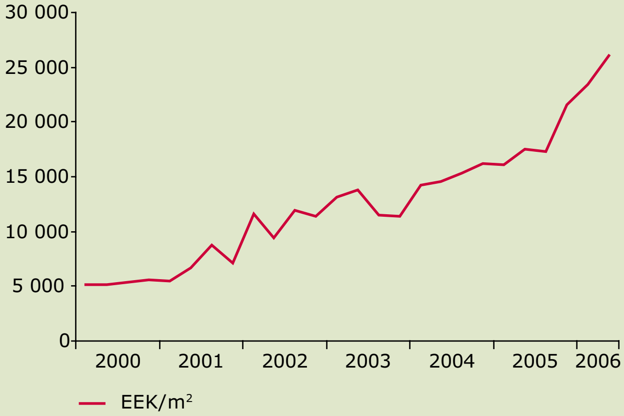
The failure to control urban sprawl at the local level despite the policies and tools that are available supports the case for the development of new initiatives and new policy visions to address these policy failures. The EU has obligations to act to address the impacts of urban sprawl for a wide variety of policy reasons. These include its commitments under environmental treaties to ensure that these impacts do not seriously undermine EU commitments to the Kyoto Protocol on greenhouse gas emissions. Other legal bases for action originate from the fact that some problems of urban sprawl arise from European intervention in other policy domains. Overall, these obligations define a clear responsibility and mandate for the EU to take an active lead in the development of new initiatives to counter the environmental and socio-economic impacts of sprawl.

The following chapter examines the principles that should define the governance framework for action at EU level to combat urban sprawl. This includes policy definition according to the principles of sustainable development, policy coherence built around measures to secure policy integration via close coordination between different policies and initiatives, and better cooperation between different levels of administration.

Box 8 Effects of residential areas pricing on urban sprawl in Tallinn

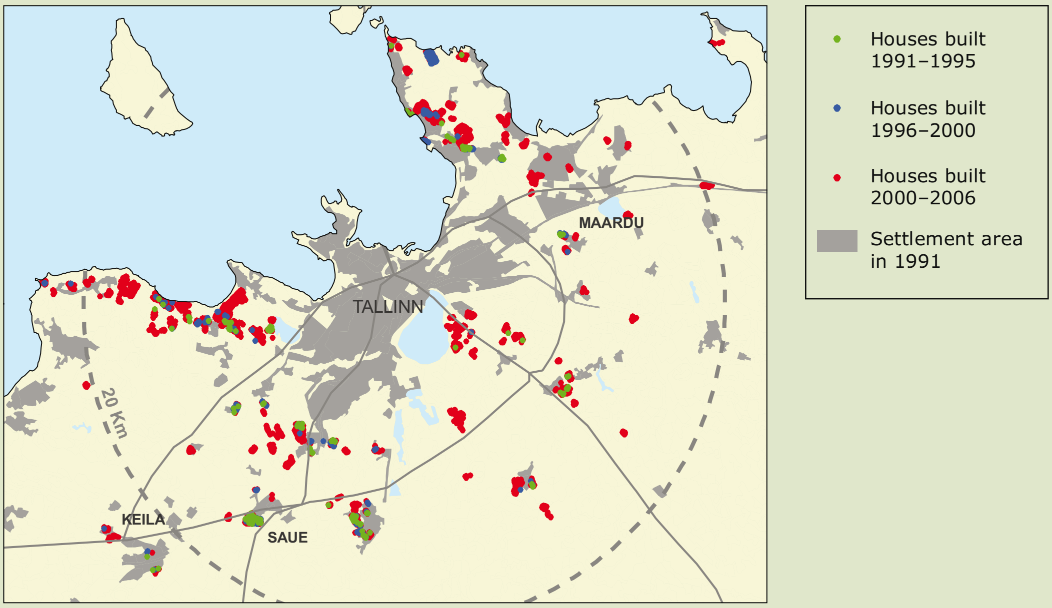
An inventory of the new residential areas (minimum 5 houses or doors in limits of 200 m from each other) in the Tallinn metropolitan area was carried out during January 2006 (Ahas *et al.*, 2006; Tammaru *et al.*, 2006). The construction of the new residential areas has grown exponentially in 1991–2005. One third of all the households living in the suburbs of Tallinn live in the houses that were completed in 2005. The 171 settlements under study consist of 3 400 dwellings housing 5 600 families and 17 200 inhabitants. It becomes evident that 46 % of settlements consist of single-family houses, but only 20 % of the households live in them. New housing is concentrated very close to the capital city, in limits of 10–15 km from city centre. New settlement areas are spatially more scattered into the new small settlements, mainly on the previous farmlands. The majority of new residential areas are located not far from the existing social infrastructure, but they are poorly equipped with it themselves. The local populations living in the city are beginning to realise new opportunities to sell their inner city apartments at higher prices and purchase new housing outside the city. These houses are located in scattered developments approximately 10–15 km from the centre of Tallinn typically on former farmlands. The majority of these new residential areas are located adjacent to the existing social infrastructures but have nonetheless poor social provision.

Figure Tallinn average price of a two-room apartment (EEK/m²)



Source: Estonian Statistical Office, 2006.

Map New settlements in Tallinn metropolitan area, 2006



Source: Tammaru *et al.*, 2006.

5 Responses to urban sprawl

'Creating high quality urban areas requires close coordination between different policies and initiatives, and better cooperation between different levels of administration. Member States have a responsibility to help regional and local authorities to improve the environmental performance of the cities of their country' (Communication from the European Commission to the Council and the European Parliament on Thematic Strategy on the Urban Environment, 2006).

5.1 Initiatives to counter sprawl

This report presents the growing evidence that the drivers of many environmental problems affecting European urban land originate outside the urban territory where the changes are observed. The global market economy, trans-European traffic networks, large-scale demographic and socio-economic changes, cross-boundary pollution, as well as differences in land-planning mechanisms at national, regional and local levels, are the main drivers of change and environmental pressure on, and from, urban areas. As a result, there is now increasing awareness of the benefits of considering urban territory as an integrated unit for stimulating better coordination of policies and analysis of their economic, social and environmental impacts.

Managing cities is a complex and interrelated task which highlights the potential dangers of ad-hoc decision making: the solution to one problem, at one scale, is often the cause of another, at a similar or different scale. It is therefore of prime importance to recognise that while the city is the main focus of socio-economic activity, and the associated pressures and impacts on the environment, it cannot be managed in isolation from forces and decisions that originate well beyond the city borders.

The EU can take a lead role in developing the best frameworks for action at all levels and pave the way for local leaders to do more, as attempted through recent decisions (European Commission, 2005; 2006).

A key dimension of such frameworks is the division of responsibilities between the different levels of city and regional governance. Urban and regional managers at the local level have prime responsibility for the management of the city and its region. But the strategies and instruments to control urban sprawl strongly depend on the interconnectedness between local, regional and national conditions that are increasingly reshaped by the realities of Europe's spatial development. New planning responses to combat urban sprawl therefore would be built on principles that recognise what is locally driven and what should be EU driven.

A further dimension concerns the revision of the thrust of policy at the local level to counter sprawl, and the replacement of the dominant trends of urbanisation ('laissez-faire') with a new urbanism ('creative control') (Laconte P., 2006). At present, planning policy solutions at all levels of governance more typically reflect the logic of economic development rather than a sustainable vision of urban Europe.

New policy interventions to counter sprawl could be focused on the need to supplement the logic of the market and be based on demand-driven rather than supply-driven management. In this context, identifying the necessary spatial trade offs between economic, social and environmental objectives and the key requirements for the sustainable development of Europe's cities requires an improved regional contextualisation of the respective assets that should be maintained, restored or enhanced.

This is the role devolved to spatial development in policy making where the EU can support the envisioning of spatial planning of Europe's cities and regions to effectively address the issue of urban sprawl. This articulated vision of sustainable urban and regional development can provide the context for a range of integrated mutually reinforcing policy responses, offering a new policy coherence to be implemented at all levels. Particular focus can be given to the key EU policy frameworks which can make major contributions to policies to combat urban sprawl, namely transport and cohesion policy.

5.2 The European spatial development perspective

While EU territorial development is the subject of continuing debate, the links between territorial cohesion and economic and social cohesion, two fundamental aims of the European Union (Article 16 of the Treaty), require further clarification and analysis. Many benefits can be secured from a broader vision of cohesion that encompasses the many dimensions of the development of territories, urban areas in particular, and their interrelationships.

Europe has continued to debate the merits of a stronger and more balanced territorial focus for its policies since the Member States and the European Commission presented the European Spatial Development Perspective (ESDP) in 1999. This debate has produced commonly agreed policy orientations focused around better territorial balance and cohesion, improved regional competitiveness, access to markets and knowledge, as well as the prudent management of natural and cultural resources.

These policy orientations reflect the ongoing geographical concentration of many parts of European society in highly urbanised areas. The long-term aim is to see a European territory with many prospering regions and areas, geographically widespread, all playing an important economic role for Europe and providing good quality of life for their citizens. Polycentric spatial development is the main concept underpinning the aims of territorial cohesion. The concept can be described as a bridging mechanism between economic growth and balanced development. Accordingly, polycentric development can bridge the divergent interests of the Member States by encouraging more balanced and coordinated competitiveness. Interest in polycentric development is also fuelled by the hypotheses put forward in the ESDP that polycentric urban systems are more efficient, more sustainable and more equitable than either monocentric urban systems or dispersed small settlements. This process should be considered in conjunction with the perspectives of land prices mentioned earlier in this report. This is particularly pertinent for agricultural land prices in the context of the new intensification of agriculture, driven by the increase of world-market prices and the evident growing demand for biofuels.

One of the central tenets of the ESDP and its follow up studies, notably the Study Programme on European Spatial Planning (SPESP) is that 'many local problems cannot be solved nowadays without an integrated way of looking at towns and countryside, since they tend to be regional problems'. In this context, a territorial dimension has been proposed for the conceptual basis of structural policies after 2007. The Commission has also proposed European territorial cooperation as an objective for Structural Funds interventions for 2007–2013 in support of territorial cohesion within the EU.

At the same time, although the Lisbon Strategy has no explicit territorial dimension, one of its three main priorities calls for Europe to be made an attractive area in which to invest and work. This priority includes considerations relating to access to markets and the provision of services of general interest, as well as to factors relating to the creation of a healthy environment for enterprise and the family. The implementation of the Lisbon Strategy and future structural policies will take place in cities, regions, in national territories and at European level (European Commission, 2005). Therefore, a key question for policy-makers at different levels is to explore, identify, understand and select potential areas for development within their own territory in order to contribute effectively to this overall European strategy.

5.3 Current barriers to addressing urban sprawl

Despite the complexity of urban systems, a piecemeal approach to urban management prevails in many cities; sprawl is seldom tackled as an integrated issue. In turn, issue integration is rarely matched by procedural integration through policy-making, problem analysis and impact assessment, planning, financing and implementation, precisely because of the wide scope of the issues involved. This constraint on effective urban management, already identified as far back as the 1980s (European Commission, 1990), still remains high on political agendas (European Commission, 2006).

In this context, there is a continuing perception of cities as isolated from their wider regional context. In reality, however, the functional influences of cities are recognised as reaching far beyond their immediate boundaries. There are also multidimensional links between urban and rural areas that are becoming more and more apparent. Typically, in Europe today, cities flow imperceptibly across municipal boundaries. This process is at different stages of development in different countries, but it occurs everywhere. At the same time, the responsibility for land use management remains divided between different administrations and this fragmentation of management, frequently exacerbated by the political tensions of neighbouring administrations, may lead to incoherent and uncoordinated land use management.

There are many more dimensions to the management of urban sprawl. Societal behaviour, as mentioned in Chapter 3, is a major factor driving urban development as the desire for detached homes combines with the widespread use of cars. This reflects social values that place great emphasis on individual achievements rather than on group solidarity. Producers of consumer goods or services have made profitable use of this trend through detailed customer socio-cultural typologies and refined market segmentation (Laconte P., 2006).

Illustrative of this reality is the fact that, for the past 20 years, there have been four times more new cars than new babies, and vehicle-kilometres traveled in urban areas by road are predicted to rise by 40 % between 1995 and 2030. Levels of car ownership in the EU-10 are still not at the same levels as for EU-15, suggesting even further growth. If nothing is done, road congestion is expected to increase significantly by 2010 and the costs attributable to congestion will increase to approximately 1 % of Community GDP (EEA, 2006).

The issue of mobility, and accessibility, therefore remains a critical challenge for urban planning and management, as well as a key factor in European territorial cohesion. The challenge is to secure a global approach that takes into account the real impacts of investments directed at the creation and sustainability of local activities and jobs, based on a balanced and polycentric development of European urban areas.

These are challenges that must also be faced at regional, local and European levels, in the framework of the common transport policy and the Trans-European Transport Network (TEN-T). It is worth mentioning, in this respect, that in April 2004 the European Parliament and the Council identified 30 priority projects that represent an investment of EUR 225 billion by 2020, involving, for example, the construction of 12 000 km of highways. Will the history of urban sprawl in the EU-15 repeat itself in the EU-10?

EU regional policy perspectives will play a major role in developing new transport networks during the 2007–2013 period, in accordance with the priority objectives proposed by the Commission, including convergence, regional competitiveness and employment, and territorial cooperation. Impact assessments of the effects on the expansion of city regions generated by these new transport investments will be critical for the attainment of all these priority objectives (Box 9).

That said, it is vital to recall that the very complex nature of urban systems remains the principal barrier for current administrative and political initiatives tackling the problems of urban sprawl. The fundamental challenge remains understanding, in both functional and operational terms, the unsustainable development patterns of our cities so that future unsustainable development can be corrected or avoided. This is still a challenge even for experts studying the most 'sustainable' forms of urban development.

In this context, the relationship between urban compactness and travel patterns (mobility) is central to the debate (Williams K. *et al.*, 2000). However, there are more dimensions, for example, to the simple causal relationship between high-density development and reductions in mobility demand. Current monitoring and analysis of such links could be improved greatly if employment catchment areas were used to define functional urban regions (Laconte P., 2006).

All things considered, the paradigm of the compact city as an immediate antidote to the sprawling city still cannot be fully substantiated. The effectiveness of compaction, as well as centralisation and concentration, have been thoroughly examined, including the various ways in which compaction can be achieved, such as intensification, new high-density development, traditional neighbourhood development etc. However, there are still uncertainties, particularly in the areas of ecological, social and economic impacts (Williams, K. *et al.*, 2000).

5.4 Policy coherence and effectiveness

To be effective policies should deliver what is needed on the basis of clear objectives, in terms of time and with an evaluation of future impacts. Effectiveness also depends on implementing policies in a proportionate manner, on taking decisions at the most appropriate level, and ensuring that decisions taken at regional and local levels are coherent with a broader set of principles for sustainable territorial development across the EU.

The EU has a responsibility and a specific capability to address the wide ranging and powerful pan-

European regional forces generating urban sprawl with impacts beyond the control of urban managers at the local level. For these reasons, policies at all levels need to have an urban dimension that tackles urban sprawl and helps to redress market failures that drive urban sprawl and undermine a sustainable vision for the spatial planning of urban Europe.

The EU white paper on European governance provides the following framework of principles underpinning good governance that assists in defining a framework for intervention to counter sprawl at all levels:

- Policy coherence: ensuring that policies are coherent and not sector-specific and that decisions taken at regional and local levels are coherent with a broader set of principles;
- Responsiveness to local conditions: flexibility in the means provided for implementing legislation and programmes with a strong territorial impact;
- Cooperation in policy development: development of systematic dialogue and increased cooperation with European and national associations of regional and local government.

5.4.1 *Policy coherence*

Policy coherence provides the first principle of good governance through which the EU can support initiatives to counter urban sprawl. Cities can benefit from initiatives and programmes spanning the entire realm of European Commission competence; the framework for trilateral agreements between the EU, national governments and regional/local authorities (COM(2002)709) provides a specific example, and some agreements have already been signed, e.g. Milan (Laconte P., 2006).

However, cities also need a long term sustainable policy vision to help synchronise the many critical success factors, including mobility, access to the natural environment, social and cultural opportunity, and employment, which all form the basis for sustainable urban development. At present, in many cases, the policy vision is poorly articulated permitting a market driven approach to dominate over the interests of sustainable development, a deficiency exacerbated by poor integration between the levels of governance. The EU can set the tone and direction for sectoral policy integration in cities whilst recognising that planning responses to the problem of sprawl must also be sensitive to the local and regional mix of priorities.

As it stands, EU Cohesion Policy (2007–2013) offers an effective framework to build a coordinated and integrated approach to the sustainable development of urban and rural areas. The approach is essential to ameliorate the impacts of urban sprawl and specific actions include:

- coordination of land use policies, as well as Structural and Cohesion Funds investments between urban areas, rural areas, the regions and the national levels to manage urban sprawl. Initiatives to make urban areas and city centres attractive places to live and support the containment of urban sprawl;
- encouragement to Member States to explicitly delegate to cities funds addressing urban issues within Structural Funds operational programmes, with full responsibility throughout the process for the design and implementation of the delegated portion of the programme;
- investments to achieve compliance with EU laws on air quality, waste-water treatment, waste management, water supply and environmental noise. Active management of congestion, transport demand and public transport networks, with a view to improving air quality, reducing noise and encouraging physical activity all of which can assist in addressing the sprawl of cities;
- co-financing of activities under the Structural Funds based on plans that address the key challenges posed by sprawl and the improvement of the overall environmental quality of urban areas.

5.4.2 *Responsiveness to local conditions*

Responsiveness to local conditions provides the second principle of good governance through which the EU can support initiatives to counter urban sprawl. The principle emphasises the need for flexibility in the means provided for implementing EU legislation and programmes with a strong territorial impact.

The EU Urban Thematic Strategy offers an umbrella framework to support actions and solutions developed at the local level to address urban management problems including urban sprawl. The strategy offers a coordinated and integrated approach to assist Member States and local and regional authorities to meet existing environmental obligations, to develop environmental management plans and sustainable urban transport plans, and so to reinforce the environment contribution to the sustainable development of urban areas.

Box 9 Dresden and Prague: economic growth and new transport links

German reunification and the collapse of the communist block led to changes in the economic regime from planned to market economy in both the former east Germany and the Czech Republic. Adaptation to the market economy caused many dramatic changes in traditional economic structures, such as a decrease in GDP and a high rate of unemployment, up to 25 % in Saxony. Towards the end of the 1990s, gradual but sustainable recovery of the economy commenced and political and social reforms took hold. These changes have created completely new driving forces for urban development. EU membership has also led to the growing engagement with European markets and access to EU development schemes e.g. TEN-T, ERDF, Cohesion Fund etc. For the new EU Member States (EU-10) gross domestic product is expected to triple and the number of households is projected to double between 2000 and 2030 (EEA, 2005). But in contrast to economic growth, the demographic trends for EU-10 show significant decreases of population, up to 7 % by 2030 (EEA, 2005). It is clear that all the above-mentioned changes will have a strong impact on land use patterns in the area.

Dresden–Prague: key driving forces for urban development

1950s to 1990s	1990s to present
Economy	
• Planning economy	• Market economy
• Emphasis on heavy industry and mining	• Foreign (Czech Republic)/western German investments
	• Emphasis on modern high-tech industries, commerce and services
	• Construction boom
Population/urbanisation	
• Slowing population growth since the 1970s	• Decrease and ageing population
• Migration to the cities due to industrialisation	• Migration of rural population into the cities compensates natural decrease of population in cities
	• Emigration to western Europe for better jobs (Saxony)
Housing and planning policy	
• Limited market for residential and land properties	• Open market for residential and land properties
• Land price was not considered in the planning process, dominance of political decisions	• Private sector interests competing with public interests in the planning process
• Construction of vast areas of block houses for industry workers (especially the Czech Republic)	• Low land prices outside cities and people's preference to move to one-family houses
Infrastructure	
• Emphasis on public transport and rail	• Growing importance of motorways

Future development paths: scenarios

Business-as-usual: Extrapolates moderate 1990s trends of land use change, indicating that the land use patterns of the area will not change considerably over the next two decades.

Built-up expansion: Elaborates the socio-economic projections of the European Environmental Agency.

Motorway impact: Evaluates the impact of motorway development (A17/D8 part of TEN Corridor IV).

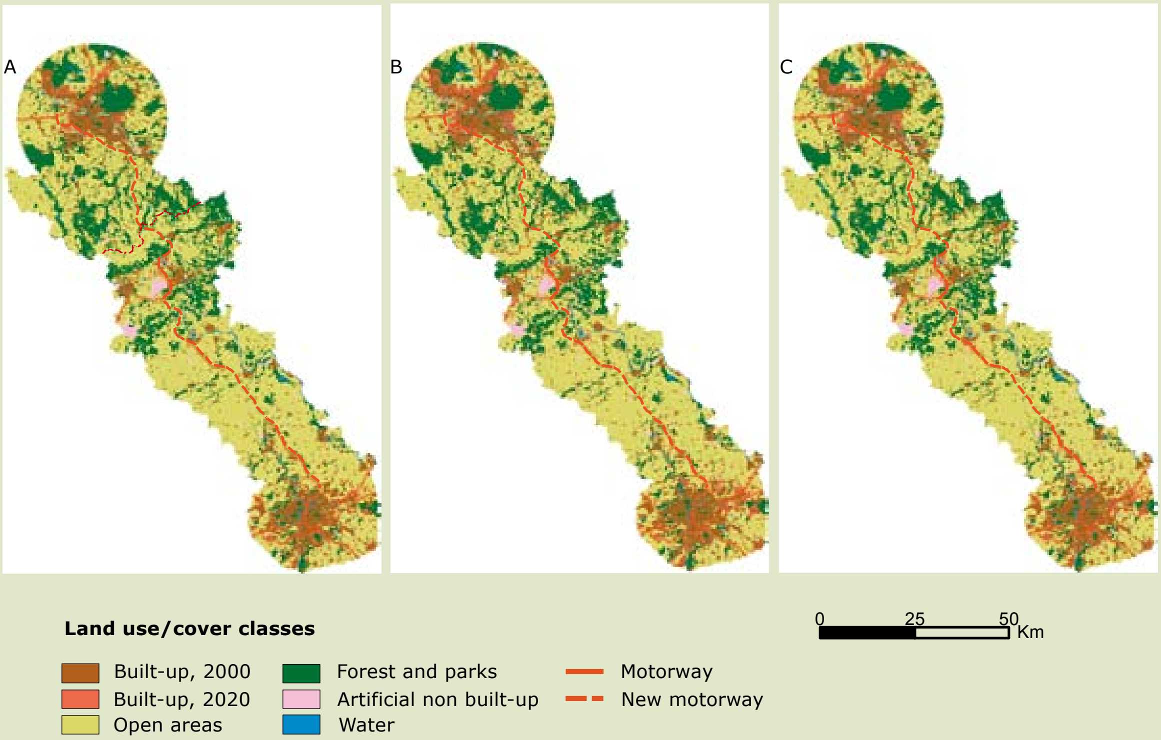
Around Dresden new residential districts are situated adjacent to existing ones and lead to the merging together of former clusters. Construction of the new motorway around the city from west to south creates a new development axis for commercial and industrial areas. The simulation results for Prague show a very different, more clustered type of future development. The radial network of motorways connecting the city to different destinations attracts the development of commercial zones and produces more clustered patterns of growth. The municipalities located in the vicinity of Prague experience intensive residential development and hence it can be assumed that demand for new housing will remain strong.

Box 9 (cont.)

The motorway A17/D8 can reinforce regional development and lead to the establishment of commercial and service areas adjacent to larger settlements and towns. In most cases the future growth pressures of Dresden and Prague will focus on agricultural land and natural areas around both cities.

Map Dresden-Prague: scenarios of urban land use development — late 2000–2020

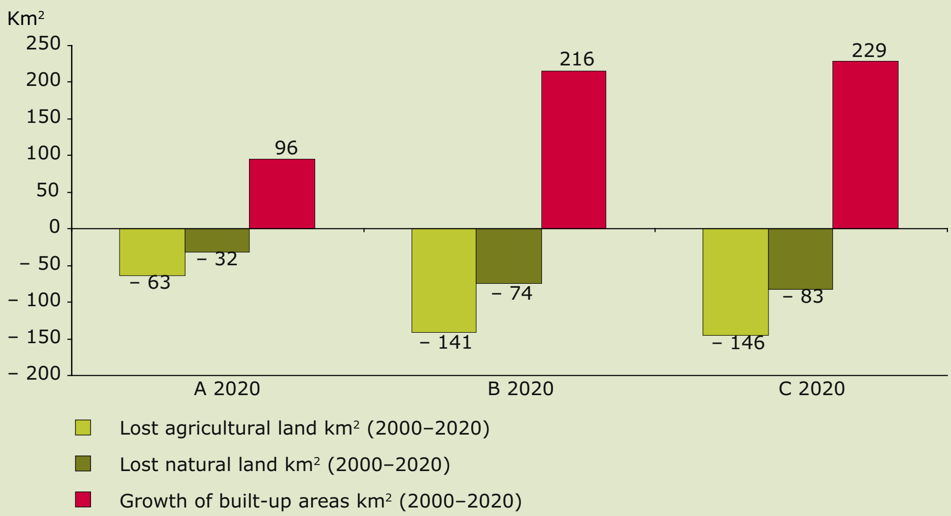
A: Business-as-usual B: Built-up expansion C: Motorway impact



Source: Moland (JRC).

Figure Land use changes in the Dresden-Prague Corridor 2000–2020

A: Business-as-usual B: Built-up expansion C: Motorway impact



Source: Moland (JRC).

The Thematic Strategy provides a context in which good practice experiences of cities in combating urban sprawl can be applied and developed such as:

- the development of long term, consistent plans promoting sustainable development and the limitation of urban sprawl supported by monitoring and evaluation systems to verify results on the ground;
- policies for the the rehabilitation of derelict brownfield sites and renovation of public spaces to assist in the creation of more compact urban forms;
- policies for the avoidance of the use of greenfield sites and complementary urban containment policies;
- identification of the key partners including the private sector and community, as well as local, regional and national government and their mobilisation in the planning, implementation and evaluation of urban development;
- management of the urban-rural interface via cooperation and coordination between urban authorities and rural and regional authorities in promoting sustainable development.

5.4.3 Cooperation in policy development

Cooperation in policy development provides the third principle of good governance through which the EU can support initiatives to counter urban sprawl. At the EU level, the Commission can ensure that regional and local knowledge and conditions are fully taken into account when developing policy proposals. In particular the aim is to develop systematic dialogue and increased cooperation with European and national associations of regional and local government and other local partners including regional and city networks and other NGOs.

The essentials of this approach are based on the development of a reinforced culture of consultation and dialogue, a culture which is adopted by all European Institutions. In some policy sectors, where consultative practices are already well established, the Commission could develop more extensive partnership arrangements. The mobilisation of a broad range of partners with different skills has underpinned the 'Bristol Accord' in which local partnerships including public, private, voluntary and community interests are viewed as essential to deliver sustainable communities.

Such partnerships need to be developed and maintained over the long term based on flexible cooperation between the different territorial levels. Regional and city networks and NGOs can in this manner make more effective contributions to EU policy development.

5.5 Local urban and regional management

The analysis of cities in this report confirms that the success of local planning policies and practices in restricting the physical expansion of built-up areas is critical to efforts to constrain urban sprawl.

The studies have identified planning policies and practices that have successfully restricted the sprawling expansion of built-up areas. Indeed, one fifth of the cities studied increased the density of residential areas from the mid-1950s. At the local level policies of urban containment are widely used in land use planning as a means of reducing urban sprawl and preserving farmland, including policies to limit greenfield and promote brownfield development based on more or less strict land use control.

Given the heterogeneity of the cities considered in this report, the array of policies and other means to limit and prevent urban sprawl is potentially extensive. Further examination of the policies and means to limit urban sprawl in these cities may therefore offer deeper insights into the nature of the effective local management of urban sprawl. The prime aim is to acquire a full understanding of the policies and practices behind the 'success stories' so that this know-how can be made available to all European cities in combating urban sprawl. The following analysis of Munich (Box 10) highlights some best practice experience that can provide catalysts for future integrated approaches to the management of urban sprawl throughout Europe.

The Munich area has remained exceptionally compact when compared to many other European cities. The roots of this success may be traced to the decisions by the city's planners in the post war period to rebuild the historical centre enclosed by a combined park and traffic ring. This was followed in the early 1960s by the replacement of traditional town planning with integrated urban development planning, providing guidelines for all municipal responsibilities including economy, social issues, education, culture as well as town planning.

By the 1990s comprehensive planning concepts were firmly established, based on an integrated urban development plan and focused on the objective of keeping the Munich region compact, urban and green. Fundamental to the attainment of the plan's objectives are a mix of policy initiatives including the reuse of brownfield land, avoidance of expansion, mixed land use development integrating residential and commercial services, improvement of public transport as well as pedestrian and cycling facilities, and reinforcement of regional cooperation.

The Munich case study clearly emphasises the dominant role of local and regional policies in defining the spatial organisation of cities and regions. Munich has successfully adopted and implemented a compact city model in the planning of the city that has effectively contained urban sprawl based on the following key objectives and actions:

- integrated city development plan;
- regional cooperation;
- stakeholders' involvement in city planning;
- emphasis on reuse of vacant brownfields;
- continuously improving public transport with as few new roads as possible;
- compact-urban-green — keep the city compact and urban and green areas green;
- guarantee the necessary resources for implementing the strategies of all relevant policy areas (transport, housing etc.) for both 'business as usual' situations and through major renovation projects.

The lessons from Munich can also provide the good practice basis for sustainable development that many other cities throughout Europe urgently require.

As well as issues concerning the potential for transfer of good practice experience, it is also clear that conflict with policy objectives at national, regional and local levels can also undermine local efforts to combat urban sprawl. The role that EU can play in combating sprawl should therefore be set not only in the context of complementing what is locally driven, but also proactively engaging at all levels, given the evident potential for local policy failure.

5.6 By way of conclusion — combat against urban sprawl

Land use patterns across Europe show that tensions are arising almost everywhere between our need for resources and space and the capacity of the land to support and absorb this need. Urban development is the main driver.

Throughout Europe in the 1990s, changes in land cover were mainly characterised by increases in urban and other artificial land development and forest area, at the expense of agricultural and natural areas. Anticipated growth of the urban population by 5 % in the coming decade, will further fuel these trends. Globalisation, transport networks, socio-demographic changes, societal aspirations for the 'urban culture' and uncoordinated land-planning mechanisms at various levels are the main sources of the environmental unsustainability of our cities.

Scientists, planners and policy-makers are becoming increasingly aware that adequate decisions on urban development cannot be made solely at the local level. This is especially important in a European context where more and more urban areas are becoming connected in order to realise common objectives, such as the Lisbon agenda for growth and competitiveness.

The history of human culture suggests that 'landscape' is one of the earliest and most obvious concepts for perceiving and describing our changing environment, be it artificial or not. It is at the landscape level that changes of land use, naturalness, culture and character become meaningful and recognisable for human interpretation. In that sense, landscape is as much vision as it is reality.

The way we perceive landscapes, the attraction we feel for some of them, and our feelings when conflicts arise over the use of land, are all matters of extreme importance for conservation and future human welfare. A landscape is essentially a photograph of what is going on; it reveals, in short, who we are. With urban sprawl-generated landscapes in continuous flux, we indeed reveal a lot about the footprints we will be leaving for the next generations.

The present report demonstrates, in this context, the potential for local policy to be isolated in overcoming the serious impacts of urban sprawl throughout Europe, a fact which highlights the requirement for urgent action by all responsible agencies and stakeholders. The EU governance white paper defines the preconditions for good governance emphasising the need to assess whether action is needed at the EU level and the principles for action when required.

Box 10 Munich — development of the compact city

Munich is the capital of the Bavarian state and the 3rd largest city in Germany. The MOLAND study area comprises the city of Munich (*Landhauptkapital*) and 44 surrounding municipalities (completely or partially). The total area is 791 km^2 and the resident population in 1990 was 1.69 million inhabitants. From 1955 to 1990 the population has grown by 49 %.

Munich — compact city

The Munich area has remained exceptionally compact if compared to many other European cities (see Chapter 2). It is the only urban area among the 24 urban areas studied where the built-up areas have grown at a clearly slower pace than the population. Another indicator of compactness is the share of continuous residential areas compared with all residential areas built after 1955. In all other Western European cities studied almost all residential areas, built after the 1950s, are discontinuous in character, but in Munich only one third is of this character and two thirds are densely built.

Bavarian planning solutions

Munich was heavily bombed and mostly destroyed in World War II and immediately after the war the city's planners faced a decision whether to completely rebuild or to reconstruct what was destroyed. The outcome, in what later proved to be an excellent decision, was a mix of both approaches. The historical centre was rebuilt largely following the pre-war pattern and style. To ease traffic problems and to increase green urban areas a combined park and traffic ring was constructed around the historical city.

By the early 1960s pressures to find new housing and transport solutions began to mount in Munich. The drivers for change were primarily the increased use of the private car, and strong inward migration from rural areas. At the same time at the Federal level in Germany, the new building law (*Bundesbaugesetz*) took effect. All these factors together influenced the far-sighted decision adopted by the Munich planners to move from traditional town planning to integrated urban development planning, providing guidelines for all municipal activities including economy, social issues, education, culture as well as town planning. The first integrated city-development plan of 1963 paved the way for Munich's modernisation.

In the late 1960s another innovative tool was also adopted as a response to citizens' opposition to the new development plans. The mayor organised an open discussion forum for urban development issues that became a permanent platform where the stakeholders and the city planners could exchange views and opinions. At the same time an independent department was created with the responsibility to coordinate all municipal planning activities, strengthen links with research and stakeholders involvement.

Regional cooperation was seen as the only way of safeguarding the balanced regional development of Munich and the mainly rural neighbouring municipalities. As early as 1950 the majority of the municipalities in the Munich region discussed common urban development issues in the form of a 'Planning Association of Munich's Economic Region' which became the Munich Regional Planning Association. However, this cooperation has remained on a voluntary and consultative basis and no planning authority has been transferred to the regional level, in contrast to other German city-regions.

The 1970s and 1980s were characterised by more incremental developments and the planning vision became less clear. Nonetheless, the steps taken in the earlier period maintained the high planning standards and resulted in a compact and high-quality urban environment. The main objectives of this era were as follows:

- city in equilibrium where various economic, social and environmental interests are in balance;
- development of areas inside the urban structure instead of urban expansion in the periphery supported by economic incentives, and made possible by large brownfields vacated by industry, the military, the Federal Railroads (DBB) and the old airport in Riem;
- strong emphasis on public transport and new road development limited to a minimum;
- preservation of large green recreational areas around the city.

In the 1990s the comprehensive planning concept gained ground and a new version of the integrated urban development plan called 'Munich Perspective' was adopted in 1998. The slogan of the plan is to keep Munich region compact, urban and green. The plan covers economy, social issues, transport, environment and town planning. The main urban structure objectives include continued reuse of brownfields and avoidance of expansion. Mixed land use (residential, commercial, services) is seen as an important way of keeping the

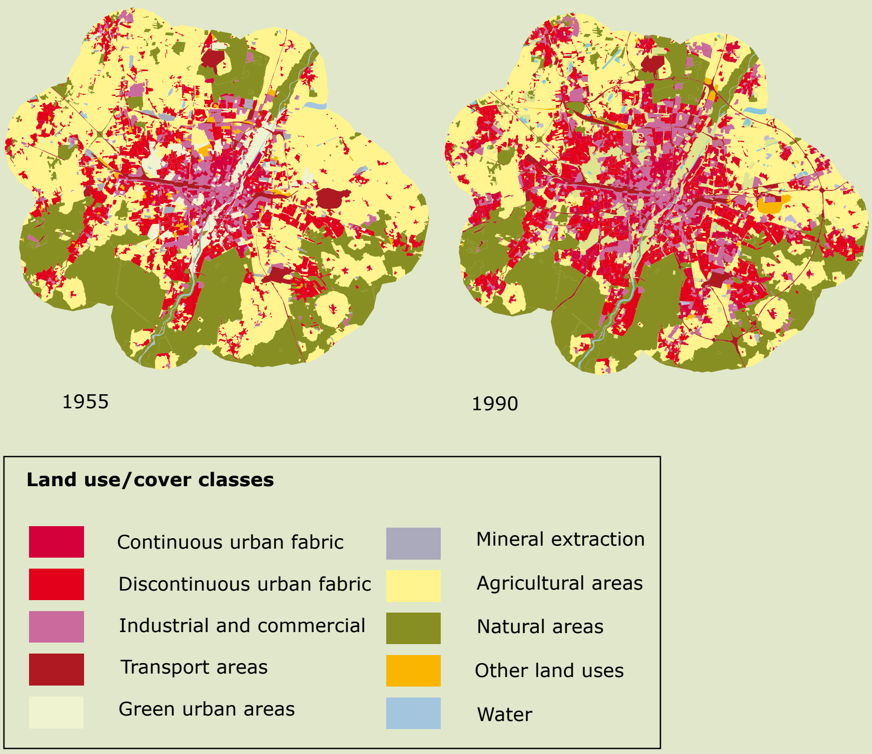
Box 10 (cont.)

city compact. Improvement of public transport as well as pedestrian and cycling facilities and reinforcing regional cooperation are also seen as fundamental for the attainment of the plan objectives.

Key objectives and actions for the compact city

- Integrated city development plan
- Regional cooperation
- Stakeholders' involvement in city planning
- Emphasis on reuse of vacant brownfields
- Continuously improving public transport with as few new roads as possible
- Compact-urban-green — keep the city compact and urban and green areas green
- Guarantee the necessary resources for implementing the strategies of all relevant policy areas (transport, housing etc.) for both 'business as usual' situations and through major renovation projects.

Map Land use changes in Munich urban area from 1955 to 1990



Source: MOLAND (JRC).

It is clear according to the good governance criteria that the EU has specific obligations and a mandate to act and take a lead role in developing the right frameworks for intervention at all levels, and to pave the way for local action. Policies at all levels including local, national and European need to have an urban dimension to tackle urban sprawl and help to redress the market failures that drive urban sprawl. The provision of new visions for the spatial development of Europe's cities and regions is vital for the creation of a range of integrated mutually reinforcing policy responses.

The policy debate on sustainable visions for the spatial planning of urban Europe is already actively underway in the European Parliament. The Parliament's advocacy of the provision of urban green areas and large natural areas to bring citizens closer to nature, can form the *entrée* for wider EU contributions to this debate on the visions. This will set the tone and direction for sectoral policy implementation at all levels, and become the basis for the new urban planning model of city regional development.

In (re)developing integrated spatial planning for the key EU policy frameworks which make major contributions to policies to combat urban sprawl, transport and cohesion policies are without doubt crucially important dimensions for the delivery of positive outcomes. EU Cohesion Policy offers in particular an effective framework to articulate better coordination of land use policies and Structural and Cohesion Funds investments between urban areas, rural areas, and the regions that can effectively manage urban sprawl.

Finally, good governance, in the context of the EU Urban Thematic Strategy, can be translated into the provision of support for actions and solutions developed at the local level to address urban management problems including urban sprawl. In this way the EU can directly assist in the transfer of good practice experience of the management of urban sprawl from one city to another and the dissemination of policy solutions that have proven effective.

The impacts of urban sprawl have for years and decades generated debates among scientists and practitioners, less so among the authorities and policy-makers in charge. We hope, with this report, to contribute to raising further awareness reactions to an issue crucial to Europe's sustainable future.

Annex: Data and methodological approach

A The challenge of scales

The assessment of the phenomena of urban sprawl at the European level requires appropriate information and tools effective at different scales. The issue of urban sprawl must be defined and comprehended in the urban-regional context in which the dynamics of urban sprawl are operational and urban management undertaken. Furthermore, there is a need to broaden the window of inquiry in order to assess the extent of the impacts of urban sprawl across on the political and geographic territory of Europe. This is the challenge of scales as both the information used and tools applied in the assessment of urban sprawl must be effective at these scales.

In this report two main data sets have been used, to establish linkages between the different scales:

- Corine land cover (1990 and 2000). CLC limitations include resolution of urban areas with minimum mapping unit 25 ha and minimum change detection of 5 ha. But CLC is currently the only harmonised spatial data covering all of Europe, with two time references shots for most countries. CLC makes it possible to assess the extent of urban sprawl in Europe, identifying different patterns and hot spots, and providing information about the neighbourhood of these zones so that change in the environmental context can be understood.
- MOLAND (Monitoring Land Use Dynamics) database. This is a comprehensive database of 28 urban areas and 6 wider regions developed by JRC since 1998. MOLAND has four time windows: mid-1950s, late 1960s, mid-1980s and late 1990s. The database includes cities from all EU-15 countries except the Netherlands and Luxemburg, from several EU-10 countries as well as some countries in the pre-accession phase. Most urban areas in the MOLAND database have 0.5 to 2 million inhabitants. The selection of urban areas and regions was influenced by European research interests, for example, the inclusion of areas with Structural Funds subsidies, border regions, areas with specific development dynamics etc. For each urban area detailed information is available on land use/cover changes, but also on socio-economic data from the 1950s. The database provides a wide time frame that is generally lacking at the European level, and the wide distribution of cities is useful to illustrate issues that are not possible with a narrower frame of reference.

It is important to emphasise that both data sources share the same definitions of land cover classes. In the case of MOLAND a more detailed level of subclasses has been derived in view of its higher level of resolution. The common basis of land use classes ensures some comparability of results.

B Definition of urban areas

Urban sprawl is extending urban growth far beyond their administrative boundaries, and in order to ensure that there is full comparability of results between cities the units of analysis need to be clearly defined. In this report urban areas have been defined by morphology and the distribution of urban land across the territory. CLC and MOLAND data sources originate from different projects, and so the definitional bases are slightly different. It should also be borne in mind that both data sources possess different resolutions. Overall, however, general trends, such as direction of change and order of magnitude of built-up areas, are consistent between both data sets. Details are provided in the following paragraphs.

Delineation of urban morphological zones with Corine land cover

Urban morphological zones (UMZ) are defined as built up areas lying less than 200 m apart. Urban areas defined from land cover classes contributing to the urban structure and function are:

- continuous urban fabric (111 according to CLC code);

- discontinuous urban fabric (112 according to CLC code);
- industrial or commercial units (121 according to CLC code);
- green urban areas (141 according to CLC code).

In addition port areas, airports, and sport and leisure facilities, are also included if they are neighbours of the core classes or are contiguous with the core classes.

Once UMZ have been identified according to the procedure outlined above, a second step is undertaken to include road and rail networks, and water courses, if they within 300 m of the UMZ defined in the first step. Finally, forest and scrub (311, 312, 313, 322, 323, 324 CLC code) are also included if they are completely within the core classes.

The UMZ has been delineated for CLC2000 (with reference year 2000). In order to reduce the large number of UMZs identified and work with a relevant subset, only UMZs with more than 100 000 inhabitants have been selected. The allocation of the population has been undertaken as follows:

- EU-25: Population was derived multiplying land cover classes by Population Density Raster provided by JRC. The source data was from Eurostat (2001).
- Non-EU-25: Population data was derived from the CITYPOPULATION (www.citypopulation.de) database, which in turn collects the information from national statistical offices. Data is provided by settlement, and settlements are then aggregated according to UMZ and data from 2001 added.

Urban areas in MOLAND

The area of investigation was selected on the basis of the contiguous artificial surface or core area of the city, plus a peri-urban buffer zone. The former usually corresponds to the Artificial Surface class of the Corine land cover map and equals an area (A). The buffer zone was calculated as follows:

Buffer zone width = $0.25 \times \sqrt{A}$ (square root)

The buffer zone typically extends the urban area by approximately twice the core area. The calculated buffer has often been modified and adapted to the neighbouring structures in order to avoid excluding or cutting land uses of major significance such as an airport, village or, simply, the administrative boundaries. In this report urban area refers to the area that combines the core area and the buffer around it. The urban area is therefore always larger than the city, e.g. Munich includes the city of Munich and 44 surrounding municipalities either completely or partially.

Overview of the main databases used in this report

Data source		MOLAND	Corine land cover 1990	Corine land cover 2000
Responsible authority		JRC	EEA	EEA
Period	**Start date**	1950	1986	1999
	End date	2000	1995	2001
Geographic coverage		28 cities and 6 wider regions in Europe In this study are included: Belgrade, Bilbao, Bratislava, Brussels, Copenhagen, Dresden, Dublin, Grenoble, Helsinki, Iraklion, Istanbul, Lyon, Marseille, Milan, Munich, Palermo, Pordenone, Porto, Prague, Sunderland, Tallinn, Trieste, Udine, Vienna	EU-25 (with the exception of Sweden, Cyprus, Malta), Bulgaria, Croatia, and Romania	EU-25 Member States of the EU and Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Liechtenstein, Macedonia
Spatial resolution		Minimum mapping unit 1 ha for the artificial surfaces and 3 ha for non-artificial surfaces	Minimum mapping unit 25 ha	Minimum mapping unit 25 ha Minimum change detection 5 ha
Temporal coverage		mid-1950s, late 1960s, mid-1980s and late 1990s	1990 +/– 8	2000 +/– 3 years
Quality		Accuracy > = 85 %	Accuracy > = 85 %	Accuracy > = 85 %

C Assessing urban sprawl at the European level: Corine land cover

The assessment of urban sprawl has been undertaken within the framework of the land and ecosystem accounts method developed by the EEA and ETC/TE (EEA, 2006). It is based on the Corine land cover 2000 database which also contains a special data layer of 1990–2000 land cover changes. The land accounting methodology permits the measurement of land use change related to relevant socio-economic land use processes. It is especially relevant the grouping of all possible one-to-one changes between the 44 Corine land cover classes (1892 possible combinations) into 9 major land use process (see box below), called land cover flows, which facilitate the interpretation of the results.

For this report the land cover changes include:

- Urban land management: Change of use e.g. from residential to commercial.
- Urban sprawl: Residential land development (class 1.1 of CLC — urban fabric) with loss of non urban land.
- Sprawl of economic sites and infrastructures: Development of land for economic and infrastructure land uses (including sport and leisure facilities) with loss of non urban land. This can be further subdivided into industrial and commercial sites, services and recreation, transport networks and facilities, and waste disposal sites (see Figure 7 as an example).

Nomenclature of land cover change (Level 1)

LCF1	Urban land management
LCF2	Urban sprawl
LCF3	Extension of economic sites and infrastructures
LCF4	Agricultural rotation and intensification
LCF5	Conversion of land to agriculture
LCF6	Forests creation and management
LCF7	Water body creation and management
LCF8	Changes of land cover due to natural and multiple causes

These land cover changes have been analysed within the UMZs, for reference year 2000. As the focus is at the European scale, results can be aggregated in 1 x 1 km grids (e.g. Maps 1 to 4).

In order to assess the extent of urban sprawl outside the UMZ, 3 buffers were defined:

- 0–5 km outside the boundary of the UMZ;
- 5–10 km outside the boundary of the UMZ;
- 10–20 km outside the boundary of the UMZ.

Within each buffer, urban sprawl was calculated and the results provided as a percentage of the total area (see Figure 8).

D Assessing urban sprawl at regional and local levels: MOLAND

The MOLAND methodology for assessing urban sprawl consists of three phases which are described in the next paragraphs: change detection, understanding changes and the production of scenarios.

Change detection (CHANGE): The objective of change detection is to measure changes in the spatial extent of urban areas and wider regions.

CHANGE produces a reference land use database on the basis of satellite images (IRS) and ancillary data (such as maps, aerial photos etc.), typically for the years 1997 or 1998, and three historical land use databases for selected European urban areas. Historical databases are produced for three time periods: mid-1950s, late 1960s, and mid-1980s depending on the availability of source materials (aerial photos, satellite images etc.).

Understanding (UNDERSTAND): Identifying and testing a number of indicators to be used to measure the 'sustainability of urban and peri-urban areas'. The total number of indicators in the MOLAND indicator databank is approximately 50.

For the purpose of this report the following indicators have been calculated:

- Growth of built-up areas from the 1950s to the late 1990s.

Built-up area includes the following land use classes: residential areas, industrial and commercial and service areas and transport areas. It does not include green urban areas. The indicator has been calculated by taking the extent of the built-up area in the 1990s and the built-up area in the 1950s has been subtracted from that area. The growth is expressed as a percentage.

- Annual growth of built-up areas from the mid-1950s to late 1990s (See above for definition). Growth has been calculated for three time periods:
  1950s–1960s, 1960s–1980s and 1980s–1990s. It has then been divided into an annual percentage.
- Share of low density residential areas compared with all residential areas built after the mid-1950s. In the MOLAND database the residential areas have been classified into two main categories: continuous and discontinuous. The discriminating factor is density. If buildings and other structures cover more than 80 % of the land, the area is classified as continuous residential area and if they cover less than 80 % it is classified as discontinuous residential area. The threshold of 80 % has been used in this context as a boundary between dense and low-density residential areas. The indicator has been calculated by measuring the extent of all residential areas built after the 1950s and low density residential areas built after the 1950s. The share is the percentage of the latter as compared with the former.
- The growth rate of residential, industrial, commercial and transport areas (from the mid-1950s to the end 1990s). The indicator has been calculated by measuring the extent of residential, industrial, commercial and transport areas in the 1990s and comparing with the same areas in the 1950s. Growth is expressed as a percentage.
- City population and built up area growth from 1950s to 1990s. The population statistics have been collected from municipal, regional and national statistical offices. If a municipality is only partially included in the MOLAND database, the population figure for that municipality is proportionally reduced.
- Residential density (measured by inhabitants/ residential km^2). The indicator has been calculated by dividing the total number of the population by the area of residential land use.

Development of scenarios (FORECAST):
Development of 'urban growth' scenarios for a sub-set of the 25 cities, using state-of-the-art urban cellular automata model.

The MOLAND urban growth model is based on dynamic spatial systems called 'cellular automata'. Inputs to the model are different types of spatially referenced digital data including:

- **Land use maps** showing the distribution of land use types in the area of interest. These maps are derived from the MOLAND reference and historical land use databases.
- **Suitability maps** showing the inherent suitability of the area of interest for different land use types. These maps are created using an overlay analysis of maps of various physical, environmental and institutional factors.
- **Zoning maps** showing the zoning status (i.e. legal constraints) for various land uses in the area of interest. These maps are derived from existing planning maps e.g. master plans, zoning plans, designated areas, protected areas, historic sites, natural reserves, land ownership.
- **Accessibility maps** showing accessibility to transportation networks for the area of interest. These maps are computed from the MOLAND land use and transportation network databases, based on the significance of access to transport networks for the various land uses.
- **Socio-economic data**: for the main administrative regions of the area of interest, comprising demographic statistics i.e. population and income, and data on production and employment for the four main economic sectors e.g. agriculture, industry, commerce, and services.

The outputs from the MOLAND urban model consist of maps showing the predicted evolution of land use in the area of interest over the next twenty years. By varying the inputs into the MOLAND urban model e.g. zoning status, transport networks etc, the model can be used as a powerful planning tool to explore in a realistic way future urban and regional development, under alternative spatial planning and policy scenarios, including the scenario of non-planning.

References and further reading

Ambiente Italia, 2003. European Common Indicators Towards a Local Sustainability Profile. Ambiente Italia, Milano.

Antrop, M., 2004. Landscape change and urbanization process in Europe. *Landscape and urban planning* 67(1–4):9–26.

Audriac, Ivonne, 2005. Information technology and urban form: Challenges to smart growth. *International Regional Science Review* 28(2): 119–145.

Austrian EU Presidency, 2006. Improving the quality of life in urban areas – Investments in awareness raising and environmental technologies. *Discussion paper, Informal meeting of EU Environment Ministers*, 19–21 May. Eisenstat/Rust.

Bannon, M.J., Thomas, S. R. and Cassidy, A., 2000. *The Role of Dublin in Europe, a Research Paper Prepared for the National Spatial Strategy Team*. DOELG, Dublin.

Barredo, J.I., Kasanko, M., McCormick, N., and Lavalle, C., 2003. Modelling dynamic spatial processes: simulation of urban future scenarios through cellular automata. *Landscape and Urban Planning*, 64(3):145–160.

Barredo, J.I., Lavalle, C., Demicheli, L., Kasanko, M. and McCormick, N., 2003. *Sustanable urban and regional planning. The MOLAND activities on urban scenario modelling and forecast*. Joint Research Centre of the European Commission 2004 EUR 206 200 73 EN.

Barredo, J.I., Demicheli, L., Lavalle, C., Kasanko, M., and McCormick, N., 2004. Modelling future urban scenarios in developing countries: an application case study in Lagos, Nigeria. *Environment and Planning B: Planning and Design*, 32:65–84.

Barredo, J.I., Lavalle, C., Kasanko, M., Sagris, V., Brezger, A.S. and McCormick, N., 2004. *Climate change impacts on floods in Europe.Towards a set of risk indicators for adaptation*. Joint Research Centre of the European Commission 2004 EUR 21472 EN.

Barredo, J.I., Petrov, L., Sagris, V., Lavalle, C. and Genovese, E., 2005. *Towards an integrated scenario approach for spatial planning and natural hazards mitigation*. Joint Research Centre of the European Commission EUR 21900 EN.

Bartley, B. and Treadwell Shine, K., 2003. Competitive City: Governance and the Changing dynamics of urban regeneration in Dublin. In: F. Moulaert, A. Rodriguez and E. Swyngedouw, ed. *The globalization city, economic restructuring and polarization in European cities*. Oxford, Oxford University Pres, pp. 145–166.

Blue Plan, 2005. *A Sustainable Future for the Mediterranean. The Blue Plan's Environment & Development Outlook*. Edited by Guillaume Benoit & Aline Comeau. Earthscan, London. 450 p.

Borrego, C., Martins, H., Tchepel, O., Salmim, L., Monteiro, A. and Miranda, A.I., 2006. How urban structure can affect city sustainability from an air quality perspective. *Environmental Modelling & Software*, 21(4):461–467.

Burton, E. 2000. The Compact city: Just of just compact? A preliminary analysis. *Urban Studies* 37(11): 1969–2001.

Çağdaş, G. & Berköz, L., 1996. Dynamic behavior of the city center of Istanbul. Comput., *Environment And Urban Systems* (20) 3, 153–164.

Camagni, R., Gibelli, M.C., and Rigamonti, P., 2002. Urban mobility and urban form: the social and environmental costs of different patterns of urban expansion. *Ecological economies*, 40(2): 199–216.

Cameron, I., Lyons T.J. and Kenworthy, J.R., 2004. Trends in vehicle kilometers of travel in world cities, 1960-1990: underlying drivers and policy responses. *Transport Policy*, 11(3):287–298.

City of Munich. Department of Urban Planning and Building Regulation. Munich as planned. http://www.munich.de/rathaus/plan/munich_as_planned/.

City of Munich. Department of Urban Planning and Building Regulation. The Munich Perspective – Our city's future. http://www.munich.de/rathaus/plan/stadtentwicklung/perspective/.

City of Munich. Department of Urban Planning and Building Regulation. Assessment of Messestadt Riem. Sustainable urban development in Munich.

Couch, C. and Karecha, J. Controlling urban sprawl: Some experiences from Liverpool. *Cities* 23(5): 242–363.

Couch, C. Karecha, J. Nuissl, H. Rink, D., 2005. Decline and Sprawl: An evolving type of urban development – observed in Liverpool and Leipzig. *European Planning Studies* (13)1:117–136.

CPMR, 2005. *Europe of the Sea: Towards a maritime policy for the Union. Contribution to the preparation of the Green Paper*. Technical Paper from the CPMR General Secretariat. France, p. 17.

dal Cin, A., de Mesones, J., and Figueroa, J., 1994. Madrid. *Cities*, 11(5):283–291.

De Ridder,K, Lefebre, P., 2004. Benefits of Urban Green Space. Case Study in the German Ruhr area and description of the methodology. Part II: Urban/regional scale (deliverable 19/20-II).

Delagado, J. Angeles, G., 2004. The rural-urban interface, a territorial approach to the spatial fragmentation of urban sprawl. Dela 21, Mexico, pp 533–555.

Department of the Environment and Local, 2002. *The National Spatial Strategy, 2002–2020*. Dublin, DOELG, p. 49.

Dosch, F., 2001. Land consumption and soil sealing in Germany — monitoring, measures, indicators. *Technical Workshop on Indicators for Soil Sealing.* Copenhagen, 26–27 March, 2001.

Drudy, P. J., 1999. Dublin Docklands: the Way Forward. In: Killen, J., and MacLaran, A., ed. *Dublin: Contemporary Trends and Issues for the Twenty-First Century. Dublin, Geographical Society of Ireland and the Centre for Urban and Regional Studies*, TDC.

Dura-Guimara, A., 2003. Population deconcentration and social restructuring in Barcelona — a European city. *Cities* 18(5):355–364.

Dökmeci, V.& Berköz, L., 2000. Residential-location preferences according to demographic characteristics in Istanbul. *Landscape and Urban Planning* 48: 45–55.

Dökmeci, V., Berköz, L., Levent, H., Yurekli H. and Çağdaş G, 1996. Residential preferences in Istanbul. *Habitat Intl.* 20(2):241–251.

EEA, 2002. *Environmental signals 2002*. Luxembourg, Office for Official Publications of the European Communities.

EEA, 2003. *Mapping the impacts of recent natural disasters and technological accidents in Europe*. Luxembourg, Office for Official Publications of the European Communities.

EEA, 2005. *The European Environment. State and outlook 2005*. Luxembourg, Office for Official Publications of the European Communities.

EEA, 2006. *Progress towards halting the loss of biodiversity by 2010*. Luxembourg, Office for Official Publications of the European Communities.

EEA, 2006. *The changing faces of Europe's coastal areas*. Luxembourg, Office for Official Publications of the European Communities.

EEA, 2006. *Environment and health*. Luxembourg, Office for Official Publications of the European Communities.

EEA, 2006. *Land accounts for Europe 1990–2000 — Integrated land and ecosystem accounting*. Luxembourg, Office for Official Publications of the European Communities. In press.

EEA & JRC, 2002. *Towards an Urban Atlas. Assessment of spatial data on 25 European cities and Urban areas*. European Environment Centre and Joint Research Centre of the European Commission. Environmental Issue Report No. 30. Luxembourg, Office for Official Publications of the European Communities.

Ergun, N., 2004. Gentrification in Istanbul. *Cities* 21 (5), 391–405.

Erkip, F., 2000. Global transformations versus local dynamism in Istanbul. Planning in a fragmented metropolis. *Cities* 17 (5), 371–377.

Estonian Statistical Office, 2006. http://pub.stat.ee/px-web.2001/Database/Majandus/09Kinnisvara/04Kinnisvaratehingud/04Kinnisvaratehingud.asp indicator KV111 (accessed on 18 Oct 2006).

European Commission, 1990. *Green Paper on the urban environment. Communication from the Commission to the Council and the European Parliament*. COM(1990) 218 final.

European Commission, 2005. *Commission Staff Working paper on Cohesion policy and cities: the urban contribution to growth and jobs in the regions*. Brussels, 23.11.2005.

European Commission, 2006. *Communication from the Commission to the Council and the European Parliament on Thematic Strategy on the Urban Environment*. COM(2005) 718 final.

Fernández-Galiano, L., 2006. Paisajes Españoles. *Babelia* (El Pais), 20, 22 April, 2006.

Gkartzios, M. and Scott, M., 2005. *Countryside, Here I Come: Urban rural migration in the Dublin City-Region, Planning and Environmental Policy*, UCD. www.ucd.ie/pepweb

Handy, S., 2005. Smart growth and the transportation-lad use connection: What does the research tell us? *International Regional Science Review* 28(2):146–167.

Holden, E. and Norland, I., 2005. Three challenges for the compact city as a sustainable urban form: Household consumption of energy and transport in eight residential areas in the greater Oslo Region. *Urban Cities*, 42 (12):2145–2166.

Horvath, A., 2004. Construction materials and the environment. *Annual Review of Environment and Resources* 29:181–204.

Kasanko, M., Barredo, J.I., Lavalle, C., McCormick, N., Demicheli, L., Sagris, V., Brezger, A., 2006. Are European Cities Becoming Dispersed? A Comparative Analysis of Fifteen European Urban Areas. *Landscape and Urban Planning*, 77:111–130.

Keilman, N., 2003. Biodiversity: The threat of small households. *Nature*, 421 (6922):489–490.

Kok, H., 1999. Migration from the city to the countryside in Hungary and Poland. *GeoJurnal* 49 (1):53–62.

López de Lucio, R., 2003. Transformaciones territoriales recientes en la región urbana de Madrid. *Urban*, 8:124–161.

Laconte, P., 2006. Urban and transport management — International trends and practices. *Paper presented at the Ecopolis Forum 'Eco-planning and management for adaptive appropriate human settlement'*, Chongquing, September 22–24, 2006.

Lyons, T.J, Kenworthy, J.R., Moy, C. and Dos Santos, F., 2003. *An international urban air pollution model for the transport sector*. Transportati.on Research D 8, 159–167.

Markus, D. and Heinz, E., 2001. Flood Events in the Rhine Basin: Genesis, Influences and Mitigation. *Natural Hazards*, 23 (2-3):271–290.

Marull, J. and Mallarach, J.M., 2002. La conectividad ecológica en el Área Metropolitana de Barcelona. *Ecosistemas*, 2002(2):22–44.

Mitchell, C.J.A., 2004. Making sense of counterurbanization. *Journal of Rural Studies*, 20:15–34.

Muñoz, F., 2003. Lock-living: urban sprawl in Mediterranean cities. *Cities* 20(6): 381–385.

Naess, P. and Jensen, O., 2004. Urban structure matters, even in a small town. *Journal of Environmental Planning and Management*, 47(1):35–57.

Newman, P. and Kenworthy, J., 1999. Sustainability and Cities, Overcoming Automobile Dependence, Washington D.C.: Island Press.

Nuissl, H. and Rink, D., 2005. The 'production' of urban sprawl in eastern Germany as a phenomenon of post-socialist transformation. *Cities*, 22(2):123–134.

Ode, Å. and Fry, G., 2006. A model for quantifying and predicting urban pressure on woodland. *Landscape and Urban Planning*, 77(1–2):17–27.

Ott, T., 2001. From concentration to deconcentration — migration patterns in the post-socialist city. *Cities*, 18(6):403–412.

Perdigão, V., and Christensen, S., 2000. *The Lacoast Atlas - Land Cover Changes in European Coastal Zones*. S.P.I.00.39 EN, European Commission, DG-Joint Research Centre. Ispra.

Pickett, S.T.A., Cadenasso, M.L., Grove, J.M., Nilon, C.H., Pouyat, R.V., Zipperer, W.C. and Costanza, R., 2001. Urban Ecological Systems: Linking Terrestrial Ecological, Physical, and Socioeconomic Components of Metropolitan Areas. *Annual Review of Ecology and Systematics*, 32(1):127–157.

Prokop, G., Bittens, M., Cofalka, P., Roehl, K.E., Schamann,M., Younger, P., 2003. *Sustainable management of soil and groundwater resources in urban areas. Proceedings of the 2nd IMAGE-TRAIN Cluster Meeting. Krakow, October 2–4*, 2002. Wien, UBA, pp. 137.

SACTRA, 1995. *Trunk roads and the generation of traffic*. Standing Advisory Committee on Trunk Road Assessment). HMSO, London.

Schäfer, D., Krack-Roberg, E. and Hofman-Kroll, E., 2002. *Results of the German Environmental Economic Accounting on the use of land for economic activities*. Federal Statistical Office of Germany.

Slak, M.F., Commagnac, L., Armitage-Lee, A. and Chery, P., 2004. Agricultural soil inheritance: depletion due to urban growth. Method for assessment of degree of loss depending on agricultural soil qualities. In: Francaviglia R., ed. *Agricultural Impacts on Soil Erosion and Soil Biodiversity: Developing Indicators for Policy Analysis. Proceedings from an OECD Expert Meeting, Rome, Italy, March 2003*. pp. 197–226.

Salama R., Hatton T. & Dawes W., 1999. Predicting Land Use Impacts on Regional Scale Groundwater Recharge and Discharge. J. Environ. Qual. 28, 446–60.

Svensson, M.K., and Eliasson, I., 2003. Diurnal air temperatures in built-up areas in relation to urban planning. *Landscape and Urban Planning*, 61:37–54.

Tammaru, T., Ahas, R., Silm, S., Leetmaa, K. 2006. *New residential areas in the Tallinn Metropolitan Area* (Study report, Institute of Geography, University of Tartu).

UBA, 2003. Special chapter on floods. *In: Seventh State of the Environment Report*. Wien, UBA, pp. 393–401.

UN, 2004. World Population Prospects: the 2004 Revision Population Database.

Van, R., Kempen, M., and Vermeulen, A.B., 2005. *Urban Issues And Urban Policies In The New EU Countries*. Ashgate Publishing, Ltd.

Williams K. *et al.*, 2000. Achieving sustainable urban forms – Conclusions. Spon Press, London & New York.

Working group, 2004. Working group on Sustainable Urban transport, Final report, January 2004. European Commission, Brussels.

Further electronic resources

European Environment Agency, http://www.eea.europa.eu/main_html.

European Topic Center on Biological Diversity, http://biodiversity.Eionet.eu.int/.

European Topic Center Terrestrial Environment, http://terrestrial.Eionet.eu.int/.

Monitoring Land Use/Cover Dynamics (MOLAND) http://moland.jrc.it/.

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Appendix A.2

Toward Low Energy Cities

A Case Study of the Urban Area of Liège, Belgium

Sigrid Reiter and Anne-Françoise Marique

Keywords:
buildings
energy consumption
geographic information system (GIS)
industrial ecology
transportation
urban modeling

Summary

Within the framework of sustainable development, it is important to take into account environmental aspects of urban areas related to their energy use. In this article a methodology is proposed for assessing residential energy uses for buildings and transport at the city scale. This method is based on the use of geographic information system (GIS) tools combined with a statistical treatment of urban and transport criteria. The methodology allows us to model building and transport energy use at the city scale, as well as to consider the possible evolution of city energy consumption and to simulate the effects of some strategies of urban renewal. An application is given to study different energy management strategies for the urban area of Liège, Belgium. Building and transport energy consumption are compared at the city scale and their possible evolution in the future is highlighted. Forecast scenarios on future energy policies for Liège's building stock show that the European Directive on the Energy Performance of Buildings and even more selective energy policies applied only to new buildings are not sufficient to widely decrease building energy consumption at the city scale. Renovation of the existing building stock has a much larger positive impact on city energy consumption reductions. The methodology developed in this article can be adapted or reproduced for many other urban regions in Belgium, but also in Europe and even further.

Introduction

In the actual context of growing interest in environmental issues, reducing energy consumption in the building and transport sectors appears as an important policy target. Urban areas are supposed to present high potentialities in terms of energy reduction. This is why the Directive on the Energy Performance of Buildings (EPB; EC 2003) came into force in 2002, with legislation in European Union (EU) member states by 2006. However, existing models and regulations often adopt the perspective of an individual building as an autonomous entity, and neglect the importance of phenomena linked to larger scales (Ratti et al. 2005), while decisions made at the neighborhood level have important consequences on the performance of individual buildings and on the transport habits of the inhabitants (Popovici and Peuportier 2004). Moreover, while politicians, stakeholders, and even citizens are now aware of the issue of energy consumption in buildings, efforts and regulations to control transport needs and consumption remain more limited. Nevertheless, transport and mobility are crucial in terms of urban planning.

This research focuses on energy management at the city level. First, a methodology is elaborated for assessing the energy use of residential buildings and transport of inhabitants at the city scale. Then, an application study uses this methodology to model the energy use of residential buildings and transport of the urban area of Liège, Belgium. This case study compares

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© 2012 by Yale University
DOI: 10.1111/j.1530-9290.2012.00533.x

Volume 00, Number 00

building and transport energy consumption at the city scale, as well as their possible evolution in the future, depending on forecast scenarios. Moreover, this case study allows us to test some strategies of urban renewal, comparing the effects of the European Directive on Energy Performance of Buildings with even more selective energy policies on new buildings and with renovation strategies on the existing building stock of the urban area of Liège.

The structure of this article is developed in seven sections: *Introduction*, *State of the Art and Method*, *Study Area and Cartographic Work*, *Modeling Energy Consumption at the City Scale*, *Forecast Scenarios*, *Discussion* of the results, and *Conclusion*.

State of the Art and Method

This section proposes a brief survey of the most important references on city energy management and the methodology developed in this research.

State of the Art

Since 1993 the International Energy Agency (IEA) has provided projections about global energy consumption using a World Energy Model. In 2008 the World Energy Outlook recognized that the factors that were influencing city energy use were different from the energy use profiles of the countries the cities were in as a whole (OECD and IEA 2008). Friedman and Cooke (2011) prove the same for New York City, NY, USA, and the U.S. database. The IEA suggests that, in industrialized countries, the energy use per capita of city residents tends to be lower than the national average. In contrast, urban residents in China use more energy per capita than the national average due to higher average incomes and better access to modern services in cities (OECD and IEA 2008).

A lot of scientific articles have already studied energy consumption at the city scale, focusing on relationships between transport energy consumption and building density. Based on data from 32 large cities located all over the world, Newman and Kenworthy (1989, 1999) highlighted a strong inverse relationship between urban density and transport consumption. In studies on Nordic cities, Naess (1996) observed that the use of energy for transportation is reduced with higher urban densities. Banister and colleagues (1997) explain the influence of urban density on energy consumption related to mobility by the average home-to-work distance reduction and the more amenable public transport system in dense urban areas. But Breheny (1995) argues that there is not strong evidence that containment policies promote transport energy savings. In the sample of cities used by Newman and Kenworthy, Breheny and Gordon (1997) demonstrated that the density coefficient and its statistical significance decrease when the petrol price and income are included as explanatory variables. Different studies underline the importance of the price of travel and the influence of socioeconomic factors on transport behaviors (Boarnet and Crane 2001; van de Coevering and Schwanen 2006). Souche (2010), studying 10 cities around the world (through the International Union of Public Transport [IUTP] database), shows that the two variables that are the most statistically significant for transport energy consumption assessment are transport cost and urban density.

On the basis of various case studies, Ewing and Cervero (2001) evaluated quantitatively the impact of urban density, local diversity, local design, and regional accessibility on the mean vehicle travel distances. The elasticity was evaluated at −0.05 for urban density, −0.05 for local diversity, −0.03 for local design, and −0.2 for regional destination accessibility. This means that if the density of a district is multiplied by two, private car commutes are only reduced by 5%. Note that the impact of destination accessibility is larger than the three others parameters combined, suggesting that areas of high accessibility, such as city centers, may produce substantially lower transport energy consumption than dense and mixed developments in less accessible areas. Ewing and colleagues (2008) found that the most compact metropolitan areas in the United States generate 35% shorter mean vehicle travel distances per capita than the most sprawling metropolitan areas. Finally, more compact developments (including density, functional mix, and transit accessibility) can reduce mean vehicle travel per capita by 25% to 30% (Ewing and Cervero 2010).

Various studies argue that more compact urban forms would significantly reduce energy consumption both in the building and transport sectors (Ewing et al. 2008b; Steemers 2003; Urban Task Force 1999). Connecting urban form to building energy use, lower density, and detached housing tend to require more energy than multiunit developments or attached housing (Ewing and Rong 2008; Marique and Reiter 2012b; Steadman et al. 1998; Steemers 2003).

The Method

There are a lot of modeling tools to assess the energy management of a specific building, including TRNSYS (Transient System Simulation Program), EnergyPlus, TAS (Thermal Analysis Software), Simula and COMFIE (Calcul d'Ouvrages Multizones Fixé à une Interface Experte), among others. However, such an approach makes it difficult to generalize the results in order to determine the best strategies on an urban scale. At the neighborhood scale, Steemers (2003) analyzed urban areas of 400 meters (m) × 400 meters in order to establish the relationship between urban form and building energy consumptions. The analysis was based on three geometric parameters: building depth, street prospect, and urban compactness. A similar analysis was performed by Ratti and colleagues (2005). The selected variables were the distance between facades, orientation of the facades, and lighting obstructions. This methodology allows in-depth study of the influence of an urban context on building energy consumption, but is too complex to be applied at the city scale.

On the other hand, there are two types of modeling methods used to predict energy consumption on a larger scale (e.g., for national predictions): the top-down and bottom-up approaches. These methodologies have already been described in detail (Kavgic et al. 2010; Swan and Ugursal 2009). Top-down modeling is generally used to investigate the relationships between the energy and economic sectors, studying the influence of economic variables such as income or fuel prices on the energy consumption of countries. These models lack details on the building stock to be able to quantify the effectiveness of specific energy policy measures on urban energy performance. Bottom-up methods are based on typologies and the component clustering modeling approach. These components can be buildings (Shimoda et al. 2004; Tommerup and Svendsen 2006; Uihlein and Eder 2010), urban blocks (Wallemacq et al. 2011), or neighborhoods (Yamaguchi et al. 2007). This implies that they need extensive databases to support the choice and description of each component of their typologies. This is usually done by a combination of building physics modeling, empirical data (e.g., from housing surveys), statistics on national or regional datasets, and some assumptions about building performance. The bottom-up method is very useful to assess the energy consumption of existing building stocks. One example of the bottom-up method applied to building energy consumption studies is the Energy and Environment Prediction (EEP) model (Jones et al. 2001), based on 100 building types commonly found in England.

The following studies are good examples of a bottom-up modeling approach applied to energy studies related to transport. Boussauw and Witlox (2009) developed a commute-energy performance index and tested it for Flanders and the Brussels capital region in Belgium. This commute-energy performance index is based on statistical data available at the district scale in order to investigate the link between spatial structure and energy consumption for home-to-work travel at the regional scale. Marique and Reiter (2012a) adapted and completed this index to develop a more detailed method for assessing transport consumption at the neighborhood scale. The method takes into account the transport energy consumption of residents for four purposes of travel (work, school, shopping, and leisure). An application of this method and a sensitivity analysis are presented concerning the comparison of four suburban districts located in Belgium (Marique and Reiter 2012a).

The proposed method uses an urban geographic information system (GIS) and statistical treatments of urban and transport data in order to develop an energy model at the city scale. This methodology combines building and transport energy consumption studies as well as top-down and bottom-up modeling approaches. The method combines national statistics, that are not associated with buildings and transport (top-down approach), with local data related to buildings and transport (bottom-up approach). For example, the forecast evolution of demographic data is deducted from global trends of recent years (top-down approach), while the energy consumption of transport and buildings are obtained thanks to empirical data and results of energy modeling (bottom-up approach). This combined approach provides a set of data as accurate as possible and the opportunity to compare different urban design strategies for limiting energy consumption in cities. An application study of this method on the urban area of Liège is developed in the next sections of this article.

Study Area and Cartographic Work

The case study concerns the urban area of Liège, which is a typical regional city (600,000 inhabitants) in Belgium, and more specifically the energy consumption of the residential buildings and transport of residents at the city scale. Spatialization of the urban area of Liège was performed using the Projet Informatique de Cartographie Continue (PICC), a computer project of continued mapping from the Public Service of the Walloon Region of Belgium, providing spatial data in the form of vector map layers that characterize the natural environment (rivers, forests), the built environment (buildings), and the infrastructure (roads, railways, etc.) at a scale of 1/1000.

In the first part of the method, a large number of variables were selected to characterize the energy efficiency of urban areas (including buildings and transport energy consumption) using an extensive literature review on this subject. The cadastral data and several energy criteria taken from the literature (net built density, type of buildings, built compactness, area of urban block, buildings' date of construction, indexes of energy performance for transport consumption, and expected modal shares for alternatives to the car, among others) have been linked through an urban GIS to the PICC data to spatialize these energy criteria through the urban area of Liège. It is important to note that some plots of the PICC found no match in the database of the cadaster. No data were taken into account for the buildings constructed on these plots. Note that these differences arise because the data from the PICC were developed from aerial rectified photographs and the data from the cadaster were developed from digital cadastral maps. These data can be considered acceptable because only 383 buildings could not be taken into account, which represents only 0.2% of the residential building stock of the urban area of Liège.

A statistical treatment of these parameters was performed using a principal component analysis. This methodology (Lebart et al. 1982; Volle 1993) allows crossing a large number of criteria and grouping them according to their similarities. This statistical treatment reduced the number of our selected criteria to characterize the energy performance of the residential building stock of Liège. Six criteria were chosen:

- Buildings' date of construction (before 1930, from 1931 to 1969, from 1970 to 1985, from 1985 to 1996, from 1996 to today), depending on the types of construction related to Belgian regulations. These data are available in the cadaster.
- Building renovation. The cadaster mentions the buildings that have undergone significant upgrades together with the year of the work. The most common energy upgrades consist of adding insulation in the roof and replacing windows. Adding insulation in the slab and the walls is pretty rare in the Walloon region (MRW 2007).

- Type of building (two, three, or four frontages). Indeed, for the same level of insulation, a terraced house uses less energy for heating than a detached house (Marique and Reiter 2012b). These data are available in the cadaster.
- Type of housing (collective or individual). These data are available in the cadaster.
- Index of energy performance for residents' transport for home-to-work travel. This index has been developed by Marique and Reiter (2012a) for the Walloon region.
- Index of energy performance for residents' transport for home-to-school travels. This index has been developed by Marique and Reiter (2012a) for the Walloon region.

The "energy performance index" (IPE) represents the energy used by one person for one trip from home to destination (in kilowatt-hours per person per trip [kWh/person/trip]). It takes into account the distances travelled, the means of transport used, and their relative consumption rates. The IPE is calculated according to equation (1),

$$\text{Energy performance index } (i) = \left(\sum m D_{mi} \times f_m\right) \Big/ T_i, \qquad (1)$$

where i represents the territorial unit; m is the means of transport used (diesel car, fuel car, train, bus, bike, on foot); D_{mi} is the total distance travelled by the means of transport m in the district i for home-to-work (or home-to-school) travels; f_m is the consumption factor attributed to the means of transport m; and T_i is the number of workers (or students) in the territorial unit i. Consumption factors (f_m) used in this article were calculated for the Walloon region of Belgium by Marique and Reiter (2012a) on the basis of regional and local data: 0.61 kilowatt-hours per person per kilometer (kWh/person/km) for a diesel car, 0.56 kWh/person/km for a fuel car, 0.45 kWh/person/km for a bus, 0.15 kWh/person/km for a train, and 0 for nonmotorized means of transportation because these do not consume any energy.[1]

The two transport indexes are based on statistical data coming from national censuses, carried out every ten years in Belgium. These data are available at the census block scale for the survey carried out in 1991 and at the individual scale for the last survey carried out in 2001. It should be noted that the transport data based on the first national survey in 1991 are less accurate than the buildings data, based on the cadastral values known for each building, because of the assumption that statistical data are evenly distributed in each census block. Nevertheless, these data are sufficiently accurate for a study at the city scale.

The result of this cartographic work is the spatialization of the six chosen energy criteria through the urban area of Liège. More details on how the GIS was used can be found in the work of Wallemacq and colleagues (2011). Figure 1 presents the mapping of the index of energy performance for home-to-school

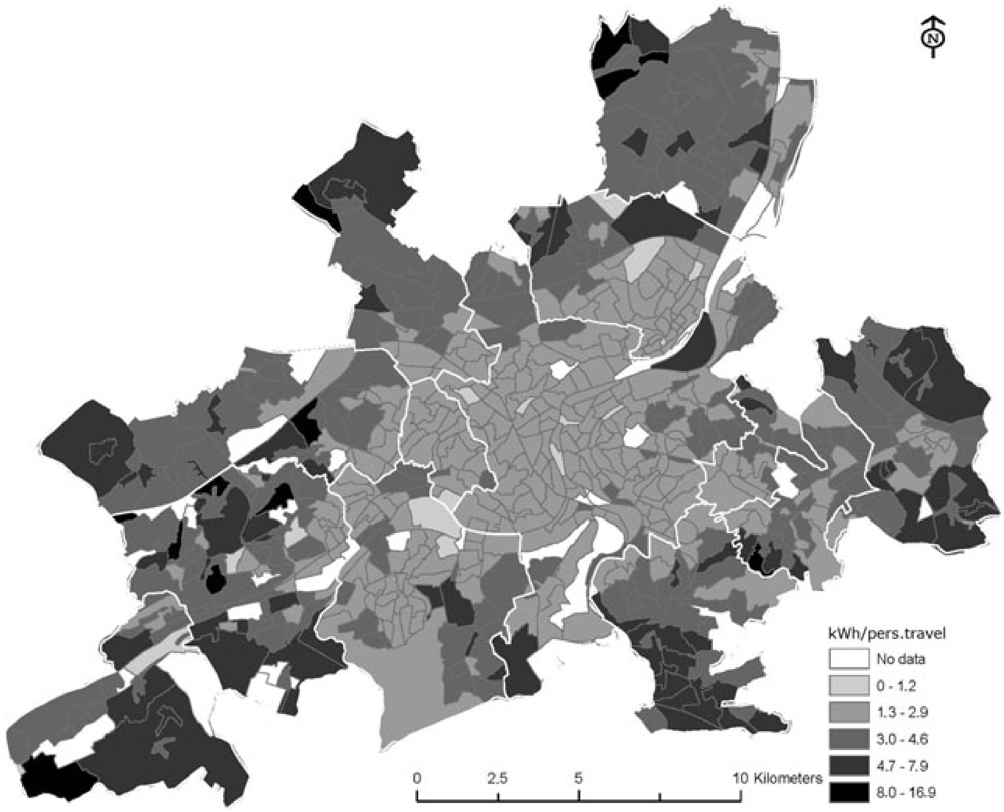

Figure 1 Mapping of the index of energy performance for home-to-school travel (IPE, in kilowatt-hours per worker [kWh/worker] for a one-way trip to school) through the urban area of Liège.

travel through the urban area of Liège (IPE in kilowatt-hours per student for a one-way trip to school). This map shows that peripheral areas tend to generate much more energy consumption than the central areas of the urban zone.

The method used to assess residential energy consumption for buildings and transport is developed and tested for Walloon cities, but it is transposable to other regions and cities. Input data for buildings and transportation models come from national surveys or are collected using a GIS, which are both commonly used tools in numerous regions and countries. Surveys similar to the one used in our model are carried out by, for example, the French National Institute of Statistics (INSEE) in France, the Office for National Statistics (ONS) in the United Kingdom, and the Census and Statistics of Population (IDESCAT) in Catalonia, whereas GISs oriented toward urban planning are now largely used by researchers and territorial communities. It would be interesting to apply the developed method to other case studies of differing urban and transport system layouts to compare their performance.

Modeling Energy Consumption at the City Scale

The city energy modeling is organized into two areas: residential building energy consumption and transport energy consumption of residents.

Residential Building Energy Consumption

For the first topic, a typology of Liège's residential building stock is drawn up by crossing the four chosen building energy criteria: building date of construction, building renovation, type of building, and type of housing. Note that the urban area of Liège has 64,079 terraced houses, 52,314 semidetached houses, 32,478 detached houses, and 13,897 community buildings.

Energy consumption (including heating, hot water, and lighting) is known for each of these types of buildings through empirical surveys on the Walloon building stock (CEEW 2007; ICEDD 2005; Kints 2008). Cooling requirements were neglected because they are minimal in Belgium. In fact, these empirical surveys show that heating represents the largest part of the overall energy consumption of Belgian households (76%). Home appliances, the production of hot water, and cooking represent 10%, 11%, and 3% of the total, respectively. The energy requirements of residential buildings at the city scale were calculated by adding the results from the energy consumption analysis for each type of house according to their distribution in the urban area of Liège.

When these values are related to each building, it is possible to establish the actual residential building energy use at the city scale. Moreover, on the basis of the cadaster, we can study the evolution of the energy consumption of the whole urban area of Liège since 1850, which is the first date of construction of a building identified in the cadaster (see figure 2). Before 1931 the dates of building construction are aggregated for periods lasting from 20 to 25 years, which explains the larger width of the bars in that portion of figure 2. This graph shows a very high growth of energy consumption in Liège's urban area during the last century, reaching 6,048 gigawatt-hours (GWh) for the year 2010.[2]

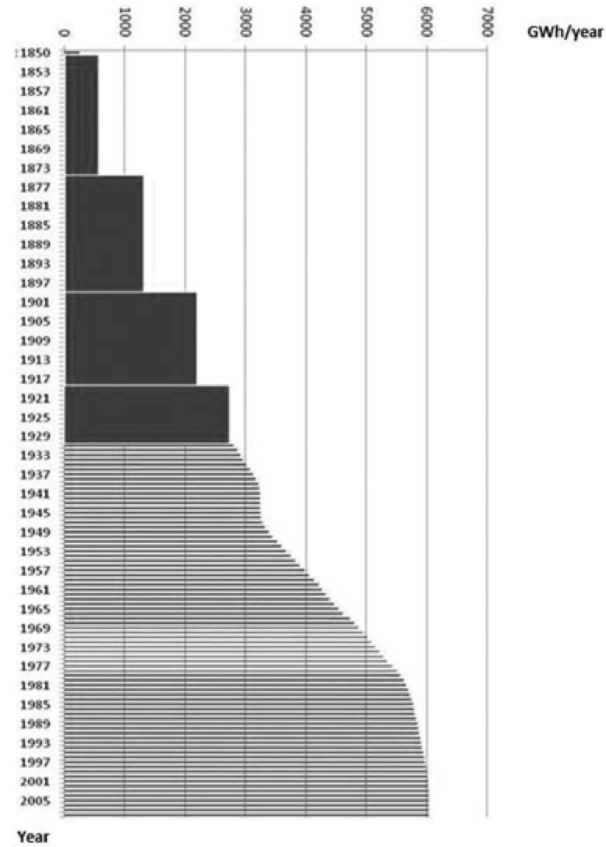

Figure 2 Evolution of the energy consumption of the urban area of Liège (in gigawatt-hours per year [GWh/year]).

Transport Energy Consumption of Residents

For modeling transport energy consumption, we followed the methodology developed by Marique and Reiter (2012a), using values available in each census block about car ownership, travel distances, main mode of transport used, and the number of working days per week and per worker, among others. We have considered the two last Belgian censuses.

The annual consumption of a worker or a student is obtained by the following calculation:

$$\text{IPE} \times \text{annual number of trips (to work or school)},$$

assuming 253 working days per year and 180 school days per year. Finally, the annual consumption calculated for a person is multiplied by the number of workers or students in the area, giving for 2010 a global value for residential transport consumption of 941.9 GWh, from which 841.6 GWh are due to home-to-work travel and 100.3 GWh to home-to-school travel.

Comparing residential energy consumption for buildings and transport at the city scale during the year 2010, building energy consumption was 6,048 GWh, while transport energy consumption accounted only for 941.9 GWh. Thus it is clear that policies to reduce energy consumption must first focus on the existing building stock, because it generates much more energy consumption than residential transport.

Note that home-to-work and home-to-school travel represent only a part of the mobility of a household. Leisure and shopping are two other important purposes of travel (Hubert and Toint 2002). Unfortunately, the Belgian national census does not give information about these purposes of travel. Even if many studies dedicated to transport and energy consumption only focus on home-to-work data because they are most often available, the limits of this method arise from the fact that data about only two types of trips (home-to-work and home-to-school travel) are available in the Belgian national census.

Following Hubert (2004), the mean percentages of home-to-work travel and home-to-school travel compared to the total amount of travel in Belgium are 30% and 17% of all trips; moreover, these account for 45% and 9%, respectively, of all the distances travelled. These data were defined through an enquiry of 3,076 workers and 1,619 students. If we add to the transport energy consumption calculated according to the method explained an approximate value for travel for shopping and leisure based on the IPE indexes previously calculated, and taking into account the proportions of transport distances proposed by Hubert (2004), the global energy consumption for residential transport in the city of Liège in 2010 increases greatly and ranges from 1,454.5 GWh to 1,802.2 GWh, depending on whether the IPE for home-to-school or home-to-work travel is used. Nevertheless, this final value for the energy consumption of residential transport in the urban area of Liège remains more than three times lower than the building energy consumption.

Home-to-school travel consumes less energy than home-to-work travel because distances from home to school are shorter than distances from home to work and because the use of public transport is greater for home-to-school travel than home-to-work travel. This first conclusion shows the importance of residential densification of buildings near the main employment areas. A good mix between work, schools, shops, and dwellings in each neighborhood or group of neighborhoods, which allows reduced travel distances, seems to be a good strategy to reduce transport energy consumption.

Forecast Scenarios

The most important actual energy policy measure in the EU is the EPB (Directive 2002/91/EC; EC 2003). It focuses on energy efficiency when new buildings are built or when big buildings (larger than 1,000 square meters [m^2]) undergo a major renovation. However, there might be energy efficient measures that are environmentally efficient and cost effective also on the existing residential building stock, on smaller buildings, and/or lighter renovation processes. Note that in the Danish implementation of the EPB directive, all existing buildings are covered by the energy efficiency measures when they undergo a major renovation (Tommerup and Svendsen 2006). Thus it is useful to model some forecast scenarios to compare the effects of the EPB directive with even more selective energy policies on new buildings and with renovation strategies on the existing building stock.

The demographic data of the population of our study area are known at the census block scale. The simplest hypothesis would estimate that the residential building stock changes proportionally to the population. However, the number of buildings in the urban area of Liège during the last eight years did not increase as rapidly as the population during those years. We have thus established a base curve of the evolution of the built stock according to the statistics of its evolution between 2000 and 2008. This trend is represented by equation (2):

$$Y = 477.35 \ln(x) + 161{,}348 \qquad (2)$$

where x is the forecast year (2000) and Y is the number of buildings. This curve follows very well the recent trend of development of the residential building stock, as the coefficient of determination calculated from the data observed between 2000 and 2008 is 99.7%.

First, six scenarios of residential building energy consumption improvements will be compared. Then, two forecast scenarios for transport energy consumption evolution will be explained. The main assumption of this forecast modeling is that the urban growth is distributed evenly across the different census blocks of the urban area.

Scenario 1: New Buildings Following the Directive on the Energy Performance of Buildings

In this first scenario, the existing building stock remains unchanged, but new buildings are constructed according to the actual standard of the EPB: the building's energy consumption should not exceed 115 kWh/m^2/year. It is therefore the most likely evolution of Liège's building stock if the energy policies are not changed in the future. Following this first scenario, energy consumption for the city of Liège in 2061 is estimated at 6,067.74 GWh/year (see figure 3).

Scenario 2: Strengthening of Energy Policy on New Buildings

Considering that 5% of new housing stock will have low energy (LE) performance (95 kWh/m^2/year), 2% of buildings will have very low energy (VLE) performances (65 kWh/m^2/year), and 1% will reach the standard passive house (50 kWh/m^2/year), building energy consumption decreases by 679 megawatt-hours (MWh) for 2061 compared with the first scenario, which represents a reduction of only 0.01% for a period of 50 years.

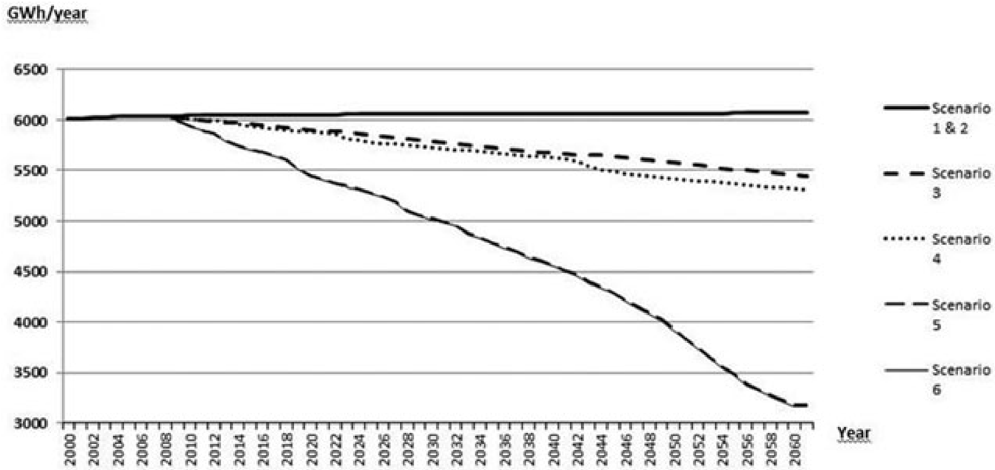

Figure 3 Energy consumption of the urban area of Liège (in gigawatt-hours per year [GWh/year]) from 2000 to 2061, following the six forecast scenarios. The lines showing scenarios 1 and 2 as well as scenarios 5 and 6 are joined because the results are too close at this scale.

Achieving a 10% reduction in energy consumption for all buildings constructed after 2010 would require that the new stock meet the following constructive standards: 63% of buildings achieving the EPB standard, 21% LE buildings, 10% VLE buildings, and 5% passive buildings. Over the whole building stock, this reduction generates a very small decrease in energy consumption (0.06%) compared with scenario 1, corresponding to the actual regulations (see figure 3).

Scenario 3: A 40% Reduction in the Energy Consumption of the Old Building Stock

A rate of renovation of buildings of 0.6% per year is chosen to simulate a realistic policy for energy renovation of the existing building stock equal to two-thirds of the total rate of renovations observed in the Walloon region on an annual basis. It is also assumed that energy management is carried out efficiently: the oldest and least energy efficient buildings are the first to be renovated. Renovating this old building stock will be incorporated as a 40% reduction in energy consumption compared with the initial energy performance of these renovated buildings, which corresponds in the context of the urban area of Liège to roof insulation of the individual terraced houses built before 1930 and to roof insulation and window improvements of detached houses built between 1931 and 1969 that are not yet renovated. Following the work of Verbeek and Hens (2005), insulation of the roof is the most effective and durable measure for an energy performance increase of households in Belgium.

It appears that the renovation of existing buildings can drastically reduce energy consumption across the urban area. The total estimated consumption amounts to 5,439.27 GWh/year in 2061, of which 99.5% is attributed to the existing stock. The decrease in total energy consumption is therefore 10.36% (628.46 GWh/year) compared with 6,067.74 GWh/year for scenario 1 (see figure 3).

Scenario 4: Renovation of the Old Building Stock Reaching the Directive on the Energy Performance of Buildings

This scenario aims to assess the amount of energy that could be saved if the existing building stock was renovated, at a rate of 0.6% per year, to meet the current EPB standard in Belgium (115 kWh/m^2/year),[3] while all the new buildings meet the same energy performance. Following this scenario, the estimated energy consumption for the city of Liège will reach 5,307.20 GWh/year in 2061. That is 760.54 GWh/year (13%) less than scenario 1 (see figure 3).

Scenario 5: Renovation of all the Existing Building Stock Reaching the Directive on the Energy Performance of Buildings

Renovation of all buildings of the residential building stock of Liège to the level of the current EPB standard in Belgium (115 kWh/m^2/year) would result in significant reductions in energy consumption in the urban area (see figure 3). Indeed, the total energy consumption would drop to 3,178.23 GWh/year, which represents a reduction of 47.6% compared with 6,067.74 GWh/year in scenario 1 (where new buildings reach the EPB standard but no renovations are undertaken).

However, to achieve complete renovation of the existing housing stock by 2061, the rate of renovation of the urban area of Liège must increase sharply, to a minimum of 1.92% per year, which would require strong policies to accelerate and strengthen the process of renovating existing buildings.

Scenario 6: All the Existing Building Stock Reaching the Directive on the Energy Performance of Buildings and New Buildings Reaching the Passive Standard

This scenario uses the same renewal policy as scenario 5, but it also assumes that each new dwelling built from 2012 will reach the passive standard (50 kWh/m^2/year). The result of scenario 6 is very close to the previous scenario. The total energy of the urban area in 2061 would be 3,161.57 GWh/year, which represents a reduction of only 0.5% compared with scenario 5.

Scenarios 7 and 8: Forecast Scenarios for Transport Energy Consumption

The evolution of the mean energy performance indexes for home-to-work and home-to-school travel between 1991 and 2001 allowed us to determine the percentage increase in the IPE over ten years: 32.3% for work travel and 8.03% for school travel. Based on this increase for the two IPEs as well as an increase in student numbers of 4.3% and the number of workers of 3% every ten years, the energy consumption for residential transport in 2061 will reach 3,955.3 GWh for home-to-work travel and 187.76 GWh for home-to-school travel, giving a total of 4,140 GWh for these two types of travel. This scenario shows that if the increase in transport consumption in the future is identical to what happened in the past, the total energy consumed at the city scale would greatly increase. In addition, by performing the same approximations for travel for shopping and leisure, the total residential energy consumption for transport would reach between 5,084.32 and 8,183.9 GWh in 2061. Thus, without specific transport policies, urban planning strategies, or important vehicle energy performance improvements, residential energy consumption due to transport is likely to exceed the energy consumption related to the existing building stock in the urban area of Liège.

However, Ewing and colleagues (2008) assume that transport energy consumption in the United States in 2030 will be at the same level as in 2005, because the number of vehicles and the mean vehicle travel will continue to increase while the energy performance of vehicles will be improved. Taking into account this scenario of a steady state of transport energy consumption in the urban area of Liège until 2061 implies that the building energy consumption will remain higher at the city scale than the transport energy consumption, regardless of the chosen scenario for the evolution of the building stock.

Discussion

The studied scenarios show that the actual city energy challenge lies mainly in renovating the existing building stock. Indeed, the first two scenarios and the small difference between scenarios 5 and 6 show that it is not possible to ensure a significant reduction in energy consumption at the city scale by applying only energy policies for new buildings, like the standard EPB already in use, or by enhancing the performance of new buildings to the LE level, VLE level, or even the passive housing standard.

However, scenarios of existing housing stock renewal (scenarios 3 through 5) can significantly reduce the overall consumption of the urban area of Liège in the following proportions:

- A 10.36% energy consumption reduction in 2060 through renovation of the oldest buildings, reducing 40% of their energy consumption at a renovation rate of 0.6% of the building stock per year.
- A 13% energy consumption reduction in 2061 through renovation reaching the EPB level in the oldest buildings at a renovation rate of 0.6% of the building stock per year.
- A 47.6% energy consumption reduction in 2061 through renovation reaching the EPB level of all the existing residential building stock, which corresponds to a renovation rate of 1.92% per year.

Thus the national climate change targets in Belgium will be impossible to reach without a strategic increase in existing housing stock renovation. Finally, at the city scale, the building renovation rate seems to be much more important than the level of insulation reached.

While current energy consumption related to the existing housing stock of the urban area of Liège is significantly higher than the transport energy consumption of residents, the forecast scenarios on transport consumption show that this gap will be reduced and may even be reversed by 2060 if solutions for reducing energy consumption related to residential transport are not implemented. It seems that transport will become an increasing challenge for energy consumption limitation at the city scale. In this respect, favoring more compact urban development while improving the energy performance of vehicles and increasing public transport use should be investigated.

Conclusion

The literature review on city energy consumption shows that density tends to receive the greatest scientific attention, although alone its travel impacts are modest. It is therefore important to make a distinction between density as an isolated parameter and compact development or smart growth, sometimes studied under the term density, that reflect the cumulative effects of various land use factors such as density, functional mix, transit accessibility, walkability, and parking management.

This article presented a methodology to model residential energy use at the city scale, using GIS tools combined with a statistical treatment of urban and transport criteria. This method assesses the energy uses of residential buildings and transport of residents at the city scale. It should help in developing strategies of urban design and urban renewal as well as improving urban management and policy making.

An application of this method was done on the urban area of Liège. This applied study concluded that the EPB and even more selective energy policies on new buildings are not sufficient to greatly decrease the energy consumption of Liège's building stock, and that renovation of the existing building stock has a much greater positive impact on city energy consumption reductions.

The proposed methodology allows comparisons of energy requirements in the building sector and in the transport sector, as well as the ability to test forecast scenarios. This method is thus a powerful tool to highlight which strategy is most efficient in reducing total energy consumption at the city scale. Some further developments of this method are planned, including more precise energy consumption related to travel for leisure and shopping. The methodology developed in this article can be adapted or reproduced for many other territories in Belgium, as well as Europe and beyond.

Acknowledgements

This research was funded by the Special Funds for Research of the French Community of Belgium, within the University of Liège, and by the Walloon region of Belgium in the framework of the SAFE (Suburban Areas Favouring Energy efficiency) project.

Notes

1. One kilowatt-hour (kWh) $\approx 3.6 \times 10^6$ joules (J, SI) $\approx 3.412 \times 10^3$ British thermal units (BTU). One kilometer (km, SI) $\approx$ 0.621 miles (mi).
2. One gigawatt-hour (GWh) $\approx 3.6 \times 10^{12}$ joules (J, SI) $\approx 3.412 \times 10^9$ British thermal units (BTU).
3. One square meter (m^2, SI) $\approx$ 10.76 square feet (ft^2).

References

Banister, D., C. Wood, and S. Watson. 1997. Sustainable cities—Transport, energy and urban form. *Environment and Planning B* 24(1): 125–143.

Boarnet, M. and R. Crane. 2001. *Travel by design. The influence of urban form on travel.* New York, NY, USA: Oxford University Press.

Boussauw, K. and F. Witlox. 2009. Introducing a commute-energy performance index for Flanders, part A. *Transportation Research* 43: 580–591.

Breheny, M. 1995. The compact city and transport energy consumption. *Transactions of the Institute of British Geographers* 20(1): 81–101.

Breheny, M. J. and I. R. Gordon. 1997. Urban densities, travel behaviour and the limits to planning. In *Proceedings of BEPAC/EPSRC Conference on Sustainable Buildings*, edited by A. K. M. Azad. Dekalb, IL, USA: Northern Illinois University.

CEEW (Cellule Etat de l'Environnement Wallon). 2007. *Rapport analytique sur l'état de l'environnement wallon 2006–2007 [Report on the state of the Walloon environment in 2006–2007].* Report D/2007/5322/45. Namur, Belgium: Ministère de la Région Wallonne. http://etat.environnement.wallonie.be/index.php?page=le-rapport-analytique-2006-2007. Accessed 10 August 2011.

EC (European Commission). 2003. Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the energy performance of buildings. *Official Journal of the European Union* L(001): 65–71.

Ewing, R., K. Bartholomew, S. Winkelman, J. Walters, and G. Anderson. 2008. Urban development and climate change. *Journal of Urbanism* 1(3): 201–216.

Ewing, R., K. Bartholomew, S. Winkelman, J. Walters, and D. Chen. 2008(b). Growing cooler: The evidence on urban development and climate change. Washington, DC, USA: Urban Land Institute.

Ewing, R. and R. Cervero. 2001. Travel and the built environment: A synthesis. *Transportation Research Record* 1780: 87–114.

Ewing, R. and R. Cervero. 2010. Travel and the built environment: A meta-analysis. *Journal of the American Planning Association* 76(3): 265–294.

Ewing, R. and F. Rong. 2008. The impact of urban form on US residential energy use. *Housing Policy Debate* 19(1): 1–30.

Friedman, K. and A. Cooke. 2011. City versus national energy use: Implications for urban energy policy and strategies. *Procedia Engineering* 21: 464–472.

Hubert, J.-P. 2004. Mobilité urbaine, périurbaine, rurale en Belgique: où sont les différences? [Urban, suburban and rural mobility in Belgium: Where are the differences?]. *Les Cahiers Scientifiques du Transport* 45: 83–100.

Hubert, J.-P. and P. Toint. 2002. *La mobilité quotidienne des belges [Daily mobility of Belgians].* Namur, Belgium: Presses Universitaires de Namur.

ICEDD (Institut de Conseil et d'Etudes en Développement Durable). 2005. *Bilan énergétique wallon 2005. Consommations du secteur du logement 2005. [Walloon energy balance in 2005. Housing consumption in 2005].* Namur, Belgium: Ministère de la Région Wallonne.

Jones, P. J., S. Lannio, and J. Williams. 2001. Modelling building energy use at urban scale. In *Proceedings of the 7th International IBPSA Conference*. Rio de Janeiro, Brazil: International Building Performance Simulation Association.

Kavgic, M., A. Mavrogianni, D. Mumovic, A. Summerfield, Z. Stevanovic, and M. Djurovic-Petrovic. 2010. A review of bottom-up building stock models for energy consumption in the residential sector. *Building and Environment* 45: 1683–1697.

Kints, C. 2008. *La rénovation énergétique et durable des logements wallons. Analyse du bâti existant et mise en évidence des typologies de logements prioritaires. [Energy and sustainable renovation of Walloon housings. Analysis of existing buildings and identification of typologies of housing renovation priority].* Louvain-la-Neuve, Belgium: Université catholique de Louvain. www.lehr.be/Reports/UCL_Les_logements_wallons.pdf. Accessed 14 August 2011.

Lebart, L., A. Morineau, and J.-P. Fenelon. 1982. *Traitement des données statistiques – méthodes et programmes [Statistical data processing—Methods and programs].* Paris, France: Dunod.

Marique, A.-F. and S. Reiter. 2012a. A method for evaluating transport energy consumption in suburban areas. *Environmental Impact Assessment Review* 33(1): 1–6.

Marique, A.-F. and S. Reiter. 2012b. A method to evaluate the energy consumption of suburban neighborhoods. *HVAC&R Research* 18(1–2): 88–99.

MRW (Ministère de la Région Wallonne). 2007. Enquête sur la qualité de l'habitat en Région wallonne 2006–2007 [Survey on the quality of housing in the Walloon region in 2006–2007]. Report no. 5. Namur, Belgium: Ministère de la Région Wallonne.

Naess, P. 1996. *Urban form and energy use for transport. A Nordic experience.* Oslo, Norway: N.T.H.

Newman, P. and J. R. Kenworthy. 1989. *Cities and automobile dependence: A sourcebook.*: Aldershot, UK: Gower.

Newman, P., and J. R. Kenworthy. 1999. *Sustainability and cities: Overcoming automobile dependence.* Washington, DC, USA: Island Press.

OECD and IEA (Organisation for Economic Co-operation and Development and International Energy Agency). 2008. *World energy outlook 2008*. Paris, France: IEA.

Popovici, E. and B. Peuportier. 2004. Using life cycle assessment as decision support in the design of settlements. In *Sustainable architecture*, edited by M. H. de Wit. Proceedings of the 21th PLEA Conference on Passive and Low Energy Architecture. Eindhoven, the Netherlands: Technische Universiteit Eindhoven.

Ratti, G., N. Baker, and K. Steemers. 2005. Energy consumption and urban texture. *Energy and Buildings* 37(7): 762–776.

Shimoda, Y., T. Fujii, T. Morikawa, and M. Mizuno. 2004. Residential end-use energy simulation at city scale. *Building and Environment* 39: 959–967.

Souche, S. 2010. Measuring the structural determinants of urban travel demand. *Transport Policy* 17: 127–134.

Steadman, P., S. Holtier, F. Brown, J. Turner, T. De La Barra and P. A. Rickaby. 1998. An integrated building stock, transport and energy model of medium sized. Report to the Engineering and Physical Sciences Research Council, Cambridge, UK.

Steemers, K. 2003. Energy and the city: Density, buildings and transport. *Energy and Buildings* 35: 3–14.

Swan, L. G. and V. I. Ugursal. 2009. Modeling of end-use energy consumption in the residential sector: A review of modeling techniques. *Renewable and Sustainable Energy Reviews* 13: 1819–1835.

Tommerup, H. and S. Svendsen. 2006. Energy savings in Danish residential building stock. *Energy and Buildings* 38(6): 618–626.

Urban Task Force. 1999. *Towards an urban renaissance*. London, UK: E&FN Spon.

Uihlein, A. and P. Eder. 2010. Policy options towards an energy efficient residential building stock in the EU-27. *Energy and Buildings* 42: 791–798.

van de Coevering, P. and T. Schwanen. 2006. Re-evaluating the impact of urban form on travel patterns in Europe and North America. *Transport Policy* 13: 229–239.

Verbeek, G. and H. Hens. 2005. Energy savings in retrofitted dwellings: Economically viable? *Energy and Buildings* 37: 747–754.

Volle, M. 1993. *Analyse des données [Data analysis]*. Paris, France: Economica.

Wallemacq, V., A.-F. Marique, and S. Reiter. 2011. Development of an urban typology to assess residential environmental performance at the city scale. In *Architecture and Sustainable Development*, edited by M. Bodart and A. Evrard. Proceedings of the 27th PLEA Conference. Louvain-la-Neuve, Belgium: Université catholique de Louvain.

Yamaguchi, Y., Y. Shimoda, and M. Mizuno. 2007. Proposal of a modeling approach considering urban form of evaluation of city level energy management. *Energy and Buildings* 39: 580–592.

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Appendix A.3

A method for evaluating transport energy consumption in suburban areas

1. INTRODUCTION

The process of urban sprawl, which commonly describes physically expanding urban areas, is a major issue for sustainable development (European Environment Agency, 2006). Urban sprawl is known to represent a significant contribution to the overall energy consumption of a territory for energy needs in buildings and for transport. In fact, for the same standard of insulation, detached houses need more energy for heating than terraced houses (Marique and Reiter, 2010). Moreover, suburban developments have created farther spatial separation of activities, which results in an increase in travel distances and transport energy consumption (Silva et al., 2007). In suburban residential neighborhoods mainly composed of detached houses and often located far away from city centers, car ownership is often high and public transport is generally less available, which tends to favor the use of private cars.

Although the environmental impact of urban sprawl and uncontrollable urbanization are receiving an increasing amount of attention and may give rise to various issues, such as environmental pollution or large-scale climate change (CPDT, 2002; He et al., 2010; Urban Task Force, 1999; Young et al., 1996), and despite the growing importance of the energy issues in public debate, low-density suburban developments continue to grow, regardless of their location. Such developments are found all over Europe, the United States and even emerging countries (Nesamani, 2010; Silva et al., 2007; Yaping and Min, 2009). An evaluation on the sustainability of these suburban neighborhoods is necessary and requires appropriate methods and tools, especially as far as the private transport is concerned. In fact, transport energy consumption is rarely taken into account when the sustainability of these suburban structures is studied, even if sharp fluctuations in oil prices and reduction efforts in greenhouse gases emissions play an important role in current discussions and policies. Even new districts that set themselves up as “eco” or “sustainable” are sometimes built far from city centers and are not necessarily very sound from an ecological point of view because of higher transport energy consumption (Harmaajärvi, 2000).

Section 2 presents a brief review of the literature relating to the interdependences between spatial planning and transport energy consumption. Section 3 describes a quantitative method that was developed to assess transport consumption at the neighborhood scale to create a decision-making tool, to highlight the most efficient strategies needed to promote awareness and to give practical hints on how to reduce energy consumption linked to urban sprawl. Statistical data available at the neighborhood scale and characteristics of cars and public vehicles were used to predict transport needs and assess consumption as far as home-to-work and home-to-school travels are concerned. "Type-profiles" were developed to complete this approach and give an approximation of transport energy consumption related to leisure and commercial purposes. Section 4 presents an application of this method concerning a comparison of four suburban districts located in the Walloon region of Belgium, which confirms that the method is applicable and practical. Finally, Sections 5 and 6 summarize our main findings and discuss the reproducibility and the limits of this approach.

2. BACKGROUND TO THE EVALUATION OF TRANSPORT CONSUMPTION

In the current context of growing interest in environmental issues, reducing energy consumption in the transport sector, which represents 32% of the overall energy in the European Union (the building sector represents 37%), appears as an important policy target (Maïzia et al., 2009). Politicians, stakeholders and even citizens are now aware of the issue of energy consumption in buildings, namely through the passing of the European Energy Performance of Buildings Directive (EPBD) and its adaptation to the Member States laws; however, efforts and regulations to control transport needs and consumption are more limited. Nevertheless, although transport and mobility are often neglected, they are crucial in terms of urban sprawl because global oil use has allowed the appearance of sprawling urban forms (Jenks and Burgess, 2002). Therefore, the performances of transport networks determine whether a piece of land is of interest to developers who are likely to expand towns (Halleux, 2008).

Existing scientific work dealing with transport consumption is mainly concerned with dense urban areas, focusing on relationships between transport energy consumption and building density, and this work remains undecided on the effects of densification strategies for the reduction of transport consumption. Maïzia et al. (2009) and Steemers (2003) argue that more compact urban forms would significantly reduce energy consumption both in the building and transport sectors. Based on data from 32 big cities located all over the world, Newman and Kenworthy (1989, 1999) have highlighted a strong inverse relationship between urban density and transport consumption, but their work is only valid for certain conditions and is often criticized by other works (Mindali et al., 2004; Owens, 1995) mainly for methodological reasons. Banister (1992) applied the same kind of approach to British cities and highlighted, on the basis of statistical data obtained from a national survey, that transport energy consumption is slightly higher in London than in smaller cities, which refutes Newman and Kenworthy observations. Boarnet and Crane (2001) are also skeptical on the relationship between urban design and transport behaviors. On the basis of several case studies, they estimate that if the use of the soil and the urban form impact transport behaviors, it is through the price of travel (public transport prices are reduced in dense areas). Gordon and Richardson (1997) demonstrated that if fuel prices are included in the analysis, urban density only plays a limited role on energy consumption in transport. Ewing and Cervero (2001), on the basis of a number of case studies, concluded that the impact of urban density on car travel reduction stays marginal. Elasticity is evaluated at -0.05, which means that if the density of a district is multiplied by two, private car commutes are only reduced by 5% because of the rise of congestion. Finally, Breheny (1995) has emphasized minor reductions in transport energy consumption thanks to the compact city model. His experiments show that, even under very strict conditions that are difficult to reproduce, energy used in transport could only be reduced by 10 to 15%. More recently, Boussauw and Witlox (2009) have developed a commute-energy performance index and tested it for Flanders and the Brussels-capital region in Belgium, including rural and suburban parts of these territories, to investigate the link between spatial structure and energy consumption for home-to-work travels at the regional scale. This method is based on statistical data available at the district scale, taking into account commuting distances, modal shares of non-car travel modes and aspects of infrastructure. This index allows for a better understanding of the energy consumption levels for commuting (home-to-work travels) in cities and less dense areas.

3. THE METHOD

We have developed a quantitative method to assess transport energy consumption, in suburban areas, at the neighborhood scale. Energy consumption in transport is in fact an interesting indicator because it is a composite measure of travel distance, modal choice and journey frequency (Banister, 1998; Muniz and Galindo, 2005). The method takes into account four purposes of travel (work, school, shopping and leisure) and will help us have a better understanding of the regional suburban situation, find the most relevant indicators to reduce transport energy consumption in suburban areas and compare different strategies of intervention in these specific types of structures. It will help to fill the critical lack of evaluation tools that local authorities could use to evaluate new and existing residential developments (Tweed and Jones, 2000), especially those dedicated to transport and location.

The method proposed in this paper only deals with transport energy consumption, which is one of the three parts of an overall method that aims at performing the total energy modeling of suburban areas. The complete package includes the energy assessment of buildings, transport and public lighting, and addresses their influences at the neighborhood scale because, even if the urban context has been mostly neglected in building energy analyses so far, decisions made at the neighborhood level have important consequences on the performance of individual buildings and on the transport habits of the inhabitants (Popovici and Peuportier, 2004). Marique and Reiter (2010; In press) described the first part of the method, dedicated to the energy assessment of suburban houses, at the district scale, and presented its application to three typical suburban districts. The overall method has also the advantage of allowing the comparison between the energy requirements in the building sector and in the transport sector, and thus, for every specific district, to highlight which strategy would be the most efficient to reduce the overall energy consumption.

3.1 Home-to-work travels

To assess energy consumption relating to home-to-work travels, we adapted and completed the performance index developed by Boussauw and Witlox (2009) for Flanders. In fact, the statistical data used in the Flemish commute-energy performance index are also available for the Walloon part of the country. However, other important parameters are not taken into account in the approach developed by Boussauw and Witlox (2009), such as type of fuel, characteristics of the local public transport network in suburban areas (significant differences exist between cities and suburban neighborhoods), number of working days per workers, pre-transportation, etc.

The input data come from the national censuses, which are carried out every ten years in Belgium and are available at the census block scale (the smallest geographical unit in which data are available in Belgium). We have considered the two last censuses, respectively carried out in 1991 and 2001. One-day travel-diary data from male and female heads of households were used. For these households, information was available in each census block about car ownership, travel distances, main mode of transport used, the number of working days per week and per worker, etc. together with their demographic and socioeconomic situation. The survey only concerns two purposes of travel: home-to-work travels and home-to-school travels, which represent the majority of travel.

To determine the total number of kilometers logged annually by various modes of transportation for home-to-work travels, the first step of the method is to combine the number of workers in a census block with the number of travels per week (thought the repartition of the number of working days in the census block), the distance travelled for home-to-work travel (one way) and the modes of transport used (car, bus, train, motorbike, bike or on foot) in this census block. A correction factor was applied to short distances covered by train and long distances covered by bus to keep the relationship between the mode and the distance travelled. As distances travelled per mode of transport are aggregated by census block in the national survey, this correction factor was calculated for each census block, on the basis of the following assumptions: trips by train shorter than 5 kilometers and trips by bus longer than 30 kilometers are spread over the others classes of distances. Non motorized trips (bike, on foot) were not considered in the following calculations because they do not consume any energy. Motorbike trips were neglected because they represent a very small part of home-to-work and home-to-school travels. In addition, if the main mode of transport used was the train, we also took into account travels from the house to the train station to investigate the role of home-to-station travels in total transport energy consumption. The mode of transport used for home-to-station travels was determined by a Geographical Information System (GIS) according to the distance travelled and the bus services available in each district.

Distances covered by diesel cars were separated from those covered by fuel cars according to the regional distribution of the vehicle stock in the Walloon region (55% diesel and 45% fuel cars). The final step of the method consists in allocating consumption factors to the distances covered in each category of vehicles (diesel car, fuel car, bus or train) to convert the distances into energy in terms of kilowatt hour (kWh). The unit of energy, kWh, was chosen to allow a comparison between energy consumption in transport with energy consumption to heat buildings in the overall method (Marique and Reiter, In press). Consumption factors take into account the mean consumption of the vehicles (liter per km), the passenger rate and the characteristics of the fuel (Table 1). For the train, the consumption factor used depends on the production of electricity as trains in Belgium are electric. The value used in this paper was calculated, for Belgium, by CPDT (2005).

Table 1

Consumption factors (per km and per person) used to convert kilometers into kWh, based on regional mean values

	Type of vehicles			
Characteristics	Diesel car	Fuel car	Bus	Train
Consumption per kilometer	0.068 l.	0.080 l.	0.46 l.	-
Occupancy rate	1.2	1.2	10	-
Density of the fuel (/1000 l. in toe)	0.859	0.745	0.859	-
Factor	**0.6134**	**0.6259**	**0.4986**	**0.3888**

Finally, we divided the total amount of energy consumption for home-to-work travels per census block by the working population that lives in the considered area to obtain an index that gives the mean annual energy consumption for home-to-work travels for one worker living in the considered district.

3.2 Home-to-school travels

The method developed for home-to-work travels is also applicable to home-to-school travels because the same types of data are available in the national census. Instead of using the number of working days, we used a mean number of days of school per year. The total amount of energy consumption for home-to-school travels per census block was divided by the number of students living in the census block to give the mean annual energy consumption for home-to-school travels for one student living in the considered census block.

3.3 Others purposes of travel

As previously mentioned, home-to-work and home-to-school travels represent only a part of the mobility of a household. Leisure and shopping are two other important purposes of travel (Hubert and Toint, 2002). Unfortunately, national censuses do not give information about those purposes of travel. As a result, we have developed a simplified calculation to take into account home-to-leisure and home-to-shop travels and compared them to home-to-work and home-to-school travels to give a more complete image of the energy consumption for transport in a district. This approach was based on “type-profiles”. According to socio-economic data, we have established several representative types of households living in a district (a family with two children, two elderly persons, a couple of unemployed people, etc.) and attributed, to each type of households, mobility characteristics for home-to-shop and home-to-leisure travels. These characteristics mainly concerned distances travelled from home to shop or leisure activities (according to the geographical location of each district) and the frequencies of travels (according to the socio-economic composition of the household). The mode of transport used was determined according to hypotheses made on the distances to travel, the distance to bus stops and the bus services available. This required information was collected by using a GIS. Different locations were taken into account: proximity shops, suburban shopping centers and main city centers. Finally, households are now known to try to combine different trips to minimize distances (Wiel, 1997); therefore, a correction factor can be applied to distances to take these “chained trips” into account. At the end, we are still able to distinguish the contribution of each mode in the final results.

4. APPLICATION OF THE METHOD

4.1 Specificities of the Walloon region of Belgium and case studies

Urban sprawl is familiar in many European regions and countries and particularly in the Walloon region of Belgium, where 52% of the building stock is made of detached or semi-detached houses (Kints, 2008). Because of the personal preferences of Walloon households for single family houses with large gardens in a rural environment, and the regulatory framework, which allows this kind of developments to grow, urban sprawl is now a concern in a large part of the regional territory. The Walloon urban sprawl presents several specificities in comparison with the neighboring regions and countries. According to cadastral data (Vanneste et al., 2007), 50% of Walloon census blocks present a mean housing density in the range between 5 and 12 dwellings per hectare, which is very low. In comparison to Flanders, where public authorities are now trying to reduce the size of the plots in new developments, or the Netherlands, where land supplies are historically very limited, land pressure stay limited in the Walloon region and land supplies are still available in large quantity. Moreover, Walloon suburban districts are not developed in continuity with dense urban centers or rural cores but are spread out on the whole regional territory according to land supplies availability and car accessibility (which is high because the transport network is very developed all over the Walloon region).

The majority of those districts are only residential, even if urban sprawl also concerns commercial or industrial functions.

As far as mobility is concerned, the dependence of these suburban areas upon cars is huge. National surveys held every ten years in Belgium show that car ownership is higher in suburban areas than in more densely populated areas (Verhetsel et al., 2007). According to these surveys, distances from home to work are also higher in suburban areas than in more densely populated areas because these neighborhoods are often developed far away from city centers where most of the employment areas are located. Moreover, because of the low population density of the Walloon suburban neighborhoods, public buses are often available at very low frequencies with low commercial speed and do not constitute a credible alternative to individual mobility.

An application of the method is presented concerning the comparison of four existing suburban neighborhoods in the Walloon region of Belgium. Given that urban sprawl is observed throughout the whole region, one representative suburban district has been selected in every urban region identified in Belgium, namely by Sporck et al. (1985), whose aim was to present a typology of the Belgian urban regions and to define their borders. This typology was used in numerous studies and research about urban sprawl, specifically in two statistical censuses held in 1998 and 2007 (Luyten and Van Hecke, 2007; Merenne-Schoumaker et al., 1998). The “operational agglomeration” was based on the morphological agglomeration, or dense urban core. Its limits were determined by the continuity of the building stock and adapted to administrative borders. The “suburbs” were the first suburban area of a city. Areas located further from the city, while keeping strong relationships with it (through home-to-work travels), constituted the “alternating migrants area,” whereas remaining areas were regrouped under the “other areas” term and represent rural and less dense areas located far away from city centers. The main characteristics of the four neighborhoods are presented in Table 2.

Table 2

Main characteristics of the four studied neighborhoods

	Studied areas (suburban neighborhoods)			
Characteristics	Jambes	Fontaine	Rotheux	Tintigny

Urban area	“operational agglomeration”	suburbs”	“alternating migrants”	“other areas”
Main types of houses	Detached houses (pretty new)	Semi-detached and terraced houses	Rural core, farms, detached houses	Detached houses (pretty old)
Distance to city center	6 km	9 km	17 km	29 km
Distance to train station	6 km	9 km	15 km	8 km
Bus services	Low	Good	Low	Very low

4.2 Main results and key indicators

The application of the method developed in section 3 to the four representative suburban neighborhoods presented in section 4.1 gave the following results (Table 3):

Table 3

Index for home-to-work, home-to-school and home-to-shop-and-leisure travels

	Studied areas (suburban neighborhoods)			
Index	Jambes “operational agglomeration”	Fontaine “suburbs”	Rotheux “alterning migrants”	Tintigny “other areas”
Home-to-work kWh/worker.year	4 646	3 945	4 782	5 785
Home-to-school kWh/student.year	888	429	2 152	2 376
Home-to-shop and home-to-leisure kWh/person.year	599	414	1335	2 216

The first main finding of the application of the method to the four case studies was that, in each case, home-to-work travels represent the most important part of the total energy consumption. Home-to-school travels, which were calculated with the same kind of data and the same method, can thus be easily comparable; they consume less energy per capita than home-to-work travels. The first explanation is that distances from home to school are shorter than distances from home to work. Several schools are indeed located in most Walloon towns, even in the more rural ones, whereas work locations remain concentrated in bigger cities and in some suburban business parks. Moreover, the use of public transport is higher for home-to-school travels than for home-to-work ones which could also explain the better results obtained for home-to-school travels.

Home-to-station travels were included in the previous results and represent between 0.9% and 3.7% of home-to-work travels and between 1.1% and 4.8% of home-to-school ones, whereas the modal part of the train was very low. These results show that it is important to take home-to-station travels into account in suburban areas. Moreover, trying to increase the modal part of the train in suburban areas should be a good strategy, but only if alternatives to individual car are proposed for home-to-station travels.

Annual home-to-work and home-to-school energy consumption was higher in the two residential districts located far away from city centers (Tintigny and Rotheux), whereas home-to-work consumption was high in Jambes, but home-to-school consumption was lower than in others districts. As Jambes is located closer to a big city center (6 kilometers), students can more easily use alternative non polluting modes of transport.

Home-to-shop and home-to-leisure travels represent between 62.0% and 96.5% of the annual energy consumption for home-to-school travels, as seen in Table 3. These values mainly depend on the distances to shops, services and leisure. The more equipped the neighborhood and its surrounding are, the smaller the energy consumption rate for home-to-shop and home-to-leisure travels is. As those purposes of travels were calculated according to “type-profiles” and not according to statistical data, results were not as robust as home-to-work and home-to-school consumption but seem to give credible results. Shops and leisure, just as schools, are spread out on the whole region, even in most rural areas (rural core, suburban centers, etc.) which allow for reduced distances from home to destination.

4.3 Sensitivity analyses

Several sensitivity analyses were performed to identify the most relevant indicators that act upon transport energy consumption. Since the main key indicators that seem to be highlighted by the first results were the distance between home and final destination and the bus services, the first sensitivity analysis deals with the location of the districts. If we consider, as a first approach, that all the studied neighborhoods keep their socio-economic characteristics but could now benefit from the same good location than the neighborhood presenting the lowest energy consumption rate (Fontaine neighborhood, close to a city center, good bus services, higher mix in functions), energy consumption relating to home-to-work and home-to-school travels decrease significantly: -55.4% in Tintigny, -22.5% in Jambes and -32.4% in Rotheux, mainly because trips by car are shorter and less numerous. These results highlight that location is paramount as far as transport energy consumption is concerned. To try to isolate the impact of the distance, we then considered that the distances between home and work and between home and school mentioned in the national census were reduced by 10% in a first theoretical calculation and by 20% in a second one. These simulations confirmed that the impact of distances on energy consumption in transport is high (see Table 4). However, these results remain purely theoretical because it is not possible to change the location of existing neighborhoods. Nevertheless, these results show the importance of promoting the implementation of future neighborhoods in areas close to large employment centers and services and increasing the population of these areas when they are already built.

The third type of sensitivity analysis deals with the energy consumption of the vehicles. If we considered that the performances of all the vehicles (fuel consumption per mode) are improved by 10%, which is a credible approach, home-to-work and home-to-school energy consumption decrease from 6.6% to 9.6%. These savings are further improved if the performances of the vehicles are improved by 20%. If only the performances of public buses are improved, resulting savings for home-to-work and home-to-school travels are low: energy consumption only decreases by 1.7% to 2.7% because the modal part of the bus is very low in these districts. Therefore, improving the performances of public vehicles will only give good results in areas where buses are used by a large part of the population.

To favor home-workers is also a credible strategy to reduce transport energy consumption. It was calculated that if 5% of the workers of a district are allowed to work at home, energy consumption savings (home-to-work and home-to-school travels) are in the range of 2.3% to 3.6%, according to the district. If the percentage of “home workers” rises to 10%, energy reductions can reach 6.9%.

The last type of sensitivity analysis deals with modal transfer. If we considered that, in each district, 10% of the workers who used a car to go to work will change their habits and use the bus, then energy consumption (home-to-work and home-to-school travels) are reduced by a maximum of 3%. If the modal transfer rises 20%, energy consumption reductions can reach 5% in one of the four studied areas. If modal transfers deal with home-to-work travels and home-to school travels, energy savings are higher by up to 8%. Therefore, the mode of transport used (car, train or bus) has, in comparison with other strategies, a smaller impact on transport energy consumption relating to home-to-work and home-to-school travels. Even if a car has a level of consumption per kilometer higher than trains or buses, home-to-work travels and home-to-school travels made by train are much longer, and the differences between energy factors for car and for bus is not very important because the bus occupation rate is low.

Table 4

Summary of the sensitivity analyses: energy consumption (home-to-work and home-to-school travels) reductions in % for each scenario tested

	Studied areas (suburban neighborhoods)			
Scenario	Jambes	Fontaine	Rotheux	Tintigny
1.All the districts have the same location as Fontaine	-22.5%	-	-32.4%	-55.4 %
2(a).Distances (home to work and school):-10%	-9.7 %	-9.8 %	-9.6 %	-9.7 %
2(b).Distances (home to work and school): -20%	-19.5 %	- 19.5 %	-19.2 %	-19.4 %
3(a).Performances of vehicles: +10%	-9.0%	-6.6%	-9.6%	-9.6 %
3(b).Performances of vehicles: +20%	-17.9%	-13.2%	-19.2%	-19.1 %
3(c).Performances of the buses only: +20%	-1.7%	-2.7%	-2.1%	-2.1 %
4(a).Home workers: 5%	-3.4%	-2.6%	-3.6%	-2.3 %
4(b).Home workers: 10%	-6.9%	-5.6%	-6.8%	-5.3 %
5(a).Modal transfer (home-to-work): 10%	-2.3%	-1.9%	-2.9%	-1.9 %
5(b).Modal transfer (home-to-work): 20%	-4.2%	-3.9%	-4.6%	-3.3 %
5(c).Modal transfer (home-to-work & school): 10%	-4.0%	-2.5%	-5.0%	-4.6 %
5(d).Modal transfer (home-to-work & school): 20%	-6.7%	-4.9%	-7.8%	-7.4 %

Table 4 summarizes the energy consumption reductions for each sensitivity analyses tested. The results indicate that location is the major impact on energy consumption. Location includes a lot of different factors and it is very difficult to isolate these spatial parameters; however, distances from home to final destination seems to have a huge impact on transport energy consumption. The second most efficient strategy is to improve the vehicles' performances. Mode choice only gives limited results in the existing suburban situation. So, in the debate presented in section 2 about the impact of density on transport energy consumption, our results indicate that distance from home to work, to school and to others activities is paramount. As a result, rather than population and building density, a good mix between work, schools, shops and dwellings, at the living area scale, seems to be the best strategy to reduce transport energy consumption in existing suburban areas.

5. DISCUSSIONS AND PERSPECTIVES

The application of the quantitative method presented in section 3 to four suburban blocks, chosen in each urban region identified by the literature in the Walloon region of Belgium, highlights that energy performances related to transport are low and that the use of public transport is low as well; therefore, suburban districts are very dependent on private cars because cars are more efficient than public transport in these types of structures (low frequencies, low commercial speed, etc.). The sensitivity analyses show, however, that the benefits of several renewal strategies exist: choosing a better location could give significant results as far as energy performances in transport are concerned. Not only is this important for new developments, but also for households who want to reduce their energy consumption and their car and fuel costs. We have also highlighted the great influence of the distance between home and destination, as well as the performances of the vehicles, and the percentage of workers working at home to a lesser extent. We have finally showed that increasing the modal part of buses gives more limited results in the studied areas.

The method is developed and tested for the Walloon region of Belgium, where urban sprawl is a concern in a large portion of the area, but it is transposable to other regions and districts that are also affected by urban sprawl in Europe and beyond, by adjusting parameters, such as those relating to vehicles performances and public transport network, on the basis on local mean values. Input data come from national surveys or are collected using a GIS that are both commonly used tools in numerous regions and countries. Surveys similar to the one used in the case studies were for example carried out by the French National Institute of Statistics

(INSEE) in France, the Office for National Statistics (ONS) in the United Kingdom or the Census and Statistics of Population (IDESCAT) in Catalunya whereas GIS oriented towards urban planning are now largely used by researchers and territorial communities.

Even if many studies dedicated to transport and energy consumption only focus on home-to-work data because they are the most often available, the limits of this method arise from the fact that data about only two types of trips (home-to-work and home-to-school travels) are available in national censuses. Those types of travels are not representative of all trips of a household even if they play a founding role in it because they are commuting journeys and affect significantly related trips for leisure or commercial purposes. We have thus developed “type-profiles” to approach this reality but, even if this approach is also used in others research, such as those performed by Cornet et al. (2005), Kritikou et al. (2009) and Saunders et al. (2008), the results obtained are only theoretical and cannot currently be validated by comparing them with in situ measures; therefore, they should be used with caution.

Finally, an interactive decision making tool, accessible on the web, is developed, on the basis of the method presented in this paper. The aim is to transfer the main results of our research to citizens and stakeholders and inject them into policy and decision making. It will help developers to plan new suburban neighborhoods, and public authorities to take location and transport energy consumption into account when issuing authorization to build new districts or transforming exiting ones. Occupants and inhabitants can also use the tool to evaluate transport energy consumption and bus services in their districts and to test the impact of different locations before choosing their future dwelling.

6. CONCLUSIONS

Although the environmental impact of urban sprawl and their associated energy consumption are receiving an increasing amount of attention, low density suburban developments continue to grow all over the world. Aiming to reduce energy consumption linked to urban sprawl, a quantitative method has been developed to assess transport energy consumption relating to home-to-work and home-to-schools travels at the district scale, which was based on statistical data available at the census block scale. A simplified calculation completes the method, as far as home-to-shop and home-to-leisure travels are concerned. The method is flexible and parameterized what makes applicable to different contexts and regions. The application of the method to four existing suburban districts and the sensitivity analyses shows its potential in identifying key parameters and strategies to improve transport energy consumption in suburban areas. A good mix between work, schools, shops and dwellings in each neighborhood, which allows reduced travel distances, seems to be the best strategy to reduce transport energy consumption in suburban areas, whereas means of transport used is only of little impact. As highlighted in this paper, it is particularly crucial that the planning of new districts will be based on proper consideration of the location of the area (distance to work places, schools, etc.) and that public authority could use tools allowing them to better take location into account.

7. ACKNOWLEDGEMENT

This research is funded by the Walloon region of Belgium in the framework of the “Suburban Areas Favoring Energy efficiency” project (SAFE).

8. REFERENCES

Banister D. Energy use, transport and settlement patterns. In: Breheny M, editor. Sustainable Development and Urban Form. London: Pion Ltd; 1992. p. 160-181.

Banister D. Sustainable development and transport. Report for the Bundesforschungsantalt für Landeskunde und Raumordnung. The Urban 21 project; 1998.

Boarnet M, Crane R. Travel by design. The influence of urban form on travel. New-York: Oxford University Press; 2001.

Boussauw K, Witlox F. Introducing a commute-energy performance index for Flanders. Transp Res Part A. 2009; 43:580-91.

Breheny M. The compact city and transport energy consumption. Transactions of the Inst of Br geographers. 1995; 20(1):81-101.

Conférence Permanente du Développement Territorial. Les coûts de la désurbanisation. Namur; 2002; 1. 135p.

Conférence Permanente du Développement Territorial. Thème 2. Contribution du développement territorial à la réduction de l’effet de serre. Rapport final de la subvention 2004-2005. Namur ; 2005.

Cornet Y, Daxhelet D, Halleux J-M, Klinkenberg A-C, Lambotte J-M. Cartographie de l’accessibilité par les alternatives à la voiture. In : Proceedings of Les Journées Géographiques Belges. Mobilité, Société et Environnement en Cartes ; 2005. p. 355-64.

European Environment Agency. Urban sprawl in Europe. The ignored challenge. Final report. Copenhagen; European Environment Agency; 2006; 1.

Ewing R, Cervero R. Travel and the built environment: A synthesis. Transp Res Rec. 2001; 1780:87-114.

Gordon P, Richardson H W. Are compact cities a desirable planning goal? J of the Am Plan Association. 1997; 63(1):95-106.

Halleux JM. Urban sprawl, Urban Containment and Land Management. A Reflection on the Concept of Urban Land Supply. In: Sitar M, editor. Urban future: Challenges and opportunities for city and region developments. Maribor: University of Maribor Press; 2008. p. 259-68.

Harmaajärvi I. EcoBalance model for assessing sustainability in residential areas and relevant case studies in Finland. Environ Impact Assess Rev; 2000; 20:373-80.

He J, Bao CK, Shu TF, Yun XY, Jiang D, Brown L. Framework for integration of urban planning, strategic environmental assessment and ecological planning for urban sustainability within the context of China. Environ Impact Assess Rev; 2010, doi:10.1016/j.eiar.2010.09.002.

Hubert JP, Toint P. La mobilité quotidienne des Belges. Namur: Presses universitaires de Namur, Facultés universitaires Notre-Dame de la Paix; 2002.

Jenks M, Burgess R, editors. Compact cities: sustainable urban forms for developing countries. London: spon Press; 2002.

Kints C. La rénovation énergétique et durable des logements wallons. Analyse du bâti existant et mise en évidence des typologies de logements prioritaires. Louvain-La-Neuve: UCL, Architecture & Climat; 2008.
Kritikou Y, Dimitrakopoulos G, Dimitrellou E, Demestichas P. A management scheme for improving transportation efficiency and contributinng to the enhancement of the social fabric. Telematics and Informatics. 2009; 26:375-90.
Luyten S, Van Hecke E. De Belgische Stadsgewesten 2001 [Internet]. Brussels: FPS Economy; 2007. Available from: http://www.statbel.fgov.be/pub/d0/p009n014_nl.pdf /.
Maïzia M, Sèze C, Berge S, Teller J, Reiter S, Ménard R. Energy requirements of characteristic urban blocks. In: Proceedings of the CISBAT 2009 International Scientific Conference on Renewables in a Changing Climate, From Nano to Urban scale; 2009 Sept 2-3; Lausanne, Switzerland. 2009. p. 439-444.
Marique AF, Reiter S. A method to assess global energy requirements of suburban areas at the neighborhood scale. In: Proceedings of the 7th International IAQVEC Conference on Indoor Air Quality, Ventilation and Energy Conservation in Buildings; 2010 Aug 15-18; Syracuse, New York, USA. 2010.
Marique AF, Reiter S. A Method to Evaluate the Energy Consumption of Suburban Neighborhoods. HVAC&R Res. In press.
Merenne-Schoumaker B, Van der Haegen H, Van Hecke E. Recensement général de la population et des logements au 1 mars 1991, urbanisation. Monographie 11a. Ministère des Affaires économiques: INS, SSTTC; 1998.
Mindali O, Raveh A, Salomon I. Urban density and energy consumption: a new look at old statistics. Transp Res Part A. 2004; 38:143-62.
Muniz I, Galindo A. Urban form and the ecological footprint of commuting. The case of Barcelona. Ecol Econ. 2005;55:499-514.
Nesamani KS. Estimation of automobile emissions and control strategies in India. Science of the Total Environ. 2010;408:1800-11.
Newman P, Kenworthy JR. Cities and Automobile Dependence: A sourcebook. Aldershot: Gower Publishing Co; 1989.
Newman P, Kenworthy JR. Sustainability and Cities: overcoming automobile dependence. Washington DC: Island Press; 1999.
Owens S. A response to Michael Breheny. Transactions of the Inst of Br geographers. 1995; 20:381-86.
Popovici E, Peuportier B. Using life cycle assessment as decision support in the design of settlements. In: Proceedings of the 21th PLEA Conference on Passive and Low Architecture; 2004 Sept 19-22; Eindhoven, The Netherlands. 2004.
Saunders MJ, Kuhnimhof T, Chlond B, da Silva ANR. Incorporating transport energy into urban planning. Trans Res Part A. 2008;42:874-82.
da Silva ANR, Costa GCF, Brondino NCM. Urban sprawl and energy use for transportation in the largest Brazilian cities. Energy for Sustainable Development. 2007;11(3):44-50.
Sporck JA, Van der Haegen H, Pattyns M. L'organisation spatiale de l'espace urbain. La cité belge d'aujourd'hui, quel devenir? Bruxelles: Bulletin trimestriel du Crédit communal de Belgique; 1985.
Steemers K. Energy and the city: density, buildings and transport. Energy and Build. 2003; 35(1):3-14.
Tweed C, Jones P. The role of models in arguments about urban sustainability. Environ Impact Assess Rev; 2000; 20:277-87.
Urban Task Force. Towards an Urban Renaissance. London: Routledge, Queen's Printer and Controller of HMSO; 1999.
Vanneste D, Thomas I, Goosens L. Le logement en Belgique. SPF Economie et Statistique, SPF Politique scientifique. Bruxelles ; 2007.
Verhetsel A, Van Hecke E, Thomas I, Beelen M, Halleux JM, Lambotte JM et al. Le mouvement pendulaire en Belgique. Les déplacements domicile-lieu de travail. Les déplacements domicile-école. SPF Economie et Statistique, SPF Politique scientifique. Bruxelles ; 2009.
Wiel M. Comportements de mobilité et évolution de l'organisation urbaine. Rapport du FIER; 1997.
Yaping W, Min Z. Urban spill over vs. local urban sprawl: Entangling land-use regulations in the urban growth of China's megacities. Land Use Policy. 2009; 26:1031-45.
Young W, Bowyer D, Naim RJ. Modeling the environmental impact of changes in urban structure. Computer Environ and Urban Syst. 1996; 20:313-26.

Appendix A.4

URBAN SPRAWL, COMMUTING AND TRAVEL ENERGY CONSUMPTION

INTRODUCTION

The problems associated with energy use, such as global climate change caused by the release of carbon dioxide and other greenhouse gases, are receiving increasingly more attention (Glicksman, 2007). In the transportation sector, which represents approximately 32% of the final energy used in Europe (European Commission, 2008), increases in energy consumption and greenhouse gas emissions due to commuting by car is of particular concern. The rise in individual mobility is namely attributed to the physical expansion of urban areas, commonly referred to as urban sprawl. Due to the combination of rapidly declining transport costs and increasing travel speed (Ewing, 1994), the accessibility of outlying areas and vehicle miles of travel (VMT) per capita have increased substantially over the recent past and have favoured the development of suburban neighbourhoods. Sprawl is believed to be facilitated by car ownership and use and also to contribute to it, in a positive feedback loop that reinforces both low-density development and motorisation (Gilbert and Perl, 2008). The environmental impacts of urban sprawl have been studied in depth and urban sprawl has been identified as a major issue for sustainable development (European Environment Agency, 2006). Although it is often defined in terms of “undesirable” land-use patterns (Ewing, 1994; Urban Task Force, 1999) in the scientific field, sprawl however often induces lower land prices and more affordable housings (Gordon and Richardson, 1997). Low-density developments also mean more room and a higher standard of living for numerous households and constitute one of the preferred living accommodations (Berry and Okulicz-Kozaryn, 2009; Couch and Karecha, 2006; Gordon and Richardson, 1997; Howley, 2009).

Although it is usually argued that more compact urban forms would significantly reduce energy consumption both in the building and transportation sectors (Ewing et al., 2008; Gillham 2002; Newman and Kenworthy, 1999; Steemers 2003), suburban developments continue to grow. An evaluation of the sustainability of suburban neighbourhoods is necessary, and such an evaluation requires appropriate methods and tools, especially regarding private transport. Transport energy

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consumption is rarely taken into account when the sustainability of suburban structures is studied, even in cases where sharp fluctuations in oil prices and reduction efforts in greenhouse gases emissions play an important role in ongoing discussions and policies. Various scientific articles have already studied the relationships between transport energy consumption and building density. Based on data from 32 big cities located all over the world, Newman and Kenworthy (1999) have highlighted a strong inverse relationship between urban density and transport consumption. But Breheny and Gordon (1997) demonstrated that the density coefficient and its statistical significance decrease when petrol price and income are included as explanatory variables. Different studies underline also the importance of the price of travel and the influence of socio-economic factors on transport behaviours (Boarnet and Crane, 2001; Van de Coevering and Schwanen, 2006). Souche (2010) studying 10 cities around the world (through the IUTP database) showed that the two variables the most statistically significant for transport energy consumption assessment are the transport cost and the urban density. On the basis of various case studies, Ewing and Cervero (2001) evaluated quantitatively the impact of urban density, local diversity, local design and regional accessibility on the mean vehicle travel distances. The elasticity was evaluated at -0.05 for urban density, -0.05 for local diversity, -0.03 for local design and -0.2 for regional destination accessibility. It means that if the density of a district is multiplied by two, private car commutes are only reduced by 5%. Note that the impact of the destination accessibility is larger than the three others parameters combined, suggesting that areas of high accessibility, such as city centres, may produce substantially lower transport energy consumption than dense and mixed developments in less accessible areas. Ewing et al. (2008) found that the most compact metropolitan areas in the US generate 35% less mean vehicle travel distances per capita than the most sprawling metropolitan areas. Ewing and Cervero (2010) showed that a 10% reduction in distance to downtown reduces mean vehicle travel by 2.2% and a 10% increase in nearby jobs reduces mean vehicle travel by 2%. Finally, more compact developments (including density, functional mix, and transit accessibility) can reduce mean vehicle travel per capita by 25-30% (Ewing and Cervero, 2010).

Finally, the issue of scale should also be addressed as existing research and studies mainly consider large and dense urban areas (e.g. Banister, 1992; Ewing and Cervero, 2001; Newman and Kenworthy, 1999) that do not exist in Belgium (with the exception of the city of Brussels). Owens

(1986), for example, found that different characteristics of the spatial structure are important in terms of the energy efficiency across different scales. Regarding the impact of land use on transportation, Van Wee (2002) distinguishes several spatial levels: the direct surroundings of the dwellings, the neighbourhood, the town/city, the region, a sub-set of a country, the entire country and the international scale. In 2008, the World Energy Outlook recognized that the factors that were influencing city energy use were different from the energy use profiles of the countries the cities were in as a whole and suggested that, in industrialized countries, the energy use per capita of city residents tends to be lower than the national average (OECD & IEA 2008). Nonetheless, the issue of geographical scale is often neglected in discussions about the compact city and transport energy savings that too often "elide scale" (Neuman, 2005).

The aim of this paper is to analyse the role of the spatial structure of the territory, and in particular the impact of urban sprawl, on transport energy consumption at the regional and local scale. Urban structure is understood here as the system defined by three main elements: i) the location of work places and services (commercial, education, leisure, etc.), ii) the spatial distribution of population according to the place of residence and iii) infrastructures (transport and technical networks). The aim of this exercise is to understand and address the sustainability of transport in our territories and highlight parameters of paramount importance. This study focuses on home-to-work and home-to-school commuting. Although home-to-work and home-to-school trips are becoming less meaningful in daily travel patterns in the Western world due to the dramatic growth in other activities (Graham, 2000; Lavadinho and Lensel, 2010; Pisarski, 2006), they have more structural power than other forms of travel because they are systematic and repetitive (Dujardin et al., 2011). Amongst all the residential commuting within the Walloon region of Belgium, home-to-work and home-to-school trips account, respectively, for 30% and 17% of trips and for 45% and 9% of the total distance travelled (Hubert, 2004).

In Section 2, the paper presents the study area and the quantitative method used to assess the transport system in Belgium. Three indexes (the energy performance index, the modal share index and the distance travelled index) are developed and mapped in Section 3 to investigate the interdependences between urban structure of the territory, urban sprawl and travel energy consumption for commuting at several territorial scales. In Section 4, Section 5 and Section 6, the difference in energy performance between home-to-work and home-to-school trips, the evolution of the performance index between 1991 and 2001 and the most influential parameters are presented and discussed. Section 7 discusses the limitations of the method and Section 8 summarises our main findings.

STUDY AREA AND METHODS

Study area: the Walloon region of Belgium and urban sprawl

Urban sprawl is particularly familiar in the Walloon region of Belgium where numerous suburban residential neighbourhoods have been developed in recent decades. These neighbourhoods are characterised mainly by low-density residential housing, the mono-functionality of the developments (functionality concerns mainly housing but also commercial or industrial developments), the discontinuity with traditional urban cores and the great dependence upon cars (Halleux et al., 2002). Such suburban neighbourhoods are often developed far from city centres where land prices are lower but where public transportation is generally less available. These developments have thus created further spatial separation of activities, which results in an increase in travel distances and transport energy consumption (da Silva et al., 2007). This phenomenon is familiar in Belgium and there are numerous studies dealing with it. However, it remains difficult to spatially represent sprawl. We propose, in this paper, to adopt the definition captured by Van der Haegen and Van Hecke's urban type classification (Sporck et al., 1985; Van der Haegen et al., 1996) (Figure 1). Based on qualitative as well as quantitative data, this classification ranks the 589 Belgian municipalities (262 for the Walloon region) in four categories according to their level of functional urbanisation, morphological and functional criteria. The "operational agglomeration" was based on the morphological agglomeration, or the density of urban cores. Its limits were determined by the continuity of the building stock and adapted to administrative borders. The "suburbs" were the first suburban area of a city. The density of the population remains inferior to 500 inhabitants per square kilometre. Areas located further from the city, while maintaining a strong relationship with the city, namely through home-to-work trips (alternating migrants, or commuters, living in these areas mainly work in the corresponding operational agglomeration), constituted the “alternating migrants area.” Remaining areas were regrouped under the “other areas” term and represent rural and less dense areas located far away from main city centres as well as secondary centres. Urban sprawl is linked to the suburbs and the alternating migrants areas (Brück, 2002). Finally note that the influence of neighbouring countries and regions was not taken into account in Van der Haegen and Van Hecke’s classification.

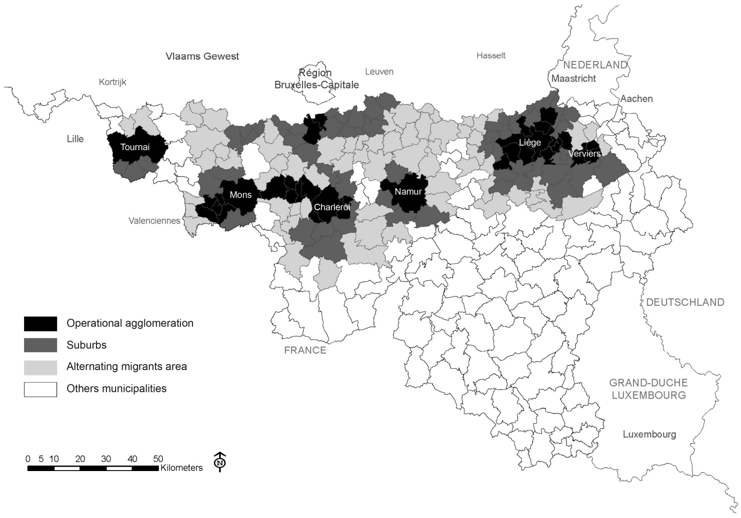

Figure 1: Urban type classification (Sporck et al., 1985; Van der Haegen et al., 1996)

The Method

A quantitative method was developed to assess the energy efficiency of home-to-work and home-to-school trips. The complete methodology and data set are presented in detail by Marique and Reiter (2012a). This method uses empirical data from Belgium’s national census, which is carried out every ten years. We used one-day travel diary data collected from male and female heads of households from the two last surveys, respectively carried out in 1991 and 2001. For these households, information about demographics, socioeconomic status, car ownership, travel distances, the main mode of transportation used and the number of days worked per week and per person is available at the individual (desegregated) scale. These data are available for both home-to-work and home-to-school trips.

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These data were also used by Boussauw and Witlox (2009) to develop a commute-energy performance index for Flanders and the Brussels Capital Region of Belgium. To build a locally specific index that is tailored to suburban areas, in addition to Boussauw and Witlox (2009) data, we took into account local characteristics of the public transport network in suburban areas (as significant differences exist between cities and suburban neighbourhoods), the type of vehicles used and the number of working days of the population in the neighbourhood. In this paper, we applied this method to the entire regional territory to investigate the relationships between the spatial structure of the Walloon region of Belgium and the transport energy consumption for home-to-work and home-to-school trips.

Three indexes are derived from this method. The energy performance index (expressed in kWh/travel.person) for a territorial unit represents the mean energy consumption for home-to-work/home-to-school trips for one worker/student living within a particular census block (district). This index takes into account the distances travelled, the means of transport used and their relative consumption rates, expressed by equation (1). In the equation, i represents the territorial unit; m the mean of transport used (diesel car, petrol car, train, bus, bike, on foot); D_{mi} the total distance travelled by the means of transport m in the district i for home-to-work (or home-to-school) trips; f_m the consumption factor attributed to means of transport m and T_i the number of workers (or students) in the territorial unit i.

$$(1)\quad \textit{Energy performance index (i)} = (\textstyle\sum_m D_{mi} * f_m) / T_i$$

Consumption factors f_m were calculated by Marique and Reiter (2012a) on the basis of regional and local data. Consumption factors are worth 0,56 kWh/person.km for a diesel car, 0,61 kWh/person.km for a petrol car, 0,45 kWh/person.km for a bus, and 0 for non-motorised means of transportation because these do not consume any energy. The consumption factor for a train was recalculated, following Teller et al. (2010). It depends on the production of electricity as trains in Belgium are electric and was calculated by dividing the total energy used to operate trains in Belgium by the total number

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of passengers-kilometres in the reference year. The consumption factor for the train is worth 0,15 kWh/person.km. Note that this is a mean value that integrates both peak and off-peak hours.

The distance index (in km) represents the mean distance travelled (one way) by one worker/student from home to work/school.

(2) *Distance index (i)* $= \sum_m D_{mi} / T_i$

$$Distance\ index\ (i) = \frac{\Sigma m\ Dmi}{Ti}$$

The modal share index (in %) represents the frequency of use for each mean of transportation per territorial unit, according to equation (3), where ND_n is the number of trips by mode n.

(3) *Modal share index mode n (i)* $= ND_n / \sum_m ND_m$ $Modal\ share\ index\ n\ (i) = \frac{NDn}{\Sigma m\ NDm}$

Indices are calculated at three territorial scale: the census block (or district) scale, the former municipality scale and the municipality scale. In addition to these indexes, the annual energy consumption for home-to-work (or home-to-school) trips is calculated according to equation (4), where TD_i represents the total number of home-to-work (or home-to-school) trips (one way) for all the workers (or students) living within the territorial unit *i*. This factor takes into account the number of working days for each worker.

(4) *Annual energy consumption (i) = Energy performance index (i)* $* TD_i$

$$Annual\ energy\ consumption\ (i) = Energy\ performance\ index\ i * TDi$$

Note that the unit of energy chosen to express the energy efficiency of home-to-work and home-to-school trips (kWh) was chosen to allow for a comparison between energy consumption in transport and energy consumption in the residential building sector (heating, appliances, electricity, etc.). This method is presented in Marique and Reiter (2012b).

SPATIAL STRUCTURE AND ENERGY CONSUMPTION FOR HOME-TO-WORK TRIPS

Figure 2 presents the energy performance index for home-to-work trips, mapped at the municipality scale (2001 data) for the Walloon region of Belgium. At first glance, the general pattern of this map is similar to Van der Haegen and Van Hecke’s urban type classification presented in Figure 1. The two main cities (operational agglomerations) of the region, Charleroi and Liège, show the lowest energy consumption rate (shown in white in Figure 2) whereas suburban and more rural or remote parts of the territory have a much higher energy consumption rate (shown in dark grey and black). The highest transport energy consumption levels are found in two suburban parts of the region: the Brabant Wallon (in the North) and the area south of Luxembourg Province (in the South). These two areas have strong relationships with the metropolitan area of Brussels and Luxembourg-city, respectively, due to the high concentration of employment in these cities. However, the price of land close to these cities is relatively high, which encourages workers to live in remote suburban neighbourhoods and commute longer distances to their places of work. Moreover, public transportation is generally less available in these low-density developments, which results in a higher modal share of the private car.

Table 1 gives the mean value of the energy performance index (kWh/travel.worker) for the three urban types and for the five biggest cities of the Region. Note that Brussels does not belong to the Walloon region, but many workers working in this city live in the Walloon region (see the yellow part on Figure 1). Table 1 highlights that transport energy consumption rises with the distance to city centres where much of the employment is concentrated. Travelled distances were also calculated for the three main urban types. These distances are shorter in operational agglomerations, as compared to the areas with less density. The modal share of the bus is higher in the operational agglomerations whereas the modal share of the train is similar in the three areas. Note that the policy of the Belgian national railway society, tend to close stations located in small towns and to reorganise its offerings around main stations and lines from west to east (Lille – Aachen, along the old industrial basin where many residents and jobs are concentrated) and from south to north (Luxembourg - Brussels).

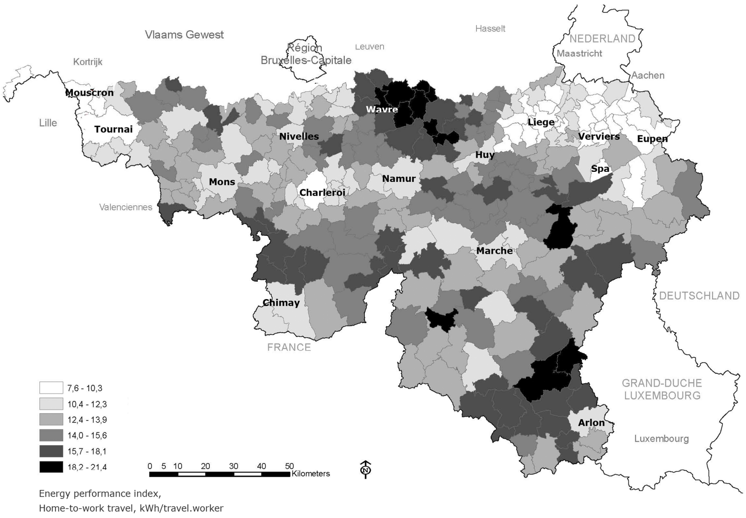

Figure 2: Energy performance index for home-to-work trips (in KWh/travel.worker) at the municipality scale; data: 2001

Table 1: Indexes for home-to-work travel (data: 2001)

	Operational agglomerations	*Suburbs*	*Alternating migrants areas*
Mean energy performance index (kWh/travel.worker)	10,4	12,9	14,2
Brussels (only the part located in the Walloon region, does not include the CBD)	11,5	12,7	15,1
Charleroi	10,3	13,5	13,9
Liège	9,4	12,7	14,0
Mons	12,2	12,9	12,0
Namur	10,8	13,8	14,2
Mean distance for one trip (km)	21,3	25,5	29,5
Mean modal share (bus)	4,0%	1,7%	1,5%

Mean modal share (train)	14,0%	12,7%	15,4%

Calculating and mapping the energy performance index for home-to-work commutes at the former municipality scale (Figure 3) and the local scale refines these initial observations. Outside the main agglomerations, several secondary municipalities and settlements (census blocks or districts) also show lower consumption rates. Most of these are cities and neighbourhoods that are located along the old industrial basin (from west to east: Mouscron, Tournai, Mons, Charleroi, Namur, Huy, Liège, Verviers and Eupen), or smaller towns in the southern, less densely populated part of the Walloon region (Chimay, Marche, Spa and Arlon). These secondary settlements are located outside the influence of the main regional cities. Population density is low, and people typically manage to find employment locally. This local-scale approach thus highlights more local phenomenon linked to the location of secondary employment centres in areas located far from major cities.

In conclusion, two distinct phenomena co-exist: the « metropolisation » and the « territorial recomposition ». Metropolisation induces higher commuting distances in the suburbs of attractive metropolises (such as Luxembourg and Brussels or, to a lesser extent, Lille (in France) and Aachen (in Germany)) where employment is concentrated. Note that these poles are all located outside the Walloon region of Belgium, and three metropolises are located outside of Belgium very close to its border. The influence area of these poles can reach 40 or 50 kilometers. The territorial recomposition occurs mainly occurs in the north part of the region (Brabant wallon) in the suburbs of Brussels. Secondary employments centers were developed over the last years and allow the local population that used to travel to Brussels for work to instead find work closer to their homes. This allows for shorter commuting distances and thus lower scores for the local energy performance index. In the case of territorial recomposition, the suburbanisation of housing is accompanied by a local re-concentration of employment.

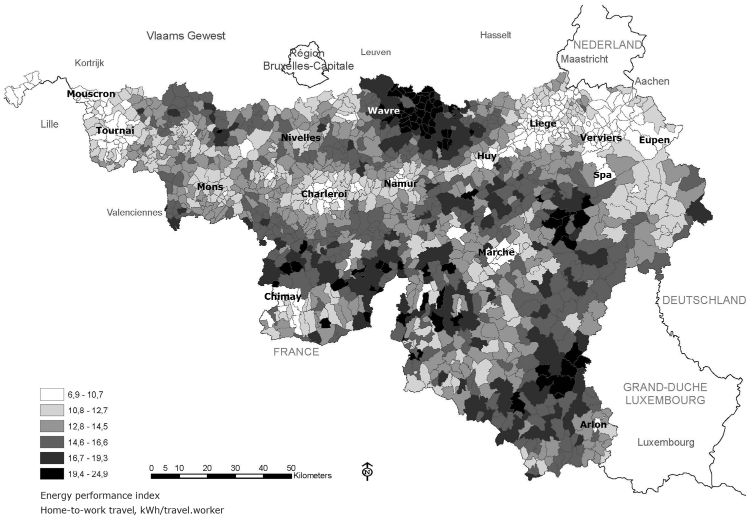

Figure 3: Energy performance index for home-to-work trips (in KWh/travel.worker) at the former municipality scale; data: 2001

The annual transport energy consumption for home-to-work trips per former municipality is mapped in Figure 4. The observations made for the energy performance index are inverted. Former municipalities with high transport energy consumption are strongly linked with areas with high density population and highlight the importance of these areas in terms of potential energy savings. The population affected by the energy-savings measures undertaken in those areas is particularly large. The total annual energy consumption for home-to-work trips in the entire region amounts to 6804 GWh.

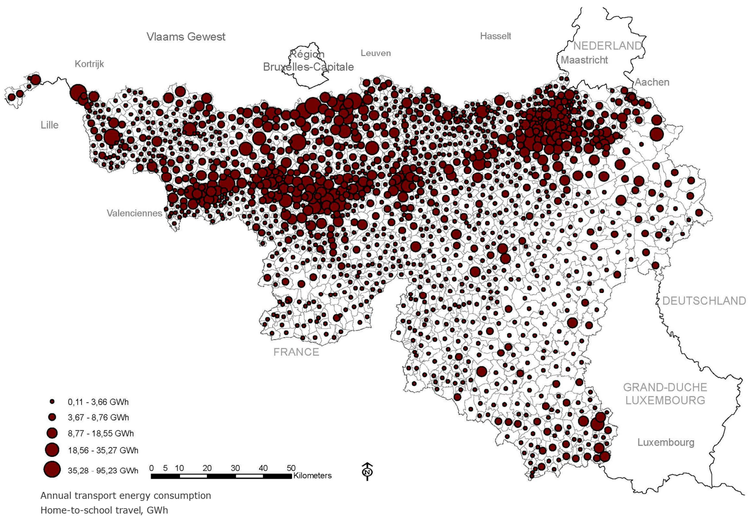

Figure 4: Annual transport energy consumption for home-to-work trips per former municipality; data: 2001

COMPARISON WITH HOME-TO-SCHOOL TRIPS

The method developed in Marique and Reiter (2012a) also allows for discussion of the energy efficiency of home-to-school trips, as data relating to these types of trips are available in the national census. Observations regarding to the relation between the transport energy consumption and the urban structure drawn for home-to-work trips, at the three territorial scales, are also valid for home-to-school trips: lowest energy performance indexes are found in dense urban former municipalities and settlements, located along the former industrial basin (Figure 5). However, home-to-school trips consume much less energy per capita and per travel than home-to-work trips, as shown in Table 2. For example, in 2001, the mean energy performance index for home-to-school trips is worth 3,5 kWh/travel.student, while the mean energy performance index for home-to-work trips was worth 12,1 kWh/travel.worker. The main explanation for this observation is that schools are spread throughout the entire regional territory, even in the most rural municipalities (rural core, suburban centres, etc., are equipped with at least one primary school). This allows for reduced distances from the homes to destinations, whereas work locations remain concentrated in main cities or suburban business centres. For example, the mean distance travelled from home to work is 24,0 kilometres, and the mean distance travelled from home to school is 8,2 kilometres.

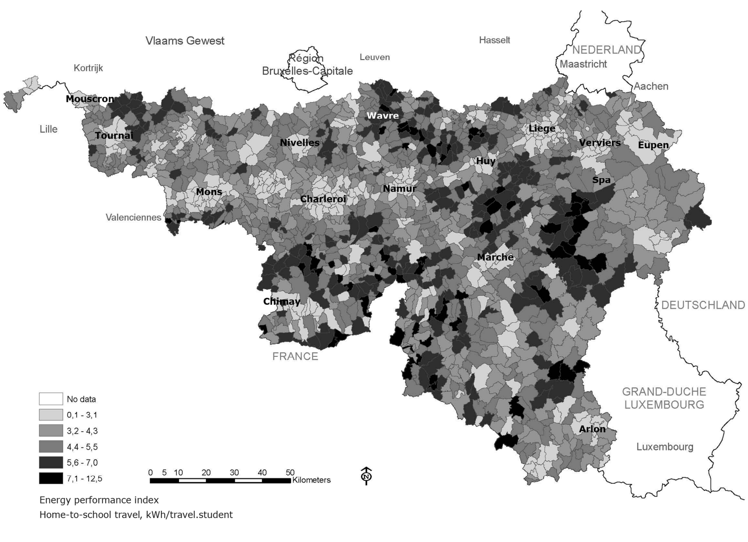

Figure 5: Energy performance index (kWh/travel.student) for home-to-school travels; data: 2001.

Table 2: Indexes for home-to-school travel (data: 2001)

	Operational agglomerations	*Suburbs*	*Alternating migrants areas*
Mean Performance index (kWh/travel.student)	2,7	4,2	4,2
Mean distance for one trip (km)	7,6	11,1	11,2

In terms of modal shares, significant differences are highlighted: the use of non-motorised means of transportation (bike, on foot) is much higher for home-to-school trips (14,7%) than for home-to-work trips (4,7%). The bus is more often used to go to school (21,8%) than to work (only 2,3 %), whereas the use of the train is more or less equivalent for these two types of commutes (6,0 % for home-to-work and 7,6 % for home-to-school). The car is the favourite means of transportation for both purposes of trips with 85,2 % for home-to-work trips and 55,8% for home-to-school trips. Furthermore, the use of car is higher in suburban areas than in central urban areas.

THE EVOLUTION BETWEEN 1991 AND 2001

The evolution of the energy performance index between 1991 and 2001 was calculated for home-to-work trips and mapped in Figure 6. A significant increase in transport energy consumption is highlighted in most former municipalities. This increase is particularly large in the south of the region (the area in relation to the metropolitan area of Luxembourg-city). Many low-density suburban neighbourhoods were developed in this area over the past decade to accommodate the rising number of people that were working in Luxembourg but were not able to pay Luxembourg's price for accommodation (Vanneste et al., 2007). These municipalities often have plenty of building land available at low prices (which is not the case in Luxembourg) but do not offer enough employment opportunities. The annual transport energy consumption for home-to-work trips was worth 5017GWh in 1991, amounting to an increase of 26.2% between 1991 and 2001. The evolution of the annual transport energy consumption for home-to-school trips follows the same trend with an increase of

23,0%, even if the annual energy consumption is lower overall (589 GWh in 1991 and 766 GWh in 2001). The use of the private car has increased for both purposes of travel (+5,2% for home-to-work and + 11,6% for home-to-school trips) to the detriment of non-motorised modes of transport and buses.

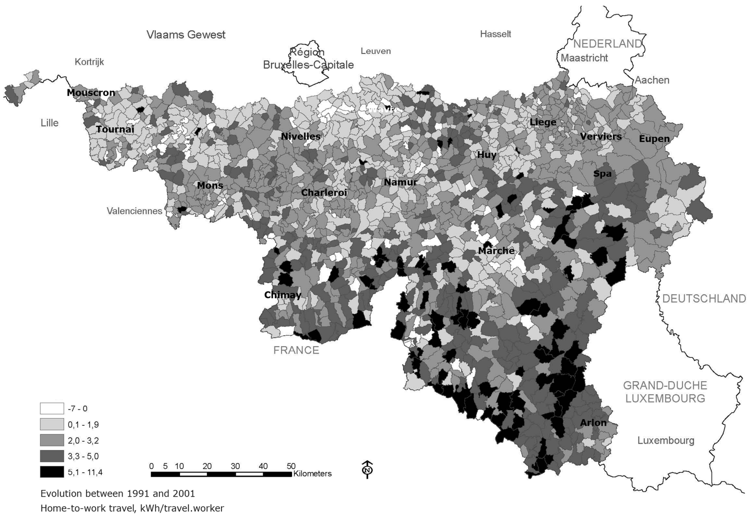

Figure 6: Difference (kWh/travel.worker) between performance indexes for home-to-work trips at the former municipality scale in 2001 and in 1991.

MAIN PARAMETERS

The general pattern of the energy performance index map is very similar to the map presenting the mean travelled distance (see Figure 7 for home-to-work trips). The energy efficiency of home-to-work and home-to-school trips is strongly determined by the distance travelled. Mode choice has less of an impact on the energy performance of those types of commutes. This can partly be explained by the relationship between distance and mode choice. The consumption factor used for the train is approximately four times lower than the consumption factors used for a private car, but trips by train are much longer than trip by car. The location of activities and a mix of functions at the living area scale are thus important strategies for promoting a reduction in transport energy consumption. Promoting more efficient public transportation in these areas could also be a credible strategy for two reasons: more energy efficient vehicles and a better occupation rate could both reduce the consumption factor for the bus.

Marique AF, Dujardin S, Teller J & Reiter S (In press) Urban sprawl, commuting and travel energy consumption. *Proceedings of the Institution of Civil Engineers – Energy*.

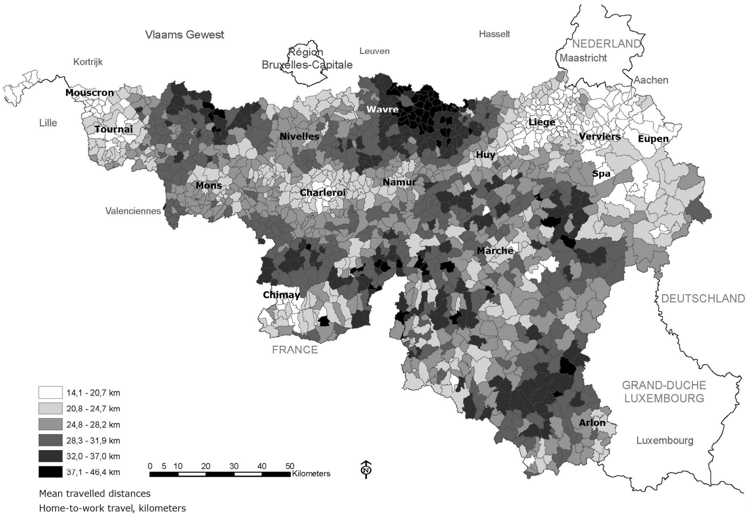

Figure 7: Mean travelled distances from home to work (in kilometres) at the former municipality scale in 2001.

DISCUSSIONS

Several limitations of the proposed method must be acknowledged. First of all, the factors used to convert kilometre per each mode of transportation into kWh are calculated for the entire territory (including urban and rural areas). Factors used for public transport are found to be slightly unfavourable as compared to urban centres. This is explained by the reduced consumption factor per person and per kilometre in urban centres because the occupancy rate of public transport is higher. Moreover, congestion in city centres and above-average speeds on non-congested motorway, which can lead to higher energy consumption rates and vehicle emission (Beevers and Carlslaw, 2005; Department for Transport, 2011; Den Tonkelaar, W. A. M.,1994) are not considered.

Secondly, even if many studies dedicated to transport and energy consumption only focus on home-to-work data because they are the most often available, a limit of the method arise from the fact that data about only two types of trips (home-to-work and home-to-school travels) are available in national censuses. Those types of travels are not representative of all trips of a household even if they play a founding role in it because they are commuting journeys and affect significantly related trips for leisure or commercial purposes. “Type-profiles” such as those performed, on smaller areas, by Saunders et al. (2008) could be developed to take into account those trips in further research.

Thirdly, although the calculations of the indexes lead to quantitative results, analyses are mainly based on visual inspections of the maps to link spatial structure of the territory and transport energy consumption, at different scales. Note that the quantitative data are necessary and that visual analysis alone can lead to misinterpretations of the results. To strengthen the qualitative visual analysis, complementary quantitative methods and techniques could be explored in further analyses. Multivariate regression analyses performed by Marique et al. (in press) for home-to-school trips confirm the qualitative findings highlighted through a qualitative assessment of map patterns

Finally, it should be mentioned that the structure of a territory is not the only parameter that influences energy consumption for commuting. The analyses presented in this paper did not take into account external factors, such as income levels, improvements of the vehicles, behaviours and lifestyles of the commuters, etc., although the authors still believe these factors may influence adults’ mobility behaviours. Due to the huge inertia of the urban structure and market forces (in particular in the neighbouring Luxembourg), major changes in the location of work places and residences can only be considered in the long term. Land use policies should namely favour the reduction of distances through a better mix of functions, at the living area scale, in areas presenting large concentration of local population and be more directives as far as the location of new work places and residences are concerned. In addition to the results presented in this paper, more efficient vehicles, alternative technologies (e.g. hybrid electric vehicles supplied by low-carbon electricity and supported, favourable tax and local charging regimes (Gibbins et al., 2007), hybrid train that uses a battery as an energy storage device (Wen et al., 2007)) and more sustainable behaviours and lifestyles related to transportation should also be encouraged to effectively reduce transport energy consumption and greenhouse gas emissions.

As far as the reproducibility of our approach is concerned, the method is parameterised and, if the same type of empirical survey data exists, it can be reproduced for other territories by adjusting parameters for vehicles, consumption factors, etc.

CONCLUSIONS AND PERSPECTIVES

Using a quantitative method developed to evaluate transport energy consumption and its application to the Walloon region of Belgium, this paper has shown that urban structure (that is to say the system defined by the location of work places and services, the spatial distribution of population according to residence and infrastructures), acts upon travel energy consumption. This study also questioned the issue of scale through an evaluation of the energy efficiency of home-to-work and home-to-school trips at several territorial scales. We have shown that a local-scale approach is useful, as it allows for a more nuanced picture of the energy performance of commuting in urban and suburban areas. The local-scale approach highlights local phenomena, particularly the existence of secondary urban cores characterised by low energy consumption inside suburban territories due to the local re-concentration of employment opportunities and sufficiently large concentration of local population. Two distinct phenomena were highlighted: the “metropolisation”, which results in a longer commuting distance in the suburbs to major employment centres (such as Luxembourg and Brussels), and the “territorial recomposition”, which tends to reduce travelled distances inside suburban or remote territories. In this respect, the current mobility policies should be more context-specific by addressing the sustainability of transport also at the local scale.

ACKNOWLEDGMENTS

This research is funded by the Walloon region of Belgium in the framework of the “Suburban Areas Favouring Energy efficiency” project (SAFE).

REFERENCES

Banister D (1992) Energy use, transport and settlement patterns. In *Sustainable Development and Urban Form* (Breheny M. (ed.)). Pion Ltd, London, UK, pp. 160-181.

Marique AF, Dujardin S, Teller J & Reiter S (In press) Urban sprawl, commuting and travel energy consumption. *Proceedings of the Institution of Civil Engineers – Energy*.

Beevers SD and Carslaw DC (2005) The impact of congestion charging on vehicle speed and its implications for assessing vehicle emissions. Atmospheric Environment **39**: 6875-6884.

Berry B and Okulicz-Kozaryn A (2009) Dissatisfaction with city life: A new look at some old questions. *Cities* **26**: 117–124.

Boarnet M and Crane R (2001) The influence of land use on travel behaviour: specification and estimation strategies. *Transportation Research Part A: Policy and Practice* **35(9)**: 823-845.

Boussauw K and Witlox F (2009) Introducing a commute-energy performance index for Flanders. *Transportation Research Part A* **43** : 580-591.

Breheny MJ and Gordon IR (1997) Urban densities, travel behavior and the limits to planning. In *Proceedings of BEPAC/EPSRC Conference on Sustainable Buildings*, Abingdon, UK, pp. 37-42.

Brück L (2002) *La périurbanisation en Belgique*. (Suburbanisation in Belgium). University of Liège, SEGEFA, Liège, Belgique.

Couch C and Karecha J (2006) Controlling urban sprawl: Some experiences from Liverpool. *Cities* **23(5)**: 353–363.

Den Tonkelaar WAM (1994) Effects of motorway speed limits on fuel consumption and emissions. *Science of The Total Environment* **146–147**: 201-207.

Department for Transport (2011) Values of Time and Operating Costs. Transport Analysis Guidance (TAG) Unit 3.5.6, London, UK.

Dujardin S, Boussauw K, Brévers F, Lambotte JM, Teller J and Witlox F (2011) Home-to-work commuting, spatial structure and energy consumption: A comparative analysis of Wallonia and Flanders. In *Proceedings of the BIVEC/GIBET Transportation Research Day* (Cornelis E. (ed)). University Press BVBA, Namur, Belgique, pp. 1-14.

European Commission (2008) *European Energy and transport – Trends to 2030*. European Commission.

European Environment Agency (2006) *Urban sprawl in Europe. The ignored challenge*. Office for Official Publications of the European Communities, Luxembourg, Report 10/2006, pp. 1-56.

Ewing RH (1994) Characteristics, causes and effects of sprawl: A literature review. *Environmental and Urban Studies* **21**: 1-15.

Marique AF, Dujardin S, Teller J & Reiter S (In press) Urban sprawl, commuting and travel energy consumption. *Proceedings of the Institution of Civil Engineers – Energy*.

Ewing R, Bartholomew K, Winkelman S, Walters J and Chen D. (2008) *Growing cooler: The evidence on urban development and climate change*. Urban Land Institute, Washington DC, USA.

Ewing RH and Cervero R (2001) Travel and the built environment: A synthesis. *Transportation Research Record* **1780**: 87-114.

Ewing RH and Cervero R (2010) Travel and the Built Environment: A Meta-Analysis. *Journal of the American Planning Association* **76(3)**: 265-294.

Gibbins J, Beaudet A, Chalmer, H and Lamperth M (2007) Electric vehicles for low-carbon transport. *Proceedings of the Institution of Civil Engineers Energy* **160 (4)**: 165-173.

Gilbert R and Perl A (2008) *Transport Revolutions: Moving People and Freight Without Oil*. Earthscan, London, UK.

Gillham O (2002) *The Limitless City: A Premier on the Urban Sprawl Debate*. Island Press, Washington DC, USA.

Glicksman LR (2007) Editorial: The Energy Crisis – The Need for More Balanced Solutions. *HVAC&R Research* **4**: 521-523.

Gordon P and Richardson H (1997) Are compact cities a desirable planning goal? *Journal of the American Planning Association* **63(1)**: 95-106.

Graham A (2000) Demand for leisure air travel and limits to growth. *Journal of Air Transport Management* **6**: 109-118.

Halleux JM, Brück L and Mairy N (2002) La périurbanisation résidentielle en Belgique à la lumière des contextes Suisse et danois : enracinement, dynamiques centrifuges et régulations collectives (Residential suburbanisation in Belgium in comparison with the danish and swiss contexts). *BELGEO* **4** : 333-354.

Howley P (2009) Attitudes towards compact city living: Towards a greater understanding of residential behavior. *Land Use Policy* **26**: 792–798.

Hubert JP (2004) Mobilité urbaine, périurbaine, rurale en Belgique : où sont les différences? (Urban, suburban and rural mobility in Belgium : where are the differences?). *Les Cahiers Scientifiques du Transport* **45** : 83-100.

Marique AF, Dujardin S, Teller J & Reiter S (In press) Urban sprawl, commuting and travel energy consumption. *Proceedings of the Institution of Civil Engineers – Energy*.

Lavadinho S and Lensel B (2010) Importons la notion de centralité en périphérie: pour une soutenable émergence de la qualité urbaine dans la Zwischenstadt (Importing centrality in the suburbs : towards sustainability and urban quality in Zwischenstadt). *Urbia* **11**: 113-143.

Marique AF and Reiter S (2012a) A method for evaluating transport energy consumption in suburban areas. *Environmental Impact Assessment Review* **33**: 1-6.

Marique AF and Reiter S (2012b) A method to evaluate the energy consumption of suburban neighbourhoods. *HVAC&R Research Journal* **18(1-2)**: 88-99.

Marique AF, Dujardin S, Teller J and Reiter S (in press) School commuting: the relationship between energy consumption and urban form. *Journal of Transport Geography*.

Neuman M (2005) The Compact City Fallacy. *Journal of Planning Education and Research* **25**: 11-26.

Newman P and Kenworthy JR (1999) *Sustainability and Cities: overcoming automobile dependence.* Island Press, Washington, USA.

OECD & IEA (2008) *World Energy Outlook 2008*. International Energy Agency, Paris, France.

Owens S (1986) *Energy, planning, and urban form*. Pion, London, UK.

Pisarski AE (2006) *Commuting in America III*. Transportation Research Board, Washington DC, USA.

Saunders MJ, Kuhnimhof T, Chlond B and da Silva ANR (2008) Incorporating transport energy into urban planning. *Transportation Research Part A* **42**: 874-882.

da Silva ANR, Costa GCF and Brondino NCM (2007) Urban sprawl and energy use for transportation in the largest Brazilian cities. *Energy for Sustainable Development* **11(3)**: 44-50.

Souche S (2010) Measuring the structural determinants of urban travel demand. *Transport policy* **17**: 127-134.

Sporck JA, Van der Haegen H and Pattyns M (1985) L'organisation spatiale de l'espace urbain. La cité belge d'aujourd'hui, quel devenir? (Spatial organization of urban space. The Belgian city today, which future ?). *Bulletin Trimestriel Crédit Communal de Belgique* **154**: 153-164.

Steemers K (2003) Energy and the city: density, buildings and transport. *Energy and Building* **35(1):** 3-14.

Teller J, Dujardin S, Labeeuw FL, Melin E and Pirart F (2010) *Structuration du territoire pour répondre aux objectifs de réduction des émissions de gaz à effet de serre* (Structuring the territory to reduce greenhouse gas emissions), Rapport CPDT 2010, p1-166.

Urban Task Force (1999) *Towards an Urban Renaissance*. Urban Task Force, Routledge, London, UK.

Van de Coevering P and Schwanen T (2006) Re-evaluating the impact of urban form on travel patterns in Europe and North-America. *Transport Policy* **13**: 229-239.

Van der Haegen H, Van Hecke E and Juchtmans G (1996) *Les regions urbaines belges en 1991* (Belgian urban regions in 1991). Etudes statistiques de l'INS, Report INS 104.

Vanneste D, Thomas I and Goossens L (2007) Woning en Woonomgeving in Belgïe. *Housing and Built Environment in Belgium*. SPF Economy and Statistics, SPT Scientific Policy, Brussels, Belgium.

Van Wee B (2002) Land use and transport: research and policy challenges. *Journal of Transport Geography* **10**: 259-271.

Wen Q, Kingsley S and Smith RA (2007) Energy simulation of hybrid inter-city trains. *Proceedings of the Institution of Civil Engineers - Energy* **160(3)**: 123-131.

Appendix A.5

Energy and Buildings 82 (2014) 114–122

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

A simplified framework to assess the feasibility of zero-energy at the neighbourhood/community scale

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ARTICLE INFO

Article history:
Received 7 March 2014
Received in revised form 13 June 2014
Accepted 1 July 2014
Available online 9 July 2014

Keywords:
Zero-energy building
Zero-energy community
Zero-energy neighbourhood
Daily mobility
On-site renewable energy
Urban form
Building stock
Retrofitting
Energy mutualisation

ABSTRACT

Zero-energy buildings (ZEBs) are attracting increasing interest internationally in policies aiming at a more sustainably built environment, the scientific literature and practical applications. Although “zero energy” can be considered at different scales (e.g., community, city), the most common approach adopts only the perspective of the individual building. Moreover, the feasibility of this objective is not really addressed, especially as far as the retrofitting of the existing building stock is concerned. Therefore, this paper aims first to investigate the opportunity to extend the “zero-energy building” concept to the neighbourhood scale by taking into account two main challenges: (1) the impact of urban form on energy needs and the on-site production of renewable energy and (2) the impact of location on transportation energy consumption. It proposes a simplified framework and a calculation method that is then applied to two representative case studies (one urban neighbourhood and one rural neighbourhood) to investigate the feasibility of zero-energy in existing neighbourhoods. The main parameters that act upon the energy balance are identified. The potential of “energy mutualisation” at the neighbourhood scale is highlighted. This paper thereby shows the potentialities of an integrated approach linking transportation and building energy consumptions.

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1. Introduction

1.1. Zero-energy at the building scale

The building sector is a major consumer of energy worldwide [1–3]. For example, it represents over 40% of the overall energy consumed in the European Union [1–3]. In the current context of growing interest in environmental issues, reducing energy consumption in the building sector is an important policy target. Politicians, stakeholders and even citizens are now aware of the issue of energy consumption in buildings, especially as a result of the passage of the European Energy Performance of Buildings Directive and its adaptation to the Member States. Its main aim was to establish minimum standards for the energy performance of new buildings and existing buildings larger than 1000 m^2 subject to major renovation [4]. Another major trend commonly proposed to reduce the energy consumption of the existing building stock is the improvement of the thermal performance of the envelope of existing buildings (sometimes in combination with more efficient heating/ventilation systems) [1,3]. As a result, new construction and renovation standards ((very) low-energy standards, passive house standards) [5–7] have been developed to drastically minimise the energy consumption of new and retrofitted buildings and the associated greenhouse gas emissions. During the last few years, “zero-energy buildings” have aroused increasing interest internationally in the scientific literature (e.g., [8–14]), policies aiming at a more sustainable built environment and even concrete applications.

In the literature, the “zero-energy” objective is most often considered on the building scale. Although existing definitions are commonly articulated around an annual energy balance equal to zero (the energy demand of the building is compensated by its renewable production) [10,11], numerous differences exist and several definitions coexist [8,12] depending on such elements as specific local conditions, political targets, connection (or not) to the grid and measures to address energy efficiency before using renewable energy sources. The “zero-energy building” (ZEB) is presented as a general concept that also includes autonomous buildings not connected to energy grids. The term “net zero-energy building” (nZEB) “*underlines the fact that there is a balance between energy taken from and supplied back to the energy grids over a period of time, nominally a year*” [8, p. 220]. The concept of a “nearly zero-energy building” is presented by the European Directive on the energy performance of buildings [15] as a “*building that has a very good energy*

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http://dx.doi.org/10.1016/j.enbuild.2014.07.006
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performance. The nearly zero energy or very low amount of energy required should be supplied to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby".

Other derived concepts are also found in the literature based on various balance metrics [9]. For example, Torcellini and Crawley [9] defined four net zero-energy building balances (net zero primary energy, net zero site energy, net zero energy cost and net zero emissions) and Mohamed et al. [16] investigated them for a single-family house with different heating alternatives. For Voss et al. [10,17], a clear definition, standardised balancing method and international agreements on the meaning of "zero-energy building" (ZEB) are lacking.

To address this issue, Marszal et al. [12] recently proposed a review of the existing ZEB definitions and various calculation methodologies. They highlighted seven main issues to be addressed in further definitions: the metric of the balance, the balancing period, the type of energy use included in the balance, the type of energy balance, the acceptable renewable energy supply options, the connection to the energy infrastructure and finally the requirements for the energy efficiency, the indoor climate and, in the case of grid-connected ZEB, the building-grid interaction. Amongst the more complete existing approaches, Sartori et al. [8] developed a systematic, comprehensive and consistent definition framework for "net zero-energy buildings". They considered "*all the relevant aspects charactering net ZEB and aims at allowing each country to define a consistent (and comparable with others) net ZEB definition in accordance with the country's political targets and specific conditions*" [8, p. 221]. This framework is articulated around two types of annual balances: the import/export balance (balance between delivered and exporter energy) and the load/generation balance (balance between load and generation). The monthly net balance can also be determined according to the same philosophy [8]. Voss et al. also [10] proposed a harmonised terminology and balancing procedure that takes into account the energy balance as well as the energy efficiency and load matching and highlighted that "*it is the optimisation and not the maximisation of electricity exported to the grid that is an essential planning goal for net zero-energy buildings, in addition to the reduction of energy consumption*" [10, p. 55]. These authors proposed a new label (ZEB *x*) allowing the distinction between the need for seasonal compensation (the lower the "*x*" value, the lower this need for compensation). In the same vein, Srinivasan et al. [18] introduced a "renewable emergy balance" as a tool to ensure that buildings are optimised for the reduced consumption of resources and that the use of renewable resources and materials is optimised over the entire lifecycle of the building. Pless and Torcellini [11] ranked the renewable energy sources used in a building to propose a classification grading system for ZEB, based on renewable energy supply options. The goal of this work is to encourage, first, the utilisation of all possible energy-efficient strategies and, then, the use of renewable energy sources and technologies located on the building [19]. Attia et al. [20] developed one of the only decision support building simulation tools that can be used as a proactive guide in the early design stages of residential net zero-energy building design. This tool is designed for a hot climate (Egypt) and allows for the sensitivity analysis of possible variations of nZEB design parameters and elements to inform the decision-making process by illustrating how these variations can affect comfort and energy performance.

As far as policies are concerned, the ZEB is currently receiving an increasing amount of attention in several countries [12–14]. In Europe, the recasting of the European Performance of Buildings Directive (EPBD) requires all new buildings, built in Member States, to be "nearly zero-energy" buildings (nZEB) by 2020. As a consequence, Member States are currently implementing this objective into their own national regulations [14]. The zero objective will then be extended to existing buildings undergoing major retrofitting works [15]. In the United States of America, the Energy Independence and Security Act (2007) [21], which concerns the energy policy of the entire country, aims to create a nationwide net zero-energy initiative for houses built after 2020 and commercial buildings built after 2025. The Asia-Pacific Partnership on Clean Development and Climate, a public-private partnership of seven countries (Australia, Canada, China, India, Japan, South Korea and the United States of America), aims also at promoting the development of net zero energy homes [13].

In practice, several buildings have recently been built that prove that "zero energy", at the building scale, is feasible. Most of these existing zero-energy buildings are (small or large) residential buildings and office buildings [17,22]. Fong and Lee [23] showed that the net zero-energy target seems not to be possible for high-rise buildings in Hong Kong. However, they note that it is feasible for low-rise residential buildings in this subtropical climate.

1.2. Zero energy at the neighbourhood/community scale

Generally speaking, most papers investigating energy issues at the neighbourhood/community scale focus on either the impact of urban form on energy consumption in buildings [e.g., 24–26] or the potential of solar energy utilisation for active and passive solar heating as well as photovoltaic electricity production, lighting and related energy supply and demand [e.g., 27–30]. Hachem et al. [31] studied and compared the electricity generation potential of neighbourhoods and their energy performance in terms of heating and cooling and found out that a significant increase in total electricity generation can be achieved by the building integrated photovoltaic systems of housing units of certain shape-site configurations, as compared to their reference case. They also highlighted that the energy load of a building is affected by its orientation and shape. The impact of urban form on transportation energy consumption has also be widely highlighted in the literature, but it is considered either alone [e.g., 32–36] or, in a few studies, in comparison with building energy consumption [e.g., 37–39].

Studies and reports dealing with zero energy at the neighbourhood/community scales are few in number. The framework proposed by Sartori et al. [8] can also be applied to a cluster of buildings. Kennedy and Sgouridis [40] addressed the question of how to define a zero-carbon, low-carbon or carbon-neutral urban development by proposing hierarchical emissions categories. Todorovic [41] investigated the role of simulation tools in the framework of zero-energy urban planning. The National Renewable Energy Laboratory [19, p. 4] defined, in a technical report, a "zero net energy" community (ZEC) as "*one that has greatly reduced energy needs through efficiency gain such that the balance of energy for vehicles, thermal, and electrical energy within the community is met by renewable energy*". They highlighted [19, p. 1] that "*community scenarios could link transportation, home and the electric grid as well as enable large quantities of renewable power onto the grid*". They also applied the ZEB hierarchical renewable classification proposed by Pless and Torcellini [11] to the concept of community to focus on the mode and location of production of renewables. A community that met the zero energy definition thanks to renewable energies produced within its built environment (or in brownfields) is at the top of the classification (rank A) whereas a community that met the definition through the purchase of renewable energy certificates is ranked C.

Although not specifically dedicated to the "Zero-energy" objectives, several neighbourhood sustainability assessment tools have recently been developed [42]. Examples of these NSA tools are, amongst others, the STAR Community Rating System (Sustainability Tools for Assessing and Rating Communities) [43] and the US Green Building Council's LEED-ND (Leadership in Energy and Environmental Design—Neighbourhood Development) [44] in the

United States, BREEAM Communities (BRE Environmental Assessment Method) in the United Kingdom [45], HQE2R (Haute Qualité Environnementale et Économique dans la Réhabilitation des bâtiments et le Renouvellement des quartiers) in France [46] and CASBEE-UD (Comprehensive Assessment System for Built Environment Efficiency–Urban environment) in Japan [47]. These tools aim to assess and rate communities and neighbourhoods against a set of defined criteria and themes. They propose a checklist of criteria (mainly optional) and a range of various guidelines to help local stakeholders, designers and citizens move towards more sustainability. Although they all include a large theme dedicated to energy, they neither allow a quantitative assessment of energy consumption or GHG emissions nor the evaluation of the energy efficiency of retrofitting scenarios.

As far as concrete projects are concerned, the West Village is a net zero-energy community, including 662 apartments and 343 single-family homes, under construction in Davis, California [48,49]. Another interesting development at the neighbourhood scale is the Beddington Zero (fossil) Energy Development (BedZED) sustainable neighbourhood, which was intended to be the UK's largest mixed-use zero-carbon community. However, the zero objective was not achieved. Others examples of very low energy neighbourhoods include Hammarby Sjosjad, Augustenborg and BO01 in Sweden, Vauban and Kronsberg in Germany, Eva-Lanxmeer in the Netherlands and Vesterbro in Denmark [50]. Finally, IEA-EBC (International Energy Agency's Energy in Buildings and Communities Programme) has currently a few Annexes/projects on zero-energy communities [22].

1.3. Aim of the paper

This paper aims to complete the existing approaches relating to “zero energy” by developing and investigating the opportunities linked to a new simplified framework dedicated to “zero-energy neighbourhoods” and articulated around the following three main challenges:

(1) The major challenge of the adaptation and retrofitting of the existing building stock (especially in the large part of Europe in which the renewal rate of the existing building stock is quite low), in complementarity with the numerous studies dealing with the production of new optimised buildings and communities, and the concrete feasibility of zero-energy in retrofitting.
(2) The impacts of parameters linked to the urban form on the energy efficiency of single buildings as well as on the choice and efficiency of on-site renewable energy sources (e.g., the possible mutualisation of energy supply and demand between individual buildings).
(3) The impact of the location of residences, work places and services on daily mobility patterns and their related energy consumption, which are considered together with building energy consumption because building or retrofitting very efficient buildings could be counterproductive if its location does not allow alternatives to private cars for daily mobility (travel to work, school, shops, etc.) and imposes long travel distances.

As architects and urban planners, we are particularly interested in investigating the possibilities to adapt the existing building stock in order to reach an annual zero-energy balance, at the neighbourhood scale, and in highlighting the main urban and architectural parameters that act upon the energy balance of a neighbourhood. Thus, in the following, we will take into account three main themes directly related to the urban form of existing neighbourhoods: building energy consumption, the on-site production of renewable energies and transportation energy consumption of inhabitants (in order to take into account the location of activities on the territory in the balance).

1.4. Content of the paper

To this extent, Section 2 proposes a simplified framework and a calculation method to assess zero-energy neighbourhoods. An application of the proposed framework is then developed in Section 3 to test its applicability, investigate the feasibility of zero-energy in retrofitting neighbourhoods and highlight key parameters in the annual energy balance of two representative neighbourhoods (in Belgium). Section 4 discusses key challenges to be addressed and perspectives to be investigated in future research. Finally, the research findings and strengths and weaknesses of the proposed framework are summarised in Section 5.

2. A simplified net “zero-energy neighbourhood” framework: method and assumptions

The net “zero-energy neighbourhood” framework (nZEN) proposed in the scope of this paper aims to articulate the three main energy uses (building energy consumption, the production of on-site renewable energy and transportation energy consumption for daily mobility), at the neighbourhood scale. A neighbourhood is understood here as an “urban block” (that is to say the smallest area of a city that is surrounded by streets) or a group of several “urban blocks”. We only consider residential neighbourhoods although the general methodology could be extended to industries, shops, etc. Also note that public services energy uses in a neighbourhood (e.g., street lighting, traffic lights) are not assessed. A previous research [38] namely showed that street lighting energy consumption is minimal in comparison with building and transportation energy consumptions.

The nZEN is here described as a neighbourhood in which the annual energy consumption for buildings and transportation of inhabitants is balanced by the production of on-site renewable energy. The main balance is annual, but monthly, daily or hourly balances could also be studied according to the same definitions to better capture the gaps between energy consumption and production by renewable sources. As far as the metric of the system is concerned, the balances are proposed in terms of primary energy. The conversion factors used to convert gross energy into primary energy are 1 for natural gas and petrol and 2.5 for electricity, as stated in the Walloon regulation on the energy performance of buildings [51]. Only the use phase of the neighbourhood is taken into account in these balances (construction and deconstruction phases are not assessed). Note also that a net zero-energy neighbourhood implies interactions among the buildings in the neighbourhood and between the building and transportation energy consumptions. The zero-energy balance is thus considered as a whole, and each building is not necessarily a zero-energy building. Finally, we assume that the neighbourhood has an electric grid that can provide energy to the neighbourhood when on-site generation from renewables is lower than the load. If greater, the on-site production can be sent to the grid.

2.1. Energy consumption in buildings

The methodology used to assess building energy consumption takes into account the annual energy consumption for space heating (E_{SH}), space cooling (E_{CO}), ventilation (E_V), appliances (E_A), cooking (E_C) and domestic hot water (E_{HW}). The neighbourhood's annual energy consumption for buildings (E_B) is calculated using Eq. (1).

$$E_B = E_{SH} + E_{CO} + E_V + E_A + E_C + E_{HW} \quad (1)$$

2.1.1. Energy consumption for space heating, cooling and ventilation

The method developed to assess energy consumption for space heating, cooling and ventilation was extensively presented in a previous paper [38]. This method combines a typological classification of buildings and neighbourhoods and thermal dynamic simulations. This typological approach classified the residential building stock of Belgium and was based on the following factors: common ownership (detached, semi-detached or terraced houses, apartments), the heated area of the dwelling in square meters (m^2), the heating and ventilation systems, the date of construction and the level of insulation, including retrofitting works performed by the owners (e.g., insulation of the roof and/or replacement of the glazing, change of the heating and/or ventilation systems). Thermal simulations were performed for all of the dwelling types of this typological classification of buildings. The results of these energy simulations (E_{SH} and E_V) are stored in a database comprised of the energy consumption of approximately 250,000 buildings. In these thermal simulations, Brussels meteorological data (temperate climate) are used. The minimum temperature in the dwellings is 18 °C, and internal gains are defined according to the surface area of the dwelling. A correction factor is applied to available solar gain according to the neighbourhood type to take into account the reduction of solar gains with increased built density. The net and gross energy consumption and primary energy consumption for space heating, cooling and ventilation at the neighbourhood scale are finally calculated by adding the results from the energy consumption analysis for each type of house according to their distribution in the neighbourhood and the neighbourhood type. Cooling (E_{CO}) is not taken into account in the case studies presented in Section 3, in accordance with regional yearbooks [52]. Moreover, the overheating indicator defined in the European Energy Performance of Building Directive [4] as the ratio between the solar and internal gains of a building to transmission and ventilation losses was calculated by [38] for Walloon residential buildings. It remains under the threshold value proposed in the Directive (29.8% under the threshold value for the worst cases), which indicate that the overheating is not unacceptable and does not require the installation of cooling system [4].

2.1.2. Energy consumption for appliances, cooking and domestic hot water

The annual energy consumptions related to appliances (E_A), cooking (E_C) and domestic hot water (E_{HW}) are assumed to depend on the number of inhabitants in the building. In the following application, regional mean values, gathered by a regional institute in charge of environment (the "Cellule Etat de l'Environnement Wallon" [53]), are used; however, in situ surveys could also be implemented in the model. The energy consumptions related to appliances and cooking are 1048 kWh per person per year and 170 kWh per person per year, respectively [53]. The energy consumption for heating water is obtained by multiplying the volume of hot water needed annually at the neighbourhood scale (m^3) by the difference in temperature between cold and hot water and a conversion factor, used to convert kilocalorie into watt-hour. This factor is worth 1.163 kWh/m^3 °C [54]. We consider each inhabitant to need 100 l of cold water (10 °C) and 40 l of hot water (60 °C) per day, in accordance with the regional trends [53].

2.2. Energy consumption for daily mobility

The annual energy consumption for daily mobility (E_{DM}) is assessed using a performance index introduced by Boussauw and Witlox [55] and adapted by Marique and Reiter [56]. This index is expressed in kWh/travel per person and represents, for a territorial unit, the mean energy consumption for travelling for one person living within a particular neighbourhood. This index takes into account the distances travelled, the means of transportation used and their relative consumption rates, as expressed by Eq. (2). In the equation, i represents the territorial unit; m the means of transportation used (diesel car, gasoline car, train, bus, bike, walking); D_{mi} the total distance travelled by the means of transportation m in territorial unit i; f_m the consumption factor attributed to the means of transportation m; and T_i the number of persons in the territorial unit i. The consumption factors depend upon the consumption of the vehicles (litres of fuel per kilometre) and their occupation rate. In the Belgian context [56], these values are 0.56 kWh/person per km for a diesel car, 0.61 kWh/person per km for a non-diesel car, 0.45 kWh/person per km for a bus, 0.15 kWh/person per km for a train and 0 for non-motorised means of transportation, as the latter do not consume any energy [56].

$$\text{Energy performance index } (i) = \sum_{m} \frac{D_{mi} f_m}{T_i} \tag{2}$$

The energy consumption for daily mobility (E_{DM}) is obtained using Eq. (3) by multiplying the energy performance index by the number of people (N) and the number of trips (T) in the neighbourhood.

$$E_{DM} = \text{Energy performance index} \times NT \tag{3}$$

In our nZEN framework, we attribute all travels to and from work and to and from school to the neighbourhood (rather than the portion that is really consumed within the neighborhood) to focus on the impact of residential locations on transportation energy consumption.

Data used in the following case studies come from a national census carried out in Belgium (the General Socio-Economic Survey 2001 [57]). Note that these data only concern home-to-work and home-to-school travel; however, we could use the same methodology with data from an in situ survey account for all travel purpose.

2.3. On-site energy production by renewable sources

On-site energy production via photovoltaic panels (E_{PV}), thermal panels (E_{TH}) and small wind turbines (E_{WT}) are considered when accounting for renewable energy sources. The annual renewable energy produced in the neighbourhood (E_{RP}) is calculated using equation 4.

$$E_{RP} = E_{PV} + E_{TH} + E_{WT} \tag{4}$$

2.3.1. Photovoltaic panels (electricity)

The potential of neighbourhoods for active solar heating and photovoltaic electricity production is obtained using numerical simulations performed with Townscope software [58]. Only photovoltaic panels on roofs are considered because those on facades are less effective in Belgium [59]. Townscope allows the calculation of the direct, diffuse and reflecting solar radiation reaching a point and the radiation distribution on a surface. As calculations are performed under clear-sky conditions, the software is used to determine a first correction factor M (the difference between the values calculated for the assessed neighbourhood and the clean site) to apply to the mean solar radiation MSR for the considered latitude (MSR = 1000 kWh/m^2·year for Belgium [60]). A second factor F is applied to take into account the roof orientation and inclination (Table 1) [61].

The solar energy received by the considered surface is obtained using Eq. (5). The potential of roofs for photovoltaic electricity production (E_{PV}, in kWh per year) is obtained by Eq. (6). In Eq. (6), S represents the surface area of the considered roofs, C the percentage of the roofs covered by panels (maximum 0.80), η_{pv} the efficiency of the photovoltaic panels, η_{inv} the efficiency of the inverter and

Table 1
Values of the correction factor F, which accounts for roof orientation and inclination [61].

		Inclination				
		0°	15°	25°	35°	50°
Orientation	East	0.88	0.87	0.85	0.83	0.77
	Southeast	0.88	0.93	0.95	0.95	0.92
	South	0.88	0.96	0.99	1	0.98
	Southwest	0.88	0.93	0.95	0.95	0.92
	West	0.88	0.87	0.85	0.82	0.76

λ a correction factor taking into account electricity losses. In the following case studies, the efficiency of the photovoltaic panels is fixed at 0.145, the efficiency of the inverter at 0.96 and the electricity loss correction factor at 0.2; in accordance to the technical characteristics of the most used type of panels in Wallonia [62].

$$E_{sol} = \mathrm{MSR} \times FM \,(\text{in} \quad \mathrm{kWh/m^2 year}) \tag{5}$$

$$E_{PV} = E_{sol} S C \eta_{pv}(1-) \tag{6}$$

2.3.2. Thermal panels (hot water)

The solar energy received annually by the roof is obtained using Eq. (5), where correction factor M is calculated with Townscope and correction factor F is defined according to Table 1. Eq. (7) allows the determination of whether the roofs of the houses of the neighbourhoods are adapted to the production of hot water. In Eq. (7), E_{sol} represents the solar energy received by the roofs, S the surface area of the panel and η_{th} the efficiency of the thermal panels. We consider that 55% of the production of hot water of each household must be covered through thermal panels (from a technical-economic viewpoint, the optimum is often considered to be between 50% and 60%). Under these conditions, the efficiency of the system is 0.35.

$$E_{TH} = E_{sol} S \eta_{th} \tag{7}$$

2.3.3. Wind turbines

The approximation used to evaluate the annual electricity production of wind turbines (E_{WT}) consists of multiplying the rated power of the wind turbine by the number of operating hours at this rated power, as in Eq. (8), in which P is the rated power of the wind turbine and OH the number of operating hours. This value is fixed at 1000 h for a small wind turbine [63].

$$E_{WT} = P \cdot \mathrm{OH} \tag{8}$$

2.4. Annual balance at the neighbourhood scale

The annual energy consumption of the neighbourhood (E_N) is calculated by adding the building energy consumption (E_B) and transportation energy consumption (E_{DM}) and subtracting the on-site renewable energy production (E_{RP}), as shown in Eq. (9).

$$E_N = E_B + E_{DM} - E_{RP} \tag{9}$$

The monthly balances can also be studied according to the same type of equation by replacing the annual energy consumption and production by the corresponding monthly values.

3. Results

3.1. Presentation of the case studies

The case studies chosen are two common archetypes of neighbourhoods (understood as urban blocks, that is to say the smallest area of a city that is surrounded by streets) and are representative of the building stock in Belgium [64]. The two neighbourhoods contain essentially the same number of buildings but in a very different urban form. Each urban form presents its own specificities and characteristics, especially as far as the built density and the types of buildings are concerned, as highlighted on Table 2, and requires personalised solutions regarding the energy efficiency in the building and transportation sectors and the on-site production of renewable energy.

Table 2
Main characteristics of the two case studies.

	Case 1	Case 2
Type	Urban	Suburban
Surface area	0.97 ha	12.02 ha
Population	180 inhabitants	150 inhabitants
Buildings	57	55
Detached houses	7%	75%
Semi-detached houses	17.5%	19.6%
Terraced houses	75.5%	3.6%
Apartments	0%	1.8%
Density	60 dw/ha	5 dw/ha
% of the surface area occupied by buildings	29%	5%

The first case study (Fig. 1) is a dense neighbourhood (60 dwellings per hectare) representative of an old compact industrial urban fabric. This neighbourhood is located close to good transportation networks (trains and buses), work places, schools, shops and services. Buildings are very poorly insulated, because the neighbourhood was built in the 19th century.

The second case study (Fig. 2) is a low-density suburban neighbourhood (5 dwellings per hectare) located in the suburbs (18 km) of the city centre. It is representative of the urban sprawl that began in Belgium in the 1960s. Public transportation is minimal, and car dependency is high. The neighbourhood is comprised of detached houses built between 1930 and 2010. Some retrofitting works (changing of the glazing, roof insulation) has been performed by the owners.

3.2. Annual energy balance

In the current situation, the energy consumption for space heating is quite large in both neighbourhoods (184 kWh/m^2 per year in case 1 and 235 kWh/m^2 per year in case 2), and the annual zero-energy balance cannot be achieved (Table 3). A clear difference is observed between the heating energy requirements of the two neighbourhoods because the first is made up terraced houses, which consume approximately 25% less energy for heating than the less compact urban form. Similarly to the building scale, to

Fig. 1. Case study 1—a representative urban residential neighbourhood (Belgium).

Table 3
Results of the application of the "zero-energy neighbourhood" framework to the two case studies.

		Case study 1	Case study 2
Consumption (kWh)	Space heating and ventilation: *ESH* + *Ev*	1,421,694	2,754,341
	(*ESH* + *Ev*—low-energy retrofitting)	(463,595)	(703,235)
	(*ESH* + *Ev*—passive retrofitting)	(143,156)	(214,074)
	Appliances: *EA*	161,139	155,485
	Cooking: *EC*	26,277	25,355
	Hot water: *EHW*	152,950	127,458
	Daily mobility: *EDM*	339,696	441,072
Production (kWh)	Photovoltaic elec.: *EPV*	139,945	314,669
	Hot water heating: *ETH*	80,417	67,170
	Wind turbine: *EWT*	0	50,000

Fig. 2. Case study 2—a representative suburban residential neighbourhood (Belgium).

achieve a net zero-energy balance at the neighbourhood scale, the energy demand (heating in these case studies herein) must be reduced using energy efficiency measures (a major retrofitting of the envelope of the building). The result must satisfy the (very) low, passive or net zero-energy standards. Moreover, the results show that the zero-energy neighbourhood objective also needs to minimise the energy needs for appliances, cooking and hot water. It is important to emphasise the influence of less energy-consuming devices as well as adapted user behaviours and lifestyles, parameters that have already been studied in detail in other references (e.g., [65–67]).

Energy consumption for daily mobility is also higher (approximately 30%) in the suburban neighbourhood, which is highly dependent on private cars and for which travel for work and school is across large distances. Taking into account energy consumption from daily mobility, as highlighted in our assumptions, the impact of the location of the neighbourhood can be included in the annual balance. This is crucial to avoid simply proposing building or retrofitting zero-energy buildings and neighbourhoods as the optimal solution to create a more sustainable built environment, regardless of their location and the impact of this location on transportation energy consumption. Moreover, the results show that the zero-energy neighbourhood objective also requires the minimisation of the energy needs for daily mobility, even in urban areas.

In contrast, as far as on-site renewable energy production is concerned, the photovoltaic production is higher in the suburban neighbourhood (case 2) because simulations performed with Townscope to calculate solar radiation on roofs (see Section 2.3.1, above) have shown that the shadowing effect is much lower in this area than in the dense neighbourhood (case 1). Quite interestingly, parametric variations show that if photovoltaic panels are only located on roofs that receive over 90% of the maximum solar energy and if the electricity production is mutualised at the neighbourhood scale, the efficiency (kWh produced per m^2 of panel) increases significantly (+10.7% in case 1 and +5.0% in case 2). The same amount of photovoltaic electricity can thus be produced by installing fewer panels than reported in Table 3, where photovoltaic panels were installed on each building. Thermal energy production is higher in case 1 thanks to the surface areas of the roofs but simulations performed to assess solar radiation on roofs (see Section 2.3.1, above) have shown that the shadowing effect is much lower in the suburban area.

The use of wind turbines in the first case study was not assessed because of the dense context in which it is located. In the suburban case, a small wind turbine produces approximately 50,000 kWh annually. This wind turbine could be located in the centre of the neighbourhood because this location is sufficiently far from existing houses (based on the noise produced by the turbine and the existing regulations); however, this solution would prohibit the future densification of the neighbourhood, which is a possible solution to increasing the sustainability of existing suburban blocks.

In comparison with building and transportation energy consumption, and for the considered climate and context, the on-site generation of renewable energy is often limited, especially in the dense case study. The zero-energy balance cannot be achieved, even if buildings are retrofitted to the passive standard. Therein, intermediate levels of performance (the [very] low, passive or net zero-energy neighbourhoods) could also be promoted, especially as far as interventions in existing neighbourhoods are concerned. Rather than the respect of a zero-energy annual balance, it seems important to promote, above all, the minimisation of building and transportation energy consumptions and the maximisation of renewable energy production.

3.3. Monthly energy balances

An annual balance was used first in this paper. Yearly balances account for the succession of the four seasons and their particularities. However, it is also interesting to investigate shorter periods of time. Monthly production and consumption curves highlight the shift between the production and consumption peaks and between supply and demand, particularly for solar energy (highest in summer) and heating consumption (highest in winter), as highlighted in Fig. 3.

4. Discussion and perspectives for further research

Achieving a net zero-energy balance in the two existing neighbourhoods is very difficult, namely because the building stock

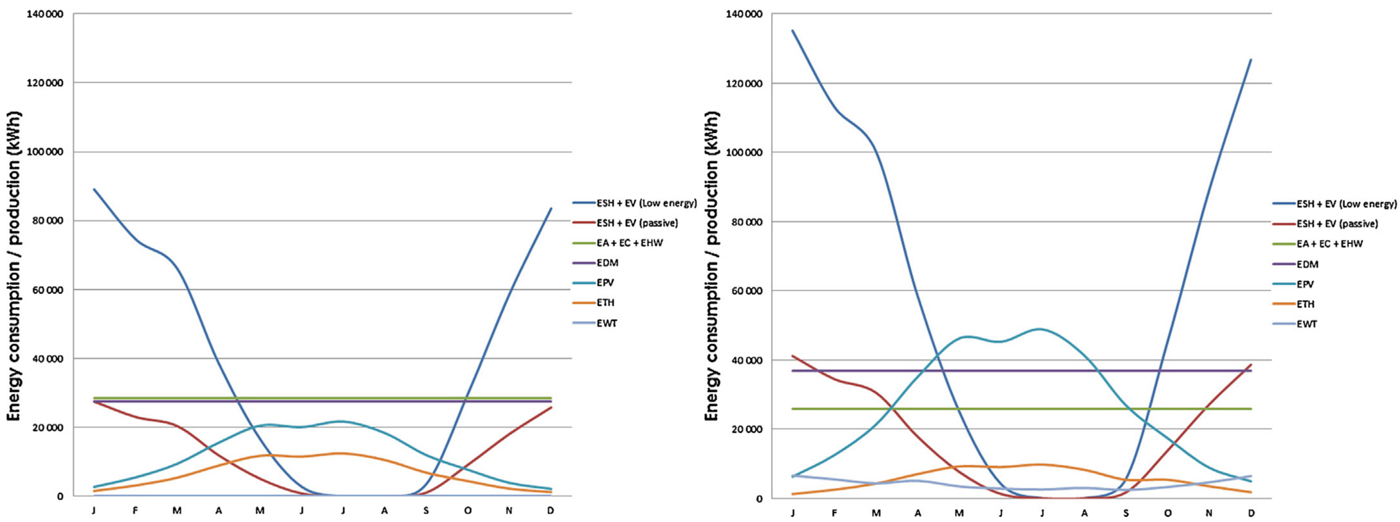

Fig. 3. Monthly production and consumption curves for the two case studies (case study 1 on the left and case study 2 on the right).

is poorly insulated. Intermediate milestone and targets could be proposed to help local communities to move towards more sustainability:

1. Improve the energy efficiency of the building stock (e.g., retrofitting to the passive house standard).
2. Minimize energy demand for buildings and for transportation through occupant behaviour (e.g., adapting the inner temperature of the dwellings, promoting car sharing).
3. Maximise on-site renewable energy production (e.g., installing PV panels).
4. Use off-site renewable energy production (e.g., using district heating and imported renewable energy).

As we highlighted significant differences between the urban and the suburban case studies, these milestones should be differentiated, according to the local opportunities in each neighbourhood.

In this course to reach sustainability in existing neighbourhoods, one of the main advantages of the neighbourhood scale is the potential for an "energy mutualisation" for both energy production and energy consumption. We have namely highlighted the interest of producing photovoltaic electricity at the neighbourhood, rather than at the individual scale. Another example was the pooling of the built envelope in dense urban neighbourhoods that allows to reduce energy needs of terraced houses, in comparison with detached houses. This concept of "pooling", at the neighbourhood scale, provides numerous avenues to increase energy efficiency in our built environment. In the same vein, it should be noted that this "energy mutualisation" or "pooling" at the neighbourhood scale offers interesting perspectives for the compensation of the monthly peaks (as well as hourly peaks) between supply and demand between individual buildings, especially in neighbourhoods presenting a wide variety of functions with different and shifted energy needs (offices, schools, etc., versus residences).

As far as perspectives for further research are concerned, the connection to the grid, the use of smart grids and the storage of energy should be investigated in the future. Cost optimisation should also be considered based on current discussions related to the European Directive on the Energy Performance of Buildings. Finally, we recommend extending the balance to the entire lifecycle of a neighbourhood by including the energy and CO_2 embodied in materials and technical installations (including transportation infrastructure).

5. Conclusions

The goal of this paper was to contribute to the existing literature on the "zero-energy" objective in the building sector by investigating the feasibility of this objective at the neighbourhood scale. The paper presented a simplified framework and a calculation method related to the "net zero-energy neighbourhood", which included building energy consumption and the on-site renewable energy at the neighbourhood scale as well as the impact of urban form and the location of the neighbourhood on transportation energy consumption for daily mobility. These developments were applied to two case studies (one urban neighbourhood and one suburban neighbourhood in Belgium) to highlight the main parameters that act upon the annual energy balance of a neighbourhood and to propose concrete steps to improve the sustainability of existing neighbourhoods. This work highlighted the opportunities for and interest in extending the boundaries of the existing frameworks from the building to the neighbourhood, which mainly concern the impact of urban form and daily mobility. The proposed nZEN framework allows to consider building energy consumption, renewable production and transportation energy consumption as an integrated system, rather than separated topics.

In a more general perspective, this works calls for a better integration of the individual building into its context in policies dealing with energy efficiency. Promoting the building and retrofitting of energy-efficient buildings is a good step towards increased energy efficiency in our built environment (i.e., by imposing mandatory minimum requirements on the energy efficiency of buildings that are crucial to reach a net zero energy balance); however, it is not sufficient. It is also crucial to consider parameters and interactions linked to a larger scale, the urban planning scale, to more effectively achieve the aims of these policies. To this end, the location of new buildings and developments appears to be crucial in the total balance, which includes both building and transportation energy consumption.

Acknowledgements

This research was funded by the Walloon region of Belgium under the SOLEN ("Solutions for Low Energy Neighbourhoods") project, Grant number 1151037.

References

[1] EC, Technical guidance, Financing the Energy Renovation of Buildings with Cohesion Policy Funding, European Commission, Directorate-General for Energy, 2014.
[2] UNEP, Buildings and Climate Change, Summary for decision-makers, United Nation Environment Programme, 2009.
[3] IEA, Modernising Building Energy Codes to Secure our Global Energy Future, International Energy Agency, 2013.
[4] EPBD, Directive 2001/91/EC of the European Parliament and of the Council of 16 December 2002 on the Energy Performance of Buildings, Brussels, 2002.
[5] L. Müller, T. Berker, Passive house at the crossroads: the past and the present of a voluntary standard that managed to bridge the energy efficiency gap, Energy Policy 60 (2013) 586–593.
[6] W. Feist, J. Schnieders, V. Dorer, A. Haas, Re-inventing air heating: convenient and comfortable within the frame of the passive house concept, Energy and Buildings 37 (2005) 1186–1203.
[7] J. Schnieders, A. Hermelink, CEPHEUS results: measurements and occupants' satisfactions provide evidence for Passive Houses being an option for sustainable building, Energy Policy 34 (2006) 151–171.
[8] I. Sartori, A. Napolitano, K. Voss, Net zero energy buildings: a consistent definition framework, Energy and Buildings 48 (2012) 220–232.
[9] P.A. Torcellini, D.B. Crawley, Understanding zero-energy buildings, ASHRAE Journal 48 (9) (2006) 62–69.
[10] K. Voss, E. Musall, M. Lichtmeb, From low energy to net zero-energy buildings: status and perspectives, Journal of Green building 6 (1) (2011) 46–57.
[11] S. Pless, P. Torcellini, Zero Energy Buildings: A Classification System Based on Renewable Energy Supply Options, National Renewable Energy Laboratory, Golden, CO, 2010, Report NREL/TP-550-44586.
[12] A.J. Marszal, P. Heiselberg, J.S. Bourrelle, E. Musall, K. Voss, I. Sartori, A. Napolitano, Zero energy buildings—a review of definitions and calculations methodologies, Energy and Buildings 43 (2011) 971–979.
[13] M. Panagiotidou, R.J. Fuller, Progress in ZEBs—a review of definitions, policies and construction activity, Energy Policy 62 (2013) 196–206.
[14] M. Pacheco, R. Lamberts, Assessment of technical and economical viability for large-scale conversion of single family residential buildings into zero energy buildings in Brazil: climatic and cultural considerations, Energy Policy 63 (2013) 716–725.
[15] EPBD, Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings, ⟨http://eur-lex.europa.eu/LexUriServ/LexUriServ.do? uri=OJ:L: 2010:153:0013:0035: EN:PDF⟩ (accessed December 2013).
[16] A. Mohamed, A. Hasan, K. Sirén, Fulfillment of net-zero energy building (NZEB) with four metrics in a single family house with different heating alternatives, Applied Energy 114 (2014) 385–399.
[17] K. Voss, E. Musall, Net Zero Energy Buildings. International Projects of Carbon Neutrality in Buildings, Institut für international Architecktur-Dokumentation, GmbH & CO.KG, Munich, 2011.
[18] R.S. Srinivasan, W.W. Braham, D.E. Campbell, C.D. Curcija, Re(De)fining net zero energy: renewable emergy balance in environmental building design, Building and Environment 47 (2011) 300–315.
[19] N. Carlisle, O. Van Geet, S. Pless, Definition of a "Zero Net Energy" Community, National Renewable Energy Laboratory, Golden, Colorado, 2009, Technical Report NREL/TP-7A2-46065.
[20] S. Attia, E. Gratia, A. De Herde, J.L.M. Hensen, Simulation-based decision support tool for early stages of zero-energy building design, Energy and Buildings 49 (2012) 2–15.
[21] Energy Independence and Security Act of 2007, Available from: ⟨http://www.gpo.gov/fdsys/pkg/PLAW-110publ140/html/PLAW-110 publ140.htm⟩ (accessed October 2013).
[22] Net Zero Energy Buildings Database, 2012. Available from: ⟨http://iea40.buildinggreen.com/⟩ (accessed October 2013).
[23] K.F. Fong, C.K. Lee, Towards net zero energy design for low-rise residential buildings in subtropical Hong Kong, Applied Energy 93 (2012) 686–694.
[24] N. Baker, K. Steemers, Energy and Environment in Architecture, E&FN Spon, London, 2000.
[25] C. Ratti, N. Baker, K. Steemers, Energy consumption and urban texture, Energy and Buildings 37 (2005) 762–776.
[26] K. Steemers, Energy and the city: density, buildings and transport, Energy and Buildings 35 (2003) 3–14.
[27] R. Compagnon, Solar and daylight availability in the urban fabric, Energy and Buildings 36 (2004) 321–328.
[28] C. Hachem, A. Athienitis, P. Fazio, Evaluation of energy supply and demand in solar neighborhood, Energy and Buildings 49 (2012) 335–347.
[29] J.H. Kampf, M. Montavon, J. Bunyesc, R. Bolliger, D.D. Robinson, Optimisation of buildings' solar irradiation availability, Solar Energy 84 (2010) 596–603.
[30] J. Burch, J. Woods, E. Kozubal, A. Boranian, Zero energy communities with central solar plants using liquid desiccants and local storage, Energy Procedia 30 (2012) 55–64.
[31] C. Hachem, A. Athienitis, P. Fazio, Evaluation of energy supply and demand in solar neighbourhood, Energy and Buildings 49 (2012) 335–347.
[32] P. Newman, K. Kenworthy, Gasoline consumption and cities—a comparison of UK cities with a global survey, Journal of the American Planning Association 55 (1989) 24–37.
[33] D. Banister, Energy use transport and settlement patterns, in: M. Breheny (Ed.), Sustainable Development and Urban Form, Pion Ltd., London, 1992, pp. 160–181.
[34] P. Naess, S. Sandberg, P.G. Roe, Energy use for transportation in 22 nordic towns, Scandinavian Housing and Planning Research 13 (1996) 79–97.
[35] M. Boarnet, R. Crane, Travel by Design. The Influence of Urban form on Travel, Oxford University Press, New-York, 2001.
[36] A.F. Marique, S. Dujardin, J. Teller, S. Reiter, School commuting: the relationship between energy consumption and urban form, Journal of Transport Geography 26 (2013) 1–11.
[37] N. Codoban, C.A. Kennedy, Metabolism of neighbourhoods, Journal of Urban Planning Development 134 (2008) 21–31.
[38] A.F. Marique, S. Reiter, A Method to Evaluate the Energy Consumption of Suburban Neighbourhoods, HVAC&R Research 18 (1–2) (2012) 88–99.
[39] S. Reiter, A.F. Marique, Toward low energy cities: a case study of the urban area of Liège, Journal of Industrial Ecology 16 (6) (2012) 829–838.
[40] S. Kennedy, S. Sgouridis, Rigorous classification and carbon accounting principles for low and zero carbon cities, Energy Policy 39 (2011) 5259–5268.
[41] M. Todorovic, BPS, energy efficiency and renewable energy sources for buildings greening and zero energy cities planning, Energy and Buildings 48 (2012) 180–189.
[42] A. Sharifi, A. Murayama, A critical review of seven selected neighbourhood sustainability assessment tools, Environmental Impact Assessment Review 38 (2013) 73–87.
[43] STAR Community Rating System, version 1.0 (2012), Available from: ⟨https://www.starcommunities.org/uploads/rating-system.pdf⟩ (accessed February 2014).
[44] ⟨http://www.usgbc.org/neighborhoods⟩, 2014 (accessed February 2014).
[45] BREEAM, ⟨http://www.breeam.org/page.jsp?id=372⟩, 2014 (accessed February 2014).
[46] HQE2R, ⟨http://www.suden.org/fr/projets-europeens/hqe2r/⟩, 2014 (accessed February 2014).
[47] CASBEE for Urban Development, Technical Manual 2007 edition, Institute for Building Environment and Energy Conservation, 2007.
[48] K. Glaiser, P. Stroeve, The impact of scheduling appliances and rate structure on bill savings for net-zero energy communities: application to the West Village, Applied Energy 113 (2014) 1586–1595.
[49] S.M. Wheeler, R.B. Segar, Chapter 12—zero net energy at a community scale: UC Davis West village, Energy efficiency, Towards the end of demand growth, 2013, pp. 305–324.
[50] A.F. Marique, S. Reiter, Towards more sustainable neighbourhoods: are good practices reproducible and extensible? in: M. Bodard, A. Evrard (Eds.), Proceedings of International Conference PLEA 2011, Presses Universitaires de Louvain, Louvain, 2011, pp. 27–32.
[51] GW, Arrêté du Gouvernement wallon déterminant la méethode de calcul et les exigences, les aggréments et les sanctions applicables en matière de performance énergétique et de climat intérieur des bâtiments, 17 avril 2008, publié au Moniteur belge le 30 juillet 2008.
[52] ICEDD, Bilan énergétique wallon 2009, Consommations du secteur du logement 2009. MRW, Direction générale des technologies, de la recherche et de l'énergie—Conception et réalisation ICEDD asbl, Namur, Belgium, 2011.
[53] Cellule Etat de l'Environnement Wallon, Rapport analytique sur l'état de l'environnement wallon 2006–2007. MRW—Direction générale des ressources naturelles et de l'environnement. Rapport D/2007/5322/45, 2007.
[54] S.-I. Takagi, Aide Mémoire, Génie climatique, 3ème édition, Dunod, Paris, 2012.
[55] K. Boussauw, F. Witlox, Introducing a commute-energy performance index for Flanders Transportation Research Part A 43 (5) (2009) 580–591.
[56] A.F. Marique, S. Reiter, A method for evaluating transport energy consumption in suburban areas, Environmental Impact Assessment Review 33 (2012) 1–6.
[57] Merenne-Schoumaker (Eds.), M. Beelen, J.M. Halleux, J.M. Lambotte, G. Rixhon, Le mouvement pendulaire en Belgique: les déplacements domicile-travail, les déplacements domicile-école. Enquête Socio-économique 2001. Monographies (n 10) (Traduit en néerlandais), Belgique: SPF Economie, PME, Classes moyennes et Energie, Bruxelles, 2009.
[58] J. Teller, S. Azar, Townscope II—a computer system to support solar access decision-making, Solar Energy 70 (2001) 187–200.
[59] A.F. Marique, T. de Meester, S. Reiter, Energy requirements and solar availability in suburban areas: the influence of built density in an existing district, in: Proceedings of the International Conference Clean Tech for sustainable buildings, From nano to urban scale, Lausanne, 2011, pp. 925–930.
[60] ⟨http://re.jrc.ec.europa.eu/pvgis/countries/countries-europe.htm⟩ (accessed December 2013).
[61] ⟨http://www.ef4.be/fr/photovoltaique/aspects-techniques/orientation-structure.html⟩ (accessed December 2013).
[62] M. Pétel, Le projet de recherche SAFE: Stage Etude et Recherche: efficacité énergétique des bâtiments et production solaire photovoltaïque. ULg report, Liege, 2011.
[63] Les Compagnons d'Eole, APERe, Vents d'Houyet, E.R.B.E., Vade Mecum pour l'implantation des éoliennes de faible puissance en Wallonie. SPW-DGO4, Jambes, 2012.

[64] A.-F. Marique, Méthodologie d'évaluation énergétique des quartiers périurbains. Perspectives pour le renouvellement périurbain wallon, University of Liege, Liege, 2013, Unpublished doctoral thesis.
[65] P. Hoes, J.L.M. Hensen, M.G.L.C. Loomans, B. de Vries, D. Bourgeois, User behavior in whole building simulation, Energy and Buildings 41 (2009) 295–302.
[66] R. Haas, H. Auer, P. Biermayr, The impact of consumer behavior on residential energy demand for space heating, Energy and Buildings 27 (2) (1998) 195–205.
[67] T. de Meester, A.F. Marique, A. De Herde, S. Reiter, Impacts of occupant behaviours on residential heating consumption for detached houses in a temperate climate of the northern part of Europe, Energy and Buildings 57 (2013) 313–323.

Appendix A.6

Building and Environment 51 (2012) 395–401

Contents lists available at SciVerse ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Life-cycle assessment of residential buildings in three different European locations, basic tool

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ARTICLE INFO

Article history:
Received 9 September 2011
Received in revised form
21 November 2011
Accepted 24 November 2011

Keywords:
Life-cycle analysis
Embodied energy/carbon
Energy mix
Climate

ABSTRACT

The paper deals with the development of a tool used for the life cycle assessment of residential buildings located in three different European towns: Brussels (Belgium), Coimbra (Portugal) and Luleå (Sweden). The basic tool focuses on the structure and the materials of the buildings and permits the evaluation of the Embodied energy, Embodied carbon and yearly energy consumption. For that purpose, a different set of original data is taken into account for each location, in which the monthly temperatures, energy mix, heating and cooling systems are defined. The energy consumption, being for heating space or water, for cooling or for lighting is transformed into CO_2 emissions to deduce the Operational carbon as well. The influence of the energy mix can therefore be assessed in the basic tool. As a matter of fact, the heating and cooling systems habitually used in the three countries are also of great importance. The District Heating system, is, for instance, incorporated in the basic tool. The presence of solar water heater or photovoltaic panels is also strongly influencing the operational carbon. After a short literature review on building LCA and the description of the basic tool, the software Pleiades + Comfie combined with Equer is used to achieve the complete LCA for one building using two different load bearing frames. The results of the calculations for Brussels climate are verified against these software results. The dependence of the results to parameters such as climate, energy mix and habits is then discussed in the companion paper.
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1. Introduction and state-of-the-art

Life Cycle Assessment (LCA) is one of the methods increasingly being used to assess the environmental impacts associated with the production, use, disposal, and recycling of products, including the materials from which they are made. It quantifies the resource use and environmental emissions associated with the product evaluated. LCA was mainly developed for designing low environmental impact products. The interest of using LCA for entire buildings evaluations began to rise in the last decade and, today, several building LCA tools are under development in different countries [1]. But, although the general LCA methodology is well defined [2,3], its application in the building sector still suffers from a lack of standardization [4]. The Technical Committee CEN/TC 350 is currently working on a European standard for the sustainability assessment of buildings using a life cycle approach and quantitative indicators for the environmental performance, social performance and economic performance of buildings.

Some building characteristics to consider when making an LCA are [1,4–11]:

- Each building is a unique product,
- The boundaries of buildings LCA are not clear,
- The long life of buildings in comparison to consumption goods,
- The great impact of the use phase and occupants' behaviour,
- Various function and composition of buildings and their parts (such as the exterior walls for instances),
- Time evolution of environmental performances with functional changes, building retrofit, etc.
- Impact of the surroundings,
- Allocation for recycling.

There exist already some review-papers on the LCA methodology applied to entire buildings [5,12–14], and various previous researches concerned the LCA of residential buildings [4,15–24], including low energy dwellings [25], and LCA studies of office

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doi:10.1016/j.buildenv.2011.11.017

buildings [17,26]. This review reflects the important developments of LCA studies applied to buildings in the last ten years. However, a lot of modelling challenges remain. Currently LCA gives benefits to retroactively design but has limited use during the design stage [17,18]. Moreover, the building demolition and recycling of materials are rarely addressed in LCA studies of complete buildings [21,27]. These references also show that a great deal of buildings environmental impacts come from their use, primarily water and energy use. Issues such as orientation, insulation, building operation, lighting and appliance use, and so forth are therefore very important. Indeed, the in-use building phase is by far the longest one of the building life cycle. By comprehensively reviewing the existing literature from a entire building life cycle perspective, the phase with the highest environmental impact is the operation phase, representing approximately 62–98% of the life cycle total impacts [28], while the construction phase accounts for a total of 1–20% and the dismantling phase represents less than about 0.2–5%. So, trying to reduce fluxes (energy, water and waste) during the utilisation phase seems to be the first action to achieve. However, in [28] and [29], it is shown that the chosen service life time of the building is crucial for the calculation results and subsequent conclusions drawn from them.

In this study, we will calculate the Embodied carbon and take the recycling potential of the different materials into account. Indeed, the recycling potential is important when compared to the shell embodied materials: it accounts for 29%–40% of the energy used for manufacturing and transporting the building materials [16,21].

The quality (precision, completeness, representativeness) of the data used has a significant impact on the results of an LCA. The existence of uncertainties in input data and modelling as well as the boundaries of the system are often mentioned as a crucial drawback to a clear interpretation of LCA results. To achieve more reliable results the quality of the input data should be analysed and, if necessary, improved but such analyses are often outside the scope of building LCA studies [30]. To understand the reliability of LCAs in the building sector more clearly, the LCA models should be elaborated using data uncertainty estimations. They are particularly important when performing comparative LCA studies [1,29]. Note that Blengini [21] carried out an extensive sensitivity analysis of his LCA study on a multi-family residential building. The impacts were re-calculated by considering different data sources for the two most important materials included in this building: steel and concrete. The differences in terms of global energy requirement of the buildings with two alternative datasets are lower than 8% in comparison with the first dataset. The differences in terms of greenhouse gas (GHG) emissions fall within a range of −15% and +11%. Higher differences occur when other indicators are considered. The conclusions of Blengini [21] on this sensitivity analysis are that the uncertainties relevant to the inventory data of building materials are quite tolerable as far as energy and greenhouse gas emissions are concerned but that the other indicators are less reliable. As far as methods are concerned, three main types of LCA tools can be identified. The first one is the "process analysis" and is based on reliable energy consumption figures for particular processes. This method is often used in research dealing with building structures, as those presented below. The second one is the "input–output analysis" that makes use of national statistical information compiled by governments for the purpose of analysing national economic flows between sectors. Economic flows are then transformed into energy flows using average energy tariffs [24]. This method is less accurate than the first one [31]. To avoid the truncation error due to the delineation of the assessed system and the omission of contributions outside this boundary, a number of researcher have suggested to use a third method, the "hybrid LCA approach", combining the strengths of process analysis with those of input–output analysis to try to develop a more complete approach [24,31,32].

According to the aim of this study, we have chosen to use a process analysis type based on comprehensive and reliable existing databases (BEES database (http://ws680.nist.gov/bees/)) and CRTI (Luxembourg Construction portal, www.crtib.lu)) providing energy consumption and equivalent CO_2 emissions for a quite wide amount of construction materials in Europe. Indeed, the main objective is to focus on the comparison of different structural frames under different climates. The results obtained using the basic tool should thus be lower than those obtained with a hybrid LCA approach but are more pertinent to draw general results regarding the aforementioned comparison of the environmental impacts.

Given the significant consumption of resources in the construction sector, impact categories related to the depletion of non-renewable resources, like land use for example, are also particularly relevant for building related LCA studies. But the models used for inventory analysis or to assess environmental impacts may not be available for all potential impacts or applications, e.g. models generally accepted by the scientific world for the assessment of land use do not exist yet in the literature [33]. It is also worth pointing that some authors take into account the transportation of buildings occupants, assuming that it is part of the building service because it is related to the location of the building and that it is thus contributing to the overall building impacts [22,34]. Nevertheless, those transport distances will not be considered herein. Additionally, in [35], the author demonstrates the need for considering not only the life cycle energy of the building but also the life cycle energy attributable to activities being undertaken by users of the buildings (such as holidays, the replacement rate of items such as washing machine and microwave oven). But because our goal is to investigate the environmental impacts of different structural frames in different locations (characterized by different climate data as well as local energy mixes), the behaviour of the inhabitants is not considered as a variable in the present study. These indicators will not be considered herein. A standard profile of occupation (including internal gains) is defined and assumed to remain unchanged in the three locations to isolate the impact of parameters dealing with the building's structure and the climate. Our tool focuses on the energy and equivalent CO_2 emissions.

The companion paper is complementary to previous research that compared LCA carried out on buildings with different construction materials or in different climates. Peuportier [15] applied LCA to the comparative evaluation of three single family houses in France: a standard construction made of concrete blocks, a solar house made of stones and wood and a well-insulated wooden frame reference house. This study concluded that the increase of CO_2 emissions of the standard concrete blocks house compared to the well-insulated wooden house represents 18% of the total emissions for the wooden house, but accounting for end-of-life processes may reduce this value. Bôrjesson and Gustavsson [30] studied the greenhouse gas balances of a wood versus concrete multi-storey building from life cycle perspective and concluded also that the concrete-framed building causes higher emissions than the wood-framed one. Comparing the environmental impacts of two dwellings during the entire building life cycle, one in Spain and one in Colombia, Ortiz-Rodriguez et al. showed that the difference in their environmental impacts is not only due to climatic differences but also to the user (energy consumption) habits in each country [36]. Another recent research [37] studied a modular building in two different European locations under the environmental point of view, concluding that the energy mix of the country strongly influences the environmental impacts of this specific modular building. In the companion paper, the LCA of two residential buildings, a traditional masonry house and a steel frame house, is carried out in three different climates: Belgium, Portugal and Sweden. A different life cycle scenario is taken into account for each location, in which the monthly temperatures, buildings insulation thicknesses, energy mix, heating and cooling systems are defined. This study allows us to compare the influence of several parameters on the LCA of residential buildings: the climate related to the temperatures and the buildings insulation thicknesses, the use of different materials, the energy mix and the heating/cooling systems.

The influence of the energy mix of different countries on their GHG emissions is a recent research subject found in the literature, that it is generally studied at national scale, working on demand-profile changes, varying electricity supply and economic issues [38–42]. These studies highlight how a shift in the energy mix toward renewable sources would yield significant reductions in per capita emissions at the national scale, even without reducing energy consumptions, but do not give solutions at the local scale. At the local scale [25], studied the life cycle primary energy analysis of residential buildings (including low energy buildings) and concluded that the operational primary energy varied considerable depending on energy supply systems (cogenerated district heating, heat pumps, electric space heating, etc.) for all the buildings analysed. The choice of energy supply system had a greater effect on the primary energy use than the energy efficiency house envelope measures. The CO_2 emissions from the building operation heavily depend on the carbon content of the fuel used in the supply systems.

Studying the influence of the energetic performance of a building and the influence of occupants' behaviours on the environmental impacts of this building, Blom et al. [23] developed a sensitivity analysis on different electricity mixes. Although each statement depends greatly on the location and the type of building that is considered, the conclusions of this study are that:

- The fraction of the environmental impact due to electricity consumption is higher than the proportion of electricity in the total energy content for all the studied scenarios. Therefore, the electricity mix used in the analysis widely influences the LCA of the building.
- A comparison between the Dutch electricity mix and an alternative electricity mix, using 35% renewable sources, based on European policy goals for 2020, shows that the 35% renewable sources scenario will not significantly reduce all the environmental impacts and will result in a maximum reduction of 14% in the Global warming potential.
- All the renewable energies have not the same environmental impact. The type of sustainable energy sources used to produce electricity greatly influences the environmental impact of the energy mix.

While, in the present paper, a basic tool is implemented and verified against an already validated software, the companion paper studies the influence of the energy mix on the environmental impacts of specific houses, at different LCA stages, allowing to optimize their design. It also shows the complex interactions between building conception, climate, energy mix, materials and energy systems into the building.

2. LCA: the basic tool

2.1. Principles, definitions and tools

The present assessment follows the recommendations of the ISO Standards 14000 series [43] and was made on the basis of a excel sheet developed by Pr. Mauritz Glaumann from the University of Gävle. Amongst other things, the tool was modified to take into account the climate over one year and more complex designs. For example, the energy demand for the space heating evaluation takes into account a scenario including business days and holidays, night and day demanded comfort temperatures, internal heat gains and solar passive heating. Two main impacts are calculated: (1) the Embodied energy/carbon and (2) the Operational energy/carbon (B6 and B7 of [36]).

Embodied energy is an important concept inasmuch as it allows energy efficiency, together with operational energy [35]. Embodied energy represents the energy used for producing building materials (from the extraction of the raw materials to the manufacture of the final product, including transportation) and their implementations in the building. The total embodied energy comprises a direct component (the energy consumed directly at each phase) and an indirect component (the energy required indirectly to support the main processes which is less obvious and more difficult to measure) [24,31]. Operational energy represents the energy used in operating the building, that is to say the energy used for space heating and cooling, hot water, lighting, cooking and others appliances and equipment operation. Similarly, Embodied carbon and Operational carbon respectively represent the equivalent CO_2 emissions due to the extraction, production and transportation of the material and the construction of the buildings and the equivalent CO_2 emissions linked to the operation of the building during its life time.

The procedures and assumptions used herein to evaluate Embodied energy/carbon and Operational energy/carbon are presented in Sections 2.2 and 2.3.

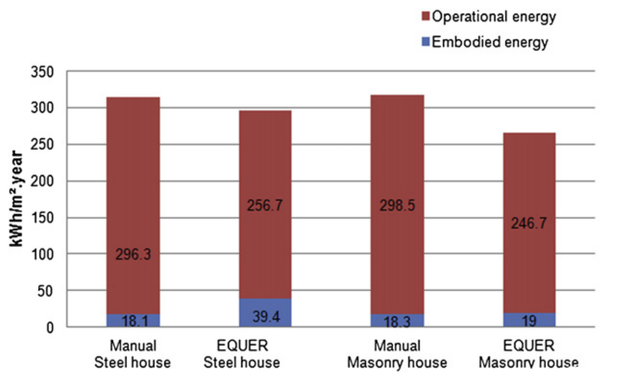

Fig. 1. Operational and embodied energy for the two houses and the two methods.

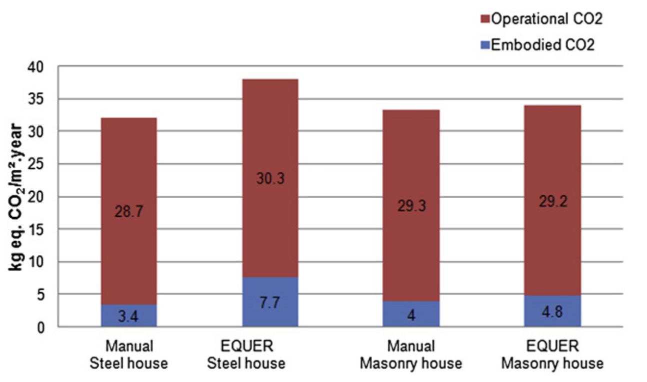

Fig. 2. Operational and embodied carbon for the two houses and the two methods.

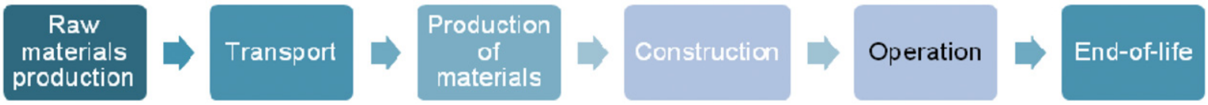

Fig. 3. Steps of the life cycle analysis.

2.2. *Embodied energy and carbon: procedures and assumptions*

The study is a cradle-to-gate study (A1 to A3 of [44]). It covers all the production steps from raw materials “in the earth” (i.e. the cradle) to finished products ready to be shipped from the factory. The non-metallic materials databases are BEES database (http://ws680.nist.gov/bees/) or preferably CRTI (Luxembourg Construction portal, www.crtib.lu) database providing energy consumption and equivalent CO_2 emissions for a quite wide amount of construction materials in Europe.

Transport to and from site (A4) is included in the present study but is only slightly affecting the final results. For instance, if the Ecoinvent database for impacts linked to transportation by trucks is considered, the energy needs for transportation only attain 2% of the embodied energy if a 50 kms distance is considered.

On-site processes (A5), such as the finishing of steel structures (cutting, shot blasting, welding) is not included but, according to steel producers, this step of the analysis is usually negligible [45]. Nevertheless, the net amount of products used for the construction of the building is increased by 5% in order to take into account the losses during construction, due to the vulnerability of products during transport and handling or due to inadequate dimensions.

The end-of-life stages (deconstruction C1, transport C2, reuse and recycling C3, disposal C4) are not included in the analysis for non-metallic material (concrete, insulation, plaster, finishes). As already mentioned for transport to the site, transport to the waste treatment facility might also not have a strong influence on the embodied impacts but are also taken into account. Transport distances are 50 kms to the construction site for all the products and 250 kms are considered between the site and the recycling plant for steel (while only 20 kms are considered for non-metallic materials).

The study includes the credits associated with the steel recycling since it can have a strong influence on the final results [46,47]. Steel is produced using two process routes. The main one is the blast furnace (BF) route (basic oxygen furnace), whereas secondary steel production process uses the electric arc furnace (EAF) route. Both processes recycle a certain amount of scrap that is melted in the furnace making steel a recyclable material. The absolute recycling potential of steel is 100% but, in reality, the net quantity of scrap introduced in the furnace depends on the steel demand. One important parameter of the analysis, especially for construction steel, is the recovery rate that can attain 60% for rebar while, for profiles, it can raise 100%. Nowadays, industries have resolutely worked to influence the methodology and include the end-of-life (EOL) treatment within the life cycle inventory data for steel. Those data are calculated for the BF route (based on iron ore and steel scrap) and the EAF route (mainly based on steel scrap) on the basis of World or European averages and can be obtained via the Worldsteel facility. It is possible to specify the recovery rate (RR is the percentage of steel that will be recovered at the end-of-life stage) or use the average RR for the considered sector. In the present study, an RR of 95% is considered. This parameter will be discussed throughout this paper.

Replacement, refurbishment and repair of materials and products (B1 to B5) is not taken into account specifically in the analysis. However, the embodied carbon/energy are simply augmented by 5% every 10 years to take that into account. A 50-year service life was considered in the analysis and is also one parameter that will be further discussed.

2.3. *Operational energy and carbon (B6 and B7): procedures and assumptions*

This part of the LCA concerns the Use phase (heating, hot water, ventilation, cooling, lighting, building automation and control, Operation in Fig. 3) in which no maintenance or repair is taken into account (B1 to B5) a part from what is described in the previous paragraph.

2.3.1. *Space heating and cooling*

The well-known heat loss factor (HLF) is provided in Equation (1) below:

$$HLF = \sum_i [U_i A_i] \tag{1}$$

where U_i = heat transfer coefficient of wall i (W/m^2 K) and A_i = surface of wall I (m^2).

The heat transfer coefficient of the windows is calculated differently. Depending on U_{glass} and $U_{profile}$, the value of U_{window} is evaluated for each window included in the building. The average heat transfer coefficient permits the user to calculate the heat loss through each window. This method leads to slightly overestimated results.

Conduction of heat may occur through the walls either inwards or outwards. This heat transfer depends on the temperature difference between the warm and cold sides of the walls. In this study, the energy demand for space heating evaluation takes into account a scenario in which (a) each month is characterized by a minimum and a maximum temperature lasting 12 h a day; (b) the required indoor temperature is considered different during the

Table 1
Total electricity use per country (source: iea.org, 2010).

	Belgium (GWh)	%	Portugal (GWh)	%	Sweden (GWh)	%
Coal	7235	8.5	11196	24.4	2235	1.5
Oil	406	0.5	4148	9.0	873	0.6
Gas	24646	29.0	15199	33.1	603	0.4
Nuclear	45568	53.7	0	0.0	63889	42.6
Hydro	1757	2.1	7296	15.9	69211	46.1
Geothermic/wind/solar/other	5318	6.3	8130	17.7	13217	8.8
Total (in 2008)	84930		45969		150028	

Table 2
Impacts from electricity generation.

	Belgium Equer	% [51]	Portugal Equer	% [51]	Sweden Equer	% [51]
CO_2 (g/kWh)	330.6	255.7	608.1	329.0	30.5	16.9
Primary energy (MJ/kWh)	19.5	6.6	9.9	7.0	13.6	9.9

night and the day; (c) during business days, only 6 h of heating are demanded, after this, the evening is supposed to start, and (d) if negative (after having added the human heat production and solar gains), the energy demand is approximately considered as cooling energy. The energy losses *E* (kWh/yr) through the building envelope is finally provided by Equation (2) below, in which $\Delta Tconf, d$ is the demanded temperature during the day (K) and $\Delta Tconf, n$ is the one demanded during the night:

$$E = HLF\sum_{m}\Big[\Big(\Delta T_{comf,d}\cdot h_b\cdot j_b\Big) + \Big(\Delta T_{comf,d}\cdot 12\cdot (j_m - j_b)\Big) + \Big(\Delta T_{comf,n}\cdot (12-h_b)\cdot j_b\Big) + \Big(\Delta T_{comf,n}\cdot 12\cdot j_m\Big)\Big] \quad (2)$$

where h_b = number of hours of occupation during business days (h) and $jb(m)$ = number of business(month) days. The monthly temperatures were used in this analysis for calculating the thermal losses, each day during one month has the same temperature.

The climate definition for the three different locations was obtained via Meteonorm software [48].

The envelope thermal properties and energy consumption of the house was verified against the Belgian regulations [49] although, in Sweden, the insulation thickness was modified in the walls, roof and basement slab of the house in accordance to the climate and regulations. The windows were also attributed a lower U value assuming that, in newly built house, better insulated windows may be used.

Thermal bridges are not taken into account in the basic tool but the comparison with Equer will show that the difference in terms of heat losses remains low.

For the solar gains, namely *S*, a simplified assessment is made. First of all, a proportion of yearly overcast sky days and bright sunny days is calculated on the basis of meteorological data for Belgium (this proportion is equivalent to a weather factor). The mean monthly solar irradiation hitting south, north, east and west oriented vertical surfaces is calculated using weather data for Belgium and the previously cited proportion. Taking into account a dirt factor (0,8), a utility factor (0,6), the G solar value of the window glass, the total yearly solar heating can be calculated. In order to keep the basic tool as simple as possible, for the other locations, the solar gains are multiplied by a coefficient that depends on the solar gains chart provided by the NASA, which is 1 herein for Sweden and 1,3 for Coimbra.

An internal heat gain, called *H*, may result from the heat output of human bodies, lamps, motors and appliances. Human heat gains (HHG), in this study, are evaluated as 75 W during the day and 25 W during the night. Only half of the inhabitants are considered to be inside the house during the day and the total heat gain depends on the chosen scenario. This value may be considered as low seen that, depending on the activity, the human body can release more than 150 W. Typical values for computer, lamps and freezer range between 40 and 100 W also but are not taken into account presently.

The calculation of the energy demand due to ventilation losses, namely *V*, is taken from [50].

In total, the total space heating demand equals

$$SHD = E + V - S - H. \quad (3)$$

2.3.2. Hot water consumption

Each inhabitant is supposed to employ 40 L of hot water per day and the energy demand is calculated subsequently. Cold water consumption is not taken into account.

2.3.3. Building and user electricity

The building electricity is proportional to the heated floor area at a rate of 15 kW/yr. Regarding the user electricity, it is assumed that each person employs 100 W during his stay inside the building, it thus depends on the scenario.

2.3.4. Related CO_2 emissions, i.e., operational carbon

Multiple databases are used in the excel file for the calculation of the materials embodied emissions or “Embodied carbon” (see section 2.2). But CO_2 emissions are also generated during operation and it is the CO_2 emissions that contribute to greenhouse gases and so, those will be displayed. The energy consumption, being for heating space or water, for cooling or for lighting is (via the energy mix for electricity amongst other) transformed into CO_2 emissions. For the regional energy mix, the related impacts were deduced from Ecoinvent database [51]. The energy mixes are gathered from official statistics provided by the International Energy Agency (www.iea.org, see Table 1) and [52]. In Belgium, electricity is thus mainly generated from Nuclear Power and Gas. In Portugal, Natural Gas was first introduced in 1997 and is gaining an increasing share in electricity generation. In Sweden, given the relatively low presence of fossil fuels in the energy mix, low CO_2 emissions are shown.

The impacts (in terms of GHG emissions and primary energy) from electricity generation are thus quite different from country to country. These impacts were calculated using [51] and taken from Equer software (see Table 2).

The Swedish District Heating system also distributes hot water via a grid of pipes to supply space heating and domestic hot water for use. In Luleå, this is the main source for both of them. The underlying central facility is a Combined Heat and Power plant that is nourished by an industrial surplus of the nearby steel mill facility (by-product) and so, the environmental impacts shall be allocated to it. In this case, very low CO_2 emissions are accounted for. In the same line of thoughts, District Cooling via cold water taken from the river is also ensured in Luleå, which is impact free. Moreover, depending on the region, habits and regulations lead to quite dissimilar local water, central heating and cooling systems. The presence of solar flat plate collector or local electricity production

Table 3
Space heating, cooling demand and solar gains calculated with Comfie + Equer and with the basic tool for the masonry house and the steel framed house in Brussels.

	Steel framed house			Masonry house		
	Basic tool	Equer	Δ	Basic tool	Equer	Δ
Space heating + Ventilation losses (kWh/m^2.yr)	55	57.0	3.6%	57	55.0	−3.5%
Cooling demand (kWh/m^2.yr)	3.9	7.0	79.5%	3.7	5.0	35.1%
Solar gains over one year (kW)	4031	4144	2.8%	4031	4144	2.8%

Table 4
Operational and embodied carbon and energy calculated with Equer and with the basic tool calculations for the masonry house and the steel frame house in Brussels.

	Steel framed house			Masonry house		
	Basic tool	Equer	Δ	Basic tool	Equer	Δ
Operational carbon (kg/m^2.yr)	28.7	30.3	5.6%	29.3	29.2	−0.3%
Operational energy (kWh/m^2.yr)	296.3	256.7	−13.4%	298.5	246.7	−17.4%
Embodied carbon (kg/m^2.yr)	3.4	(7.7)	125.1%	4	4.8	20.0%
Embodied energy (kWh/m^2.yr)	18.1	(39.4)	117.7%	18.3	19.0	3.8%

using photovoltaic panels will thus also strongly influence the operational CO_2 emissions, regional scenarios will be considered. All those options are incorporated in the tool.

3. Case-study and preliminary conclusion

The considered house, dedicated to 5 persons, has one floor plus an attic or so-called under-roof space. It accommodates one kitchen, one combined living/dining room, one office, one bathroom, one WC and four bedrooms. The surface area of the house is worth 192 m^2 and the heated volume (100%) is worth 409 m^3. All the information concerning the functional unit, the wall compositions, U-values, ventilation rates, etc is provided in the companion paper. As a matter of fact, one house is considered using two structural systems: masonry and steel frame house. The reference house is firstly modelled in the software Pleiades + Comfie, allowing the user to evaluate the house thermodynamic behaviour. Via Equer, the achievement of the complete LCA is then possible.

Equer software is specialized in LCA of building [53]. It is directly linked with thermal simulation software (Pleiades + Comfie [51].) and geometrical description software that allows the life cycle assessment of a whole building. Equer uses the Oekoinventare 96 life cycle inventory database and derives 12 environmental indicators, among which primary energy consumption and global warming potential (obtained by adding the contribution of all emitted greenhouse gases) will be discussed. These indicators, in majority evaluated according to the CML 1992 methodology [54], correspond to a single building type during its life cycle [55]. The construction, operation and demolition phases can be taken into account. The LCA tool Equer has been compared to seven other building LCA tools in the frame of the European thematic network PRESCO. The calculated CO_2 emissions for a case study were differing by ±10% between the tools, but other environmental indicators like toxicity are more uncertain. Further work is planned to progress towards harmonization of the methods [56]. Equer software is used in the next section to evaluate the validity of the calculations made using the basic tool.

Heating loads (space heating and ventilation losses), cooling demand and solar gains (Table 3) are close together which highlight the validity of the calculations and the assumptions made, as Pleiades + Comfie has been validated by the International energy Agency Bestest (Benchmark for Building Energy Simulation Programs) [57,58].

The basic tool and Equer software give similar results regarding operational carbon and operational energy (Table 4) with a relative difference that doesn't exceed 17,4%. Nevertheless, the calculations include so many different data that it is hard to draw conclusions from a comparison of only two specific buildings. In fact, a comprehensive analysis should compare the single parameters *E, V, S and H* in order to improve the basic tool results but this is out of the scope of this study. Higher differences in embodied carbon and embodied energy highlight the influence of the database on the results, especially for the steel framed house. In fact, the 1996 Oekoinventaere database used in Equer does not provide value for "building" steel elimination and recycling. The comparatively large difference between the embodied impacts of the steel building is explained by different input data. Indeed, the Embodied impacts take the recycling potential of the different materials into account in the basic tool. And, for steel, the recycling potential has an important influence on the accuracy of the results of the basic tool.

It is also worth pointing that the total energy use and total carbon emissions over the life cycle of the house (building + operation phase) are quite similar for the steel frame and for the masonry house (as also illustrated in Figs. 1 and 2) making the results acceptable seen the simplicity of use of the basic tool. So, at least, in an introductory phase, the basic tool can be used for simplified LCA of relatively complicated building and is enough for the comprehension of the relative importance of the embodied impacts, the consequence of a change in the energy mix and local energy harvesting…

The companion paper uses the basic tool presented in this paper to perform the life cycle assessment of a masonry house and a steel framed house in three European locations. The functional unit considered in the LCA and the main assumptions are presented in the companion paper. Then, the influence of several parameters, such as those related to database, heating system and climate are discussed. Finally, we summarize our main findings and discuss their limits and reproducibility. Using one practical case-study, the second part of this paper is dedicated to show that, for instance, such tool could be useful in the pre design phase.

References

[1] IEA. Energy related environmental impact of buildings, technical synthesis report annex 31: International energy agency buildings and community systems. FaberMaunsell Ltd, http://www.ecbcs.org/docs/annex_31_tsr_web.pdf; 2005 [accessed 10.06.2010].
[2] ISO (international Standardization Organization). ISO 14040. Environmental management – Life cycle assessment – Principles and framework; 2006a. Geneva.
[3] ISO. ISO 14044. Environmental management – Life cycle assessment – Requirements and guidelines; 2006b. Geneva.
[4] Verbeeck G, Hens H. Life cycle inventory of buildings: a calculation method. Build Environ 2010;45:1037–41.
[5] SETAC. LCA in building and construction—A state-of-the-art report of SETAC-EUROPE; 2001. Sittard, Holland: Intron. 150 p.
[6] Erlandsson M, Borg M. Generic LCA-methodology applicable for buildings, constructions and operation services – today practice and development needs. Build Environ 2003;38(7):919–38.
[7] Pushkar S, Becker R, Katz A. A methodology for design of environmentally optimal buildings by variable grouping. Build Environ 2005;40(8):1126–39.
[8] Lutzkendorf T, Lorenz DP. Using an integrated performance approach in building assessment tools. Build Res Inf 2006;34(4):334–56.
[9] Bribian IZ, Uson AA, Scarpellini S. Life cycle assessment in buildings: state-of-the-art and simplified LCA methodology as a complement for building certification. Build Environ 2009;44:2510–20.
[10] Ortiz O, Castells F, Sonnemann G. Sustainability in the construction industry: a review of recent developments based on LCA. Construction Build Mater 2009;23:28–39.
[11] Vrijders J, Delem L. Economical and environmental impact of low energy housing renovation. BBRI, LEHR Res; 2010. p. 1 à 107.
[12] Sartori I, Hestness AG. Energy use in the life cycle of conventional and low-energy buildings: a review article. Energ and Build 2007;39:249–57.
[13] Dixit MK, Fernandez-Solis JL, Culp CH. Identification of parameters for embodied energy measurement: a literature review. Energ and Build 2010; 42:1238–47.
[14] Reiter S. Life cycle assessment of buildings - a review, Proceedings of ArcelorMittal International network in steel construction, sustainability workshop; 2010. Bruxelles, P. 1–19.

[15] Peuportier B. Life cycle assessment applied to the comparative evaluation of single family houses in the French context. Energ and Build 2001;33(5):443–50.
[16] Thormark C. A low energy building in a life cycle - its embodied energy, energy need for operation and recycling potential. Build Environ 2002;37:429–35.
[17] Scheuer C, Keoleian GA, Reppe P. Life cycle energy and environmental performance of a new university building: modeling challenges and design implications. Energ and Build 2003;35:1049–64.
[18] Malmqvist T, Glaumann M, Scarpellini S, Zabalza I, Aranda A, Llera E, et al. Life cycle assessment in buildings: the ENSLIC simplified method and guidelines. Energy 2010;36(4):1–8.
[19] Gerilla GP, Teknomo K, Hokao K. An environmental assessment of wood and steel reinforced concrete housing construction. Build Environ 2007;42: 2778–84.
[20] Huberman N, Pearlmutter D. A life-cycle energy analysis of building materials in the Negev desert. Energ and Build 2008;40:837–48.
[21] Blengini GA. Life cycle of buildings, demolition and recycling potential: a case study in Turin, Italy. Build Environ 2009;44:319–30.
[22] Marique AF, Reiter S. A method to evaluate the energy consumption of suburban neighbourhoods. HVAC&R Res, in press, doi:10.1080/10789669.2011.592103.
[23] Blom I, Itard L, Meijer A. Environmental impact of building-related and user-related energy consumption in dwellings. Build Environ 2011;46:1657–69.
[24] Fay R, Treloar G, Iyer-Raniga U. Life-cycle energy analysis of buildings: a case study. Build Res Inf 2000;28(1):31–41.
[25] Gustavsson L, Joelsson A. Life cycle primary energy analysis of residential buildings. Energ and Build 2010;42:210–20.
[26] Xing S, Xu Z, Jun G. Inventory analysis of LCA on steel- and concrete-construction office buildings. Energ and Build 2008;40:1188–93.
[27] Blengini GA, Di Carlo T. The changing role of life cycle phases, subsystems and materials in the LCA of low energy buildings. Energ and Build 2010;42: 869–80.
[28] Sartori I, Hestness AG. Energy use in the life cycle of conventional and low-energy buildings: a review article. Energ and Build 2007;40:249–57.
[29] Wallhagen M, Glaumann M, Malmqvist T. Basic building life cycle calculations to ecrease contribution to climate change - case study on an office building in Sweden. Build Environ 2011;46(10):1863–71.
[30] Börjesson P, Gustavsson L. Greenhouse gas balances in building construction: wood versus concrete from life-cylce and forest land-use perspectives. Energ Policy 2000;28:575–88.
[31] Treloar G. Extracting embodied energy paths from input-output tables: towards an input-output-based hybrid energy analysis method. Econ Syst Res 1997;9(4):375–91.
[32] Lenzen, Treloar G. Embodied energy in buildings: wood versus concrete-reply to Börjesson and Gustavsson. Energ Policy 2002;30:249–55.
[33] Peuportier B. Contribution to the Life Cycle Assessment of settlements, PhD thesis, Ecole des Mines de Paris; 2006.
[34] Peuportier B, Kohler N. REGENER. European methodology for evaluation of environmental impact of buildings—life cycle assessment. REGENER Project, summary report, European Commission Directorate General XII for Science. Research and Development; 1997 [Program APAS].
[35] Treloar G, Fay R, Love PED, Iyer-Raniga U. Analysing the life-cycle energy of an Australian residential building and its householders. Build Res. Inf. 2000; 28(3):184–95.
[36] Ortiz-Rodriguez O, Castells F, Sonnemann G. Life cycle assessment of two dwellings: one in Spain, a developed country, and one in Colombia, a country under development. Sci Total Environ 2010;408(12):2435–43.
[37] Andrade P. Structural assessment and optimization of the modular system of the student residential building in Luleå and Coimbra, Master thesis, Coimbra: Universidade de Coimbra (Portugal); 2010.
[38] Burke PJ. Income, resources and electricity mix. Eng Econ 2010;32:616–26.
[39] Hennicke P. Scenarios for a reobust policy mix: the final report of the German study commission on sustainable energy supply. Energ Policy 2004;32: 1673–8.
[40] Luickx PJ, Helsen LM, D'haeseleer WD. Influence of massive heat-pump introduction on the electricity-generation mix and the GHG effect: comparison between Belgium, France, Germany and The Netherlands. Renew Sustain Energ Rev 2008;12:2140–58.
[41] Marrero G. Greenhouse gases emissions, growth and the energy mix in Europe. Energy Econ 2010;32:1356–63.
[42] Foidart F, Oliver-Sola J, Gasol CM, Gabarell X, Rieradevall J. How important are current energy mix choices on future sustainability? Case study: Belgium and Spain-projections towards 2020-2030. Energ Policy 2010;38: 5028–37.
[43] ISO14041. Environmental Management - Life-cycle assessment - Goal and scope - Definition and inventory analysis. Geneva: International Organization for Standardization; 2000.
[44] FprEN 15643-2. Sustainability of construction works - Assessment of buildings - Part 2: framework for the assessment of environmental performance. Brussels: European Committee for Standardization; 2010.
[45] ARCELORMITTAL. Software AMECO, http://www.arcelormittal.com; 2010.
[46] INTERNATIONAL IRON & STEEL INSTITUTE (IISI). Appendix 5 Application of the IISI LCI data to recycling scenarios, life-cycle inventory methodology report. Brussels: IISI; 2002.
[47] Rossi B. Sustainable steel constructions - Life-cycle inventory, methods and applications. In: Proc. Sustainability Workshop. Brussels: university of Liège; 2010.
[48] METEOTEST, Meteonorm software, http://www.meteonorm.com.
[49] SERVICE PUBLIC DE WALLONIE (SPW). Performance Energétique des Bâtiments (PEB), http://energie.wallonie.be; 2010.
[50] Garcia de Campos Coaelho FM, Assessment of the life-cycle environmental performance of buildings: a case study Master thesis, Coimbra: Universidade de Coimbra, 2010.
[51] ECOINVENT CENTER. EcoInvent 1996", Dübendorf: Swiss Centre for life-cycle Inventories; 1996.
[52] EURELECTRIC. Statistics and prospects for the European electricity sector (EURPROG 2005); 2005 [Brussels, Belgium].
[53] Polster B, Peuportier B, Blanc-Sommeureux I, Diaz Pedregal P, Gobin C, Durand E. Evaluation of the environmental quality of buildings towards a more environmentally conscious design. Sol Energy 1996;57:219–30.
[54] Heijungs R. Environmental life cycle assessment of products. Leiden: Centre of environmental science; 1992.
[55] Popovici E, Peuportier B. Using life cycle assessment as decision support in the design of settlements. 21th Conference on Passive and Low Energy Architecture. The Netherlands: Eindhoven; 2004. Septembre 200419–22.
[56] Thiers S, Peuportier B. Thermal and environmental assessment of a passive building equipped with an earth-to-air heat exchanger in France. Sol Energy 2008;82:820–31.
[57] Peuportier B. Validation of Comfie. Report CEC. Germany: University of Stuttgart I.T.W; 1989.
[58] Peuportier B. Bancs d'essai de logiciels de simulation thermique; 2005. Proceedings Of Journée Thématique SFT-IBPSA.

Appendix A.7

Building and Environment 51 (2012) 402–407

Contents lists available at SciVerse ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Life-cycle assessment of residential buildings in three different European locations, case study

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ARTICLE INFO

Article history:
Received 8 September 2011
Received in revised form
2 November 2011
Accepted 5 November 2011

Keywords:
Steel frame house
Life-cycle analysis
Embodied energy/carbon
Energy mix

ABSTRACT

The paper presents the comparative results of the life-cycle assessment (LCA) of one residential building with two constructive systems in Brussels and one steel frame house located in three different European towns: Brussels (Belgium), Coimbra (Portugal) and Luleå (Sweden). In a recent study, a modular building was studied in Coimbra and Luleå. It was shown that in terms of CO_2 emissions, the Use Stage was the most harmful stage during the building life-cycle for Coimbra climate. Contrarily, in Luleå, it was the Product Stage, despite energy consumption being higher than Coimbra, due to the way electricity and heat are generated. In the present study, two structural systems are first compared for the Belgian house: steel frame and traditional masonry. A different life-cycle scenario is taken into account for the steel frame house for the three different locations, in which the monthly temperatures, energy mix, heating and cooling systems are defined. The LCA is carried out using the basic tool described in the companion paper. It is worth recalling that the results obtained with the basic tool were verified against Pleiades + Comfie and Equer software, enabling to carry out a complete LCA, for Brussels. Our results confirm that for all the three climates, the Use Stage (Operational energy) is the most harmful period during the building life-cycle and that the energy mix of the country strongly influences the equivalent CO_2 emissions related to the Use Stage (Operational carbon) and may entirely reverse the conclusions about the life-cycle carbon footprint of the building.

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1. Introduction

The total energy use over the life-cycle of a building is an emerging research field although a great number of studies have already been achieved about it. Embodied energy of common construction materials such as timber, steel, glass, insulation or reinforced concrete as well as alternative materials such as phase changing materials is one of the topic currently researched all over the world thanks to the ever-growing concern on sustainability in the construction domain. Two main conclusions can be drawn from current studies about total energy consumption in buildings: (1) the assessment of the Embodied energy in buildings can vary substantially due to a quite high variability in the cradle-to-gate material data as well as regional characteristics (although those differences usually remain tolerable [1]) and (2) the Embodied energy can take an important place in the total life-cycle energy use if passive or zero-energy buildings are considered [2]. In the literature, guidelines for reducing the Embodied energy are also provided usually by selecting low Embodied energy materials, designing lightweight/efficient structures to minimize material consumption, using recycled/reusable materials/components and so by ensuring that materials can be separated, guaranteeing future refurbishment and adaptability instead of demolition, preferring locally sourced materials. The most important one is obviously to design for long life using durable low maintenance materials.

The present study focuses on steel frame residential houses located in three different towns: Brussels (Belgium), Luleå (Sweden) and Coimbra (Portugal). The objective of the study is to compare the Embodied energy with the Operational Energy first of all but also to evaluate the corresponding Operational carbon via assumptions on the local resources used to produce energy for heating, cooling, warming water and supplying electricity. The three regions considered indeed show highly different climates but also very different energy mixes as well as regional characteristics such as the use of solar flat plate collector to heat water in Coimbra or District Heating in Luleå.

Section 2 presents the functional unit considered in the LCA and the main assumptions. Let's recall that the methodology, the

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doi:10.1016/j.buildenv.2011.11.002

assumptions, the indicators (Embodied energy/carbon and Operational energy/carbon) and the basic tool used for the LCA are described in the companion paper. In Section 3, the results of the calculations are presented. First of all, two constructive systems are compared in Brussels climate. Secondly, the steel frame house is located in three different European towns and the influence of the climate and energy mixes is assessed. Finally, the main conclusions of both papers are presented and discussed in Section 4.

2. Functional unit

2.1. Reference house

For the purpose of the study, a reference house was designed based on the most common characteristics of typical detached Belgian houses [3]. The considered house has one floor (ground floor), plus an attic or so-called under-roof space. Basement floor is not taken into account in the present study. The house accommodate one kitchen, one combined living/dining room, one office, one bathroom, one WC and four bedrooms. The surface area of the house is worth 192 m^2 and the heated volume (100%) is worth 409 m^3. Figs. 1 and 2 present the plans and a 3D model of the reference house.

2.2. Composition of the envelopes

Even though the traditions may differ from one region to another, we considered the same reference house in the three climates to focus on the influence of materials, climate and energy mix in the analyses. The steel frame was based on the European Light Steel Construction Association recommendations and the masonry model is based on standard usage in Belgium. The insulation thickness used in the reference case is designed according to the current thermal regulations in Belgium [4] that limit the *U*-value of walls, roofs and slabs, respectively to 0.4, 0.3 and 0.4 W/m^2 K (amongst other regulations). Double glazed timber windows and wooden insulated doors were used. The insulation thickness (and windows type) was slightly modified in Sweden to fit the local regulations regarding the energy performance of buildings (the Swedish regulations limit the maximum energy consumption of the building, if it's located in the North part of the country, to 95 kWh/m^2 year), which is more difficult to obtain in Sweden than in Belgium due to its colder climate.

The compositions of the envelopes and the corresponding *U*-value are indicated in Table 1 for each type of external wall of the masonry house and in Table 2 for the steel frame house. Note that the thicknesses are to be understood with care seen that, for steel purlins namely, the quantity of material is somehow transformed into an equivalent thickness during the manual calculations. Thus, the number of purlins per metre must be mentioned during the evaluation. Those dimensions could be somewhat reduced (let's say optimized) by considering for instance sandwich panels in the roof and less high profile in the walls, but this is not the scope of this research. Finally, the design of the house leads to a quantity of steel of 64 kg/m^2 distributed in the different walls as indicated in the Table 3. The interested reader can find more information on cradle-to-gate assessment of steel frame walls, roofs or floors in [5]. The necessary moisture and air barrier are not indicated in the present research nor taken into account in the LCA neither are the plumbing devices, finishes or furniture.

Database used in the LCA manual calculations are mentioned in Tables 1 and 2. BEES is the database included in the **B**uilding for **E**nvironmental and **E**conomic **S**ustainability software developed by the National Institute of Standards and Technology (U.S.) and CRTI is the database published by the Centre de Ressources Henri Tudor. Both databases are freely available online and well documented in terms of sources, functional unit considered and so forth. Comparisons were made against the Inventory of Carbon & Energy database of the University of Bath (Sustainable Energy Research Team) and EcoInvent database in order to assess the level of confidence of our database.

3. Results and discussions

3.1. Masonry house VS steel frame house in Brussels

In the companion paper, the reference house was modelled in the software Pleaides + Comfie [6], allowing the user to evaluate the house thermodynamic behaviour. Via Equer [7], the achievement of the complete LCA was possible. The results were used to verify the validity of the manual calculations indicating the level of confidence to be put in our calculations. This analysis was made for the steel fame and the masonry houses located in Brussels. In the next section, the steel house envelope composition is slightly modified such that the materials embodied CO_2 emissions almost reach the masonry house ones. As a result, the energy consumption of the steel frame house decreases.

Actually, the previous comparison described in the companion paper, intended for validating our manual calculations furthermore showed that both houses construction methods lead to very similar Embodied carbon and Operational energy. So, increasing the insulation thicknesses in order that the steel house reaches the same Embodied carbon permit us to conclude that, if the roof and exterior walls can reach a lower *U*-value, the heat losses are even more decreased for the steel frame house. The space heating demand is thus decreased to 76% of its previous value that equalled 43 kWh/

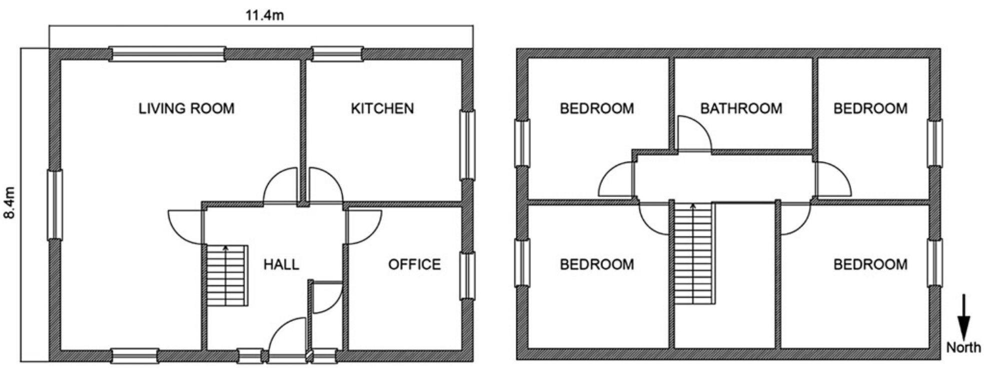

Fig. 1. Plans of the ground and attic floors of the reference house.

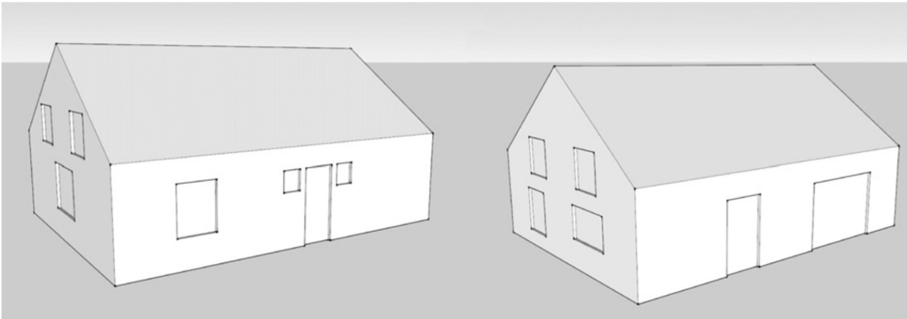

Fig. 2. 3D model of the reference house.

HFA yr if the insulation thickness in the exterior walls, the roof and the slab are respectively increased to 160 mm, 240 mm and 120 mm The results of the manual calculations are indicated in Table 4.

In Fig. 3, both case studies are represented in terms of Embodied carbon (production of materials) whereas Fig. 4 provides the Operational carbon versus Embodied carbon throughout the life-span of the building. These results are coherent with an analysis carried out in the University of Liège on houses presenting various types of envelope [8].

It is then possible to affirm that the Use Stage is the most harmful period during the building life-cycle in terms of Operational carbon. In the same line of thoughts, the energy consumption is the major source of impacts. But the lifetime is crucial to draw general conclusions from the case study. With a very long reference time or a relatively high operational energy use, the embodied impacts can seem comparatively small. And if the lifetime or the operational energy decreases (even by a small percentage), the relative yearly impacts (operational to embodied impact) can rise up to more than 50%.

Coming to the Embodied carbon, it is possible to reach the legislation requirements with fewer materials emissions for the steel house than for the traditional masonry house at least on the basis of the present assumptions, taking into account the recycling credits for steel.

Analysing the share of Embodied energy of each part of the building, it is not possible to make one part responsible for the biggest amount of Embodied energy. The exterior walls, the roof, the ground floor, the intermediate floor have, more or less, the same importance. The ground floor is nevertheless the biggest contributor to the impact mainly because of the reinforced concrete foundation. In the masonry house, the difference in Embodied carbon comes from the roof, intermediate floor and the internal walls. One could claim that the non consideration of the recycling of non-metallic materials leads to overestimated results. For wood, which uptakes CO_2, the end-of-life (burning with energy recovery) increases the Global warming potential impact while producing energy. So the manual calculations would yield even more unfavourable results for the masonry house. For concrete blocks and bricks, used material can be broken down into chips, which can be used for landscaping, or broken down further to be used as aggregate for new construction materials. About 75–80% of secondary and recycled aggregates are thought to end up as sub-base and fill, including use in road building and airfield pavements. Recycled aggregates can also be used to replace a part of the aggregates in concrete. But, recycled aggregate will typically have higher absorption and lower specific gravity than natural aggregate and will produce concrete with slightly higher drying shrinkage and creep. These differences become greater with increasing amounts of recycled fine aggregates. In Ref. [9], the LCA results show that the impacts of cement and aggregate production phases are slightly larger for recycled aggregates concrete than for natural

Table 1
Composition of the envelope of the steel frame house.

	Material	Thickness (mm)		Database
Basement slab	Slab on grade	150		BEES
(U_{SH} = 0.36 W/m^2 K)	Expanded polystyrene	80		CRTI
	Slab (cement mortar)	60		CRTI
	Plywood sheathing	20		CRTI
	Plaster slab	13		CRTI
External wall	Steel siding	0.8	100%	WORLDSTEEL
(U_{SH} = 0.35 W/m^2 K)	Rockwool insulation	120		CRTI
	Steel studs	260	2.7–100%	WORLDSTEEL
	Steel internal supports	20	1–50%	WORLDSTEEL
	Plaster board	13		CRTI
Roof	Steel roof tiles	0.8	100%	WORLDSTEEL
(U_{SH} = 0.21 W/m^2 K)	Steel rafters	60	1–50%	WORLDSTEEL
	Steel purlins	260	2.7–100%	WORLDSTEEL
	Rockwool insulation	200		CRTI
	Steel internal supports	20	1–50%	WORLDSTEEL
	Plaster board	13		CRTI
Floor	Plaster slab	13		CRTI
	Plywood sheathing	20		CRTI
	Rockwool insulation	40	2.7–100%	CRTI
	Steel beams	260	1–50%	WORLDSTEEL
	Steel internal supports	20		WORLDSTEEL
	Plaster board	13		CRTI
Internal walls	Plaster board	13		CRTI
	Rockwool insulation	40		CRTI
	Steel internal supports	40		WORLDSTEEL
	Plaster board	13		CRTI

Table 2
Composition of the envelope of the masonry house.

	Material	Thickness (mm)		Database
Basement slab	Slab on grade	150		BEES
(U_{SH} = 0.35 W/m^2 K)	Expanded polystyrene	80		CRTI
	Slab (cement mortar)	60		CRTI
	Plywood sheathing	20		CRTI
	Plaster slab	13		CRTI
External wall	Clay brick	100		CRTI
(U_{SH} = 0.37 W/m^2 K)	Expanded polystyrene	80		CRTI
	Concrete blocks	190		CRTI
	Plaster	13		CRTI
Roof	Ceramic roof tiles	18		CRTI
(U_{SH} = 0.22 W/m^2 K)	Plywood sheathing	10		CRTI
	Rockwool insulation	180		CRTI
	Timber	230	5%	CRTI
	Timber	19	8%	CRTI
	Plaster board	13		CRTI
Floor	Slab	80		CRTI
	Reinforced light concrete slab	90		CRTI
	Plaster	13		CRTI
Internal walls	Plaster	13		CRTI
	Concrete blocks	190		CRTI
	Plaster	13		CRTI

Table 3
Distribution of the steel weight within the walls.

Wall designation	% of steel
Roof	43
Floor	21
External walls	27
Internal walls	9

aggregates concrete mainly because of transportation. In fact, even if, in an LCA, the original concrete is produced with recycled aggregates, the production of cement is the main contributor to all studied impact categories. It causes approximately 77% of the total energy use and 88% of the total GWP. The main reason for such a situation is a large CO_2 emission during the calcinations process in the clinker production and the fossil fuel usage. The contribution of the aggregate and concrete production and demolition is very small. The same conclusions are drawn in [9]. At this stage, it is important to note that the transportation related to the end-of-life is taken into account with a higher distance for metallic materials than for non-metallic materials. Even though, the preliminary conclusion is still the same.

3.2. Comparative analysis in three different locations

3.2.1. Introduction

To be able to draw general conclusions, it is necessary to conduct a sensitivity analysis of the results to chosen parameters to truly understand their influence on the final values. Herein, the goal is to compare the LCA results of a building located in three different towns and to assess the influence of climate and energy mix. The following parameters (inputs) are thus not included in the sensitivity analysis seen the fact that they don't change the conclusion of the comparative analysis, although having (for some of them) a strong influence on the final results:

(1) Transportation modes and distances could differ from one town to another but as it is only slightly affecting the results, it is thus not considered in the sensitivity analysis;
(2) The energy mix: different energy mixes for electricity production will be considered for the three climates but, in one country, the energy mix will not be modified;
(3) The scenario and envelope composition: naturally, if the occupation scenario, demanded temperature or insulation type are modified, the indicators change consequently. Herein those parameters will be kept constant but the interested reader can refer to [10] and [11] for more information;
(4) The house configuration, the percentage of windows, the house plan, the envelope composition and orientation are of course of great influence on the final results. They will remain unchanged in the present sensitivity analysis;
(5) The presence of local heat/electricity production or energy saving equipment was not investigated in the present paper, although ventilation heat recovery is taken into account because it is becoming a common measure in new built house. Nevertheless, its influence will be briefly discussed;
(6) The carbon payback will be indicated on the next graphs and, naturally, a modification of the lifespan (50 years until now) will influence it.

Table 4
Manual calculations – Masonry house versus steel house (kWh/m^2 yr).

	Masonry	Steel
Building Electricity (including cooling and double flux ventilation)	20.97	21.97
User Electricity	18.79	18.79
Total electricity demand	39.76	40.75
Space heating	44.85	32.38
Ventilation	12.07	12.07
Hot water	5.57	5.57
Total heating demand	62.50	50.02
Heat recovery (double flux ventilation)	−9.05	−9.05
Total bought energy for heating	53.44	40.97
Total energy demand	102.26	90.77
Total bought energy	93.20	81.72
Without user electricity	74.42	62.93

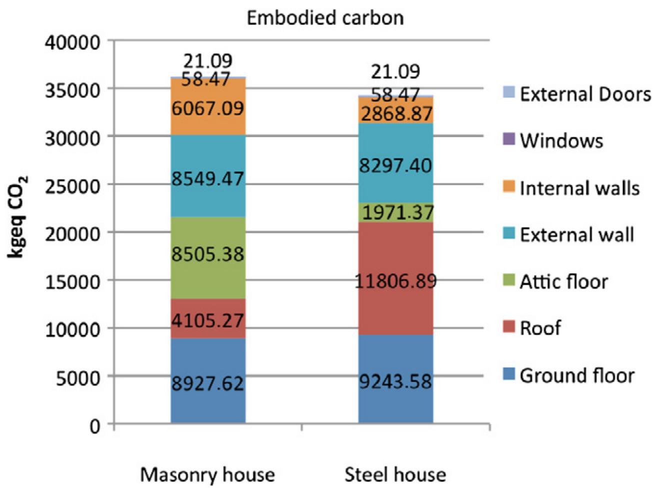

Fig. 3. Manual calculations – Share of each building part in the Embodied carbon – Masonry house versus steel house.

The influence of two important parameters was so therefore assessed since they might have an influence on the main conclusion stated before:

(1) The database: The quality (precision, completeness, representativeness) of the data used can have a significant impact on the results of an LCA. The existence of uncertainties in input data and modelling is often mentioned as a crucial drawback to a clear interpretation of LCA results. First of all, it can be seen that Equer database (EcoInvent) and the databases used in our manual calculations provide similar results for the masonry house (see the companion paper). The uncertainties in the database yield to tolerable differences as far as these impacts are concerned. Secondly, the steel embodied emissions initially taken as EcoInvent ones in Equer, were replaced by the Worldsteel database (IISI 2002) taking into account the recycling of steel at the end of its life in our manual calculations ([12] and [13]) It was shown that the end-of-life credits have a strong influence on the Embodied carbon/energy of the steel house.
(2) The design of the steel house: It was shown that the quantity of steel used per HFA, that was initially evaluated as 64 kg/m^2, can be increased to approximately 25% of its value, and that, in order to reach the Embodied carbon of the masonry house. Similarly, if the design is modified and the steel quantity increased, the Embodied carbon will increase subsequently in all climates. It is thus concluded that the design of the house presented in this analysis does not affect the final conclusion of the paper.

On top of these considerations, the main conclusions are provided in the next paragraph which highlight the influence of the energy mix and climate.

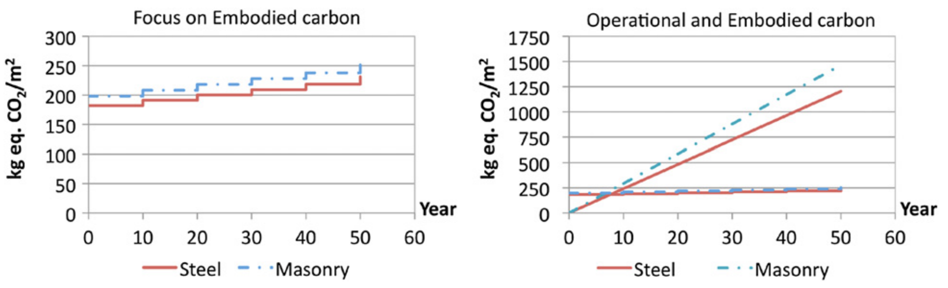

Fig. 4. Manual calculations – Operational and Embodied carbon versus lifespan for steel and masonry houses.

Table 5
Regional scenarios for energy supply.

	Belgium	Portugal	Sweden
Space heating	Natural gas	Oil	District heating
Hot water	Natural gas	Oil	District heating
Cooling	Belgium mix	CO_2 free electricity	District cooling
Building elec.	Belgium mix	Portugal mix (20%)	Sweden mix
User elec.	Belgium mix	Portugal mix (20%)	Sweden mix

3.2.2. Influence of the energy mix and the climate

First of all, in [13], it was showed that the electricity mix used in the analysis widely influences the LCA of the building. In the case study provided in the companion paper (masonry house for instance, but the same conclusion can be drawn for the steel house), the fraction of GWP due to electricity consumption (13.14/22.85 = 45%) is higher than the proportion of electricity in the total energy content (39.76/102.26 = 39%) and this fraction raises 72% (215.36/298.5) if the Operational energy is concerned. Secondly, if an alternative electricity mix is considered for the previous analysis, using for instance 35% of renewable sources (based on European policy goals for 2020), it will lead to a GWP and Energy reduction of 10% and 20% respectively.

Besides, the use of one wood furnace as back-up heater in winter can significantly reduce the GWP (up to 12% in this case study), the reason lays of course in the heating system that uses natural gas in Belgium and is therefore highly releasing CO_2. In the frame of this analysis, Oil was also considered for providing heat and how water in Belgium, because it is as popular as the use of natural gas. In this case, the GWP is increased by 12% whereas Primary energy remains more or less the same.

Finally, two more different climates are studied for the steel house with, obviously, their regional energy mixes (see companion paper) and heating systems most likely to be used for each region (see General Direction of Energy and Geology http://www.dgge.pt and [14–17]). The assumptions and results are summarized in Table 5 and Table 6 for the three regions. The Swedish District Heating system, distributing hot water via a grid of pipes to supply space heating and domestic hot water for use, uses a Combined Heat and Power plant that is nourished by an industrial surplus of the nearby steel mill facility (by-product). In this case, very low CO_2 emissions are observed.

To be perfectly clear, in this study, Embodied energy/carbon accounts for all impacts related to Product, Construction, Installation and End-of-Life (only partly), its value remains constant throughout the lifetime of the building. Operational energy/carbon is related to the energy needs during the life of the building and is thus proportional to the lifetime. As a matter of comment, normally, the Embodied impacts that include maintenance, repair or refurbishment should be dependant of the lifetime also. Indeed, depending on the considered moment of replacement or refurbishment, the Embodied energy/carbon is commonly represented using a stair graph.

In Table 7, the results are given in terms of Operational and Embodied energy as well as Operational and Embodied carbon for the three climates. The influence of the energy mix is clearly visible in the Operational carbon line. As for the Fig. 5, it depicts the Operational and Embodied energy/carbon together for the three case studies versus the lifespan.

First of all, in the frame of this study that concerns "ordinary" well-insulated house and not "passive" or "zero-energy" houses, it is possible to affirm that the Use Stage is the most harmful stage (in terms of energy consumption) during the building life-cycle for the three climates, which is also clearly stated in Tables 6 and 7. The total Operational energy (after the whole life which is, indicatively, taken as 50 years herein) is much higher than the Embodied energy.

Secondly, the Embodied carbon payback (the number of years required for the Operational carbon to exceed the Embodied carbon) is smaller than 50 years for Belgium and Portugal, whereas for Sweden, it equals 87 years (see Fig. 5 showing the Operational carbon over the lifespan together with the Embodied carbon although the embodied impacts are more visible in Table 7).

In the same line of thoughts, the Operational energy consumption is the major source of impacts for Belgium and Portugal, even if

Table 6
Results (kWh/m^2 yr).

	Belgium	Portugal	Sweden
Building Electricity (including cooling and double flux ventilation)	21.97	33.44	20.21
User Electricity	18.79	18.79	18.79
Total electricity demand	40.75	52.22	39
Space heating	32.38	11.77	62.57
Ventilation	12.07	6.57	26.15
Hot water	5.57	5.57	5.57
Total heating demand	50.02	23.91	94.29
Heat recovery (double flux ventilation)	−9.05	−4.93	−19.61
Total bought energy for heating	40.97	18.99	74.68
Total energy demand	90.77	76.13	133.29
Total bought energy	81.72	71.21	113.68
Without user electricity	62.93	52.42	94.89

Table 7
Operational and Embodied carbon/energy, Payback.

	Belgium	Portugal	Sweden
Operational carbon (kg/m^2 yr)	24.09	38.72	2.79
Operational energy (kWh/m^2 yr)	274.41	174.72	327.79
Total Embodied carbon (kg/m^2 yr)	4.62	4.62	4.89
Total Embodied energy (kWh/m^2 yr)	24.39	24.39	26.18
Embodied carbon payback	9.59	5.97	87.47
Embodied energy payback	4.44	6.98	4.89

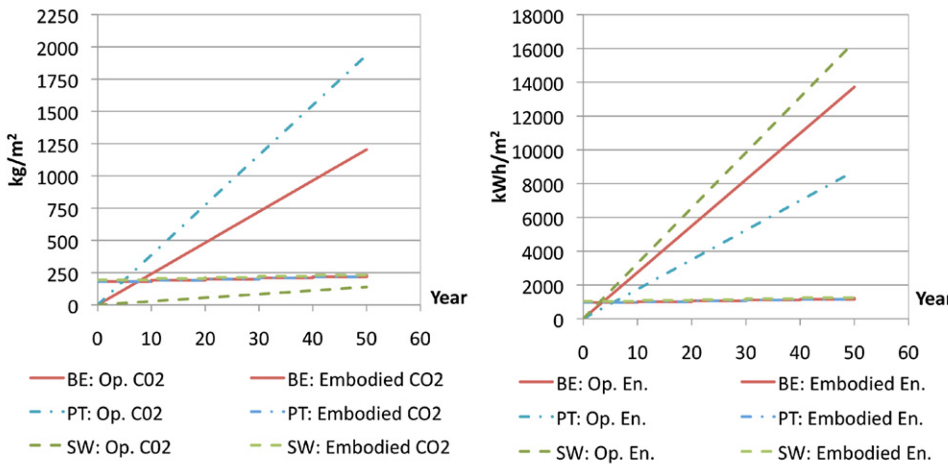

Fig. 5. Operational and Embodied energy/carbon (for the three climates).

the three case studies exhibit a strongly different response to their respective energy mixes combined with a totally different heating demand for the three cases. Especially, the way the electricity supplied to the households has been generated has a strong influence on the results. While for Belgium and Portugal, one could claim that the Embodied carbon is still not the most important contributor to this environmental impact, for Sweden, it is not anymore the case. The very low emissions associated to the production of electricity or heat reveal especially low Operational carbon.

4. Final conclusion

The companion paper described the development of a basic tool used for the life-cycle assessment of buildings located in different European climates. This tool permits the evaluation of the Embodied energy, the Embodied equivalent CO_2 emissions (or Embodied carbon), the Operational energy (or yearly energy consumption of the buildings) and the Operational carbon. The influence of the energy mix (solar water heater, district heating, etc) is included in the basic tool. This simplified tool has been verified thanks to a comparison between our calculations and results of already validated tools: the software Pleiades + Comfie combined with Equer. The basic tool can be used for simplified LCA of relatively complicated building. It provides information on the relative importance of the embodied impacts, on the consequence of a change in the energy mix or local energy harvesting. In addition to the uncertainties linked to LCA presented in the introduction of the companion paper and as in all LCA studies, the results must however be interpreted carefully according to the assumptions used in the calculation. Finally, note that the behaviour of the inhabitants, the economics criteria and the energy consumptions relating to services are beyond the scope of our study, which explains the differences in results of LCA carried out with others methods such as the hybrid LCA.

However, our results confirm the existing literature highlighting that, from an entire building life-cycle perspective, the operation phase represents the highest environmental impact (62–98% of the life-cycle total impacts). So, trying to reduce fluxes (energy, water and waste) during the utilisation phase seems to be the first action to achieve. But how? The usual way encountered in many countries is to decrease the Operational energy by increasing the insulation thickness and air leakage protection leading to very low or even zero-energy houses. But, the present paper and recent researches seem to highlight that the energy mixes strongly influence the Operational carbon especially when district heating is considered. We have shown how a shift in the energy mix towards renewable sources yields significant reductions, even without reducing energy consumptions. This is especially true in Sweden where a very cold weather inducing quite high heating demand is nevertheless responsible for less environmental impacts. In this respect, it should be interesting to investigate the Embodied and Operational energy and carbon of the same houses in radically different climates, including a city of tropical climate. CO_2 free electricity production or solar water heating flat plates can also reduce those impacts but to a shorter extent. The consequence of such decrease is that the Embodied impacts take a more representative place within the buildings life-cycle analysis when the energy mixes are more environmental. And, in those cases, green materials become of great interest. Last, it is worth pointing, that steel frame could lead to less Embodied impacts than masonry when taking into account the recycling credits.

References

[1] Blengini GA. Life cycle of buildings, demolition and recycling potential: a case study in Turin, Italy. Build Environ 2009;44:319–30.
[2] Andrade P, 2010. Structural assessment and optimization of the modular system of the student residential building in Luleå and Coimbra, Master thesis, Coimbra: Universidade de Coimbra.
[3] Marique AF, Reiter S. A method to evaluate the energy consumption of suburban neighbourhoods. HVAC&R Res, in press.
[4] Service Public de Wallonie (SPW). Performance Energétique des Bâtiments (PEB), http://energie.wallonie.be; 2010.
[5] Almeida AMB. 2011. Cradle-to-gate assessment of steel frame walls, roofs and floors for residential houses, Master thesis, Liège: Université de Liège.
[6] IZUBA ENERGIES. Software PLEAIDES + COMFIE, http://www.izuba.fr; 2011.
[7] IZUBE ENERGIES. Sotware EQUER, http://www.izuba.fr; 2011.
[8] Bourcy E. 2011. Analyse de cycle de vie des bâtiments, Master thesis (in French), Liège: Université de Liège.
[9] Marinković S, Radonjanin V, Malešev M, Ignjatović I. Comparative environmental assessment of natural and recycled aggregate concrete. Waste Manag 2010;30(11):2255–64.
[10] Rossi B, Courard L. Techniques d'analyse de cylce de vie appliquées aux structures. In: Proc. Journées scientifiques du Regroupement francophone pour la recherche et la formation sur le béton. Luxembourg: Université du Luxembourg; 2011.
[11] Hallard T, 2011. Comparaison des solutions passive et basse énergie pour des logements passifs, Master thesis (in French), Liège: Université de Liège.
[12] Rossi B. Sustainable steel constructions – Life-cycle inventory, methods and applications. In: Proc. sustainability workshop. Brussels: University of Liège; 2010.
[13] Rossi B. Integrated approach towards sustainable constructions – datasheet for steel products. Guimaraes, Portugal: Bragança L; 2011.
[14] European energy review 2010. Herbert Smith; 2010.
[15] Marchal D. Le parc d'appareils de chauffage au bois en Wallonie: première évaluation; 2011 [ValBiom asbl].
[16] Elfgren E, Grip C-E, Wang C, Karlsson J. Possibility to combine exergy with other process integration methods for a steelmaking case. Chem Eng Trans 2010;21.
[17] Energy in Sweden. Swedish Energy Agency; 2010.

Appendix A.8

Macrothink Institute™
Environmental Management and Sustainable Development
ISSN 2164-7682
2014, Vol. 3, No. 2

Retrofitting the Suburbs: Insulation, Density, Urban Form and Location

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Received: September 30, 2014 Accepted: October 13, 2014
doi:10.5296/emsd.v3i2.6589 URL: http://dx.doi.org/10.5296/emsd.v3i2.6589

Abstract

The effects of urban sprawl have been well documented, particularly regarding energy consumption. Suburban neighbourhoods are known to be energy inefficient and urban sprawl is considered as a major issue for sustainable development. To improve the energy efficiency of existing suburban urban fabrics is a major challenge that must be addressed to favour a sustainability transition of our built environment. In this context, this paper aims at investigating several scenarios that could be developed to improve the sustainability of existing suburban neighbourhoods: three main types of scenarios (building insulation, density, and urban form) and twelve sub-scenarios, which are focused on the possible evolution of the existing suburban building stocks, are proposed. Quantitative methods developed in previous research are used to assess and compare building and transportation energy consumption of a representative suburban case study. This application aims at investigating two main research questions: (1) "how to intervene in suburban neighbourhoods?" and (2) «where to intervene?" The main results of this application, which are focused on energy efficiency, are then studied in

a larger framework to highlight their opportunities and constraints. The main findings of the paper are that, beyond the traditional polarisation of the debates on the energy efficiency of our built environment between the "compact" and the "sprawled" city, a new pragmatic paradigm, which is focused on the smooth densification of existing suburban neighbourhoods, can make them evolve towards greater sustainability.

Keywords: Urban Sprawl, Suburban retrofitting, Energy efficiency, Urban form, Smooth densification

1. Introduction: Urban Sprawl and Energy Efficiency in Urban Planning

The process of urban sprawl, which commonly describes physically expanding urban areas, is a major issue for sustainable development (EEA, 2006). Urban sprawl is known to represent a significant contribution to the overall energy consumption of a territory, particularly for energy needs in buildings and for transport. The environmental effect of urban sprawl and uncontrollable urbanisation are receiving an increasing amount of attention and may lead to various issues such as environmental pollution or large-scale climate change (CPDT, 2002; He et al., 2011; UTF, 1999; Young et al., 1996). However, despite the growing importance of energy issues in public debate, low-density suburban developments continue growing regardless of their location. Even new districts that set themselves up as "eco" or "sustainable" are sometimes built far from city centres and are not necessarily ecological because of the high transport energy consumption (Harmaajärvi, 2000). Such developments are found all over Europe, the United States and even emerging countries (Nesamani, 2012; da Silva et al., 2007; Yaping and Min, 2009)and have become an important part of our contemporary metropolitan areas (Phelps, 2012). An evaluation on the sustainability of these suburban neighbourhoods is necessary and requires the appropriate methods and tools.

The problems of urban sprawl and its numerous environmental, economic and societal effects inevitably refer to the question of "urban form" and its densities and, in particular, the validity of two prevailing and opposite models: the "compact city" and the "sprawled city". The opponents of sprawl articulate the "compact city" model in opposition to the "sprawled city" model using the concepts of centrality, high density, mixed use and performing urban transportation systems. Numerous authors argue that more compact urban forms will significantly reduce the energy consumption in both the building and the transportation sectors (e.g., Ewing et al., 2008; Gillham, 2002; Newman and Kenworthy, 1989 and 1999; Riera and Rey, 2013; Steemers, 2003). However, the concrete feasibility of this model, which is often presented as an ideal urban form, is questionable. In fact, numerous research studies and policies at the national, regional and local levels pretend that it is crucial to favourthe compactness of cities and to thwart urban sprawl but do not propose adequate tools or policies to meet these goals. Moreover, several effects that are related to high compactness (such as congestion, pollution, increase of land prices, etc.) are not adequately addressed. In addition, in numerous European countries, the renewal rate of the building stock is notably low (1 to 2% per year), which implies that the main challenge is this existing building stock and its transition towards greater energy efficiency and greater sustainability. More problematically, this model does not propose any solution for the existing suburban building stock.

The “sprawled city” model dates back from the 19th century and was first developed to reduce the use of urban soil and the production prices. Because the transport costs rapidly declined and the travel speed increased (Ewing, 1994), the mobility levels per capita have substantially increased over the recent past and have favoured the development of suburban neighbourhoods. The sprawl is believed to be facilitated by car ownership and use and to contribute to them in a positive feedback loop that reinforces both low-density development and motorisation (Gilbert and Perl, 2008). Ewing (1994) and Urban Task Force (1999) also defined sprawl in terms of “undesirable” land-use patterns. However, if some authors are clearly critical of suburbs, others propose a more critical conversation (Modarres, 2009). Sprawl often induces lower land prices and more affordable housing (Gordon and Richardson, 1997). The low-density developments mean more space and a higher standard of living for numerous households and constitute one of the preferred living accommodations (Berry and Okulicz-Kozaryn, 2009; Couch and Karecha, 2006; Gordon and Richardson, 1997; Howley, 2009). However, the promotion of this development model even at notably high construction standards (low energy or passive standards that limit the heating energy requirements of buildings at 60 and 15 kWh/m ²year, respectively) will not help to solve numerous problems that are related to urban sprawl, such as soil waterproofing, car dependency or the costs of infrastructure, networks and services.

Three main types of strategies could be investigated to limit the urban sprawl at the regional / national level. The first strategy could consist in an adaptation of the urban planning regulation framework to prohibit the urbanisation of new suburban neighbourhoods in a plain area. However, this strategy seems unrealistic because of its numerous financial consequences (compensation for depreciation, etc.). Moreover, this strategy is only efficient at a large (national) scale. The second strategy, which is often mobilised in the current policies, favours the urban renewal of city centres to propose dwellings that are better adapted to the new comfort and insulation standards (houses with gardens for families, etc.) The third strategy that could be developed follows the same goal as the previous one and consists in building new sustainable neighbourhoods located near good transportation hubs, with have attractive green and public spaces, high quality of life, etc. These last two scenarios could favour a soft transition of our built urban environment towards greater sustainability, but there is one major limitation: they do not consider the future and the possible evolutions of the numerous existing suburban neighbourhoods.

There are intervention scenarios for the existing suburban neighbourhoods to adapt them to climate change, which have been recently developed in the literature, particularly in the United States of America, the United Kingdom and Australia (e.g., Dunham-Jones and Williamson, 2011; Modarres and Kirby, 2012; Rice, 2012; Tachieva, 2012; Williams et al., 2013). These authors propose concrete approaches, at the local level, to retrofit suburbs and increase their sustainability. Amongst various approaches (e.g., an increase in the diversity of functions, good public transportation, a retrofitting of existing networks to increase walking), an increase in the density of both people and uses is often presented as the key means for success. In France, the intensification of suburban areas is also an emerging research topic. A recent French research was dedicated to the issue of Bimby, or “Build In My Back Yard” (Miet and Le Foll, 2013) and specifically proposed to exploit the large land resources available in suburban gardens to accommodate new dwellings. Since the first works on this issue of residential developments in gardens (Whitehand et al., 1991), and despite its potential for suburban intensification and urban compactness, this topic remains relatively little-researched (Sayce et al., 2012). Moreover, and more generally speaking, although one of the main aims of the approaches developed to retrofit suburban areas is to increase their sustainability, their energy efficiency is not evaluated.

In this context, this paper investigates the necessary conditions to improve the energy efficiency of existing suburban areas, by focusing on the impact of urban planning on building and transport energy consumptions at the neighbourhood scale. The following sections present (1) three main retrofitting scenarios that can be investigated to favour this evolution of suburban areas, (2) a quantitative method to assess the energy efficiency of these scenarios regarding thebuilding and transport energy consumptions at the neighbourhood scale, (3) its application to one representative neighbourhood in Belgium and (4) the confrontation between these results, focused on the energy efficiency, with the required practical conditions to achieve the proposed scenarios, such as the regulation framework, the cost and the social acceptability of the proposed measures. Finally, our main findings are summarised to conclude the paper and offer perspectives for further study onsustainability, energy efficiency and retrofitting in the suburbs.

2. Retrofitting Scenarios

In this paper, three main scenarios that address a possible evolution of these existing suburban neighbourhoods are investigated and assessed. These scenarios address the characteristics of buildings and urban form. They do not address parameters that are not directly linked to urban planning. The behaviour of the inhabitants, that is known to have a significant impact on energy consumption, is not discussed in this paper that focused on urban form. The behaviour of the inhabitants in suburban houses has been extensively studied in a previous paper (de Meester et al., 2013).

2.1 Improving the Insulation of the Existing Suburban Building Stock

The first scenario improves the insulation of the existing suburban building stock without any other intervention on the urban form of the existing neighbourhoods (thus, it maintains their characteristics in terms of the density, the diversity of functions, etc.). These scenarios are identified in the following of this paper by the letter “A”. Five sub-scenarios are defined to capture different levels of intervention: A1 -insulating the roof with 20 centimetres of mineral wool, A2 -insulating the roof and replacing the glazing, A3 -retrofitting the entire envelope to fit the actual energy requirements for new buildings, A4 and A5 -retrofitting the entire building envelope to satisfy the low-energy (heating requirements < 60 kWh/m^2year) and the passive (heating requirements < 15 kWh/m^2year) standards, respectively.

2.2 Increasing the Built Density of Existing Suburban Neighbourhoods

The second scenario addresses an increase in the built density of the existing neighbourhoods by constructing new houses or apartments in the gardens, where land opportunities are available. There are identified by the letter “B” in the following of the paper. Four sub-scenarios are defined. In B1, new dwellings are built on the remaining unoccupied plots. In B2, the existing plots are divided to construct new dwellings at the bottom of the plots. In B3, new dwellings (detached houses) are built among the existing houses.In B4, new dwellings (terraced houses) are built among the existing houses. These four sub-scenarios are illustrated on Figure 1.

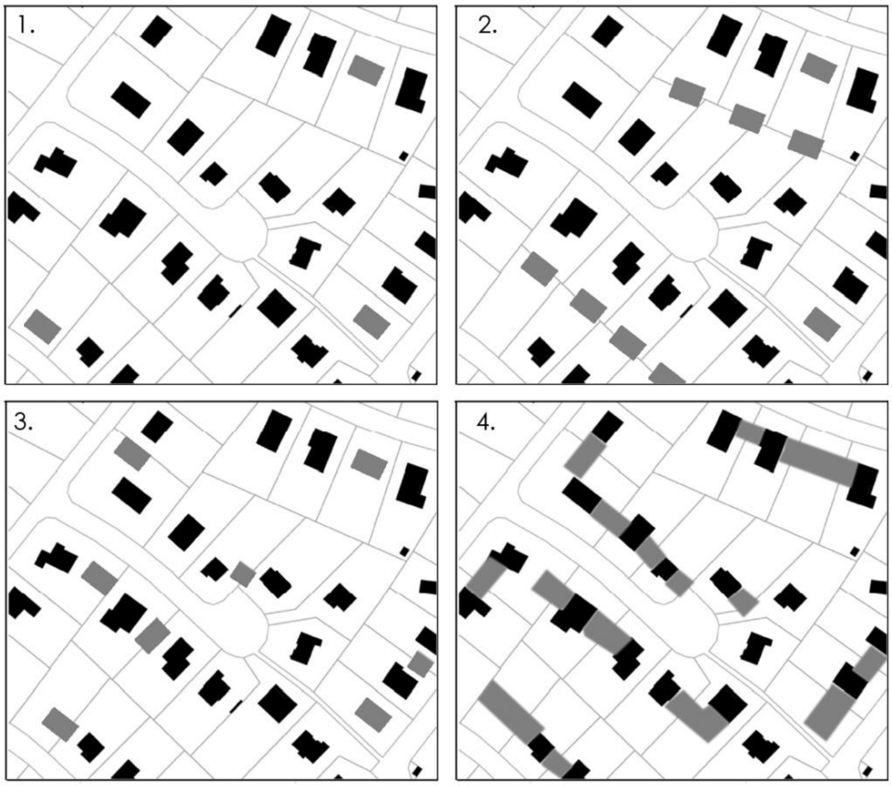

Figure 1. Illustration of the four sub-scenarios that increase the built density of the existing suburban neighbourhoods thanks to the construction of new dwellings in the gardens (the existing houses are in black, and the new dwellings are in grey). In B1, new dwellings are built on the remaining unoccupied plots. In B2, the existing plots are divided to construct new dwellings at the bottom of the plots. In B3, new dwellings (detached houses) are built among the existing houses. In B4, new dwellings (terraced houses) are built among the existing houses.

2.3 Re-Building More Compact Suburban Neighbourhoods

The third scenario is the most theoretical because it implies to demolish existing neighbourhoods and to re-build new neighbourhoods. It investigates the energy efficiency of more compact urban forms than the "detached houses". This scenario is proposed because it allows the comparison between low-density suburban neighbourhood and more compact urban forms, for one fixed level of insulation, the same number of dwellings and the same built surface area. Scenarios dealing with urban form are identified by the letter "C" in the following of the paper. C1 is the reference case; the urban form of the suburban neighbourhood remains unchanged (the detached houses are built on large individual plots), but the houses are built according to the actual European standard for new buildings, which includes the energy requirements. Two more sub-scenarios are defined. In these sub-scenarios, the number of dwellings and the built surface area remain constant; however, in C2, the dwellings are terraced houses (ground floor + 1 floor) that are organised in the traditional urban blocks, whereas in C3,the dwellings are collective apartment buildings (ground floor + 2 or 3 floors) as illustratedin Figure 2. In the sub-scenarios C2 and C3, the dwellings are built according to the actual standard for new buildings regarding the energy requirements for heating.

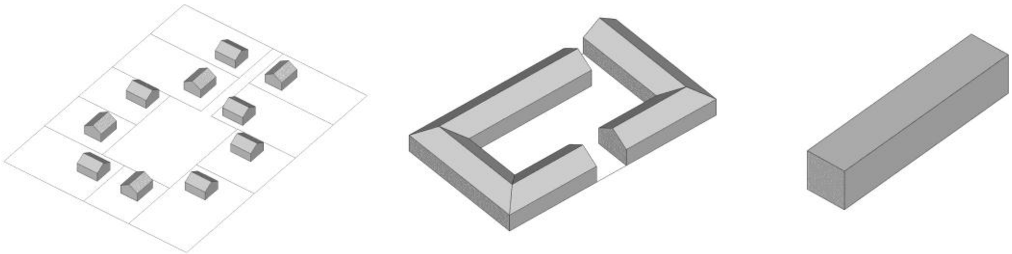

Figure 2. Schematic representation of the reference case and the two sub-scenarios dealing with more compact urban forms. Sub-scenario C1 (illustrated on the left of this image) C1 is the reference case; the urban form of the suburban neighbourhood remains unchanged (the detached houses are built on large individual plots), but the houses are built according to the actual European standard for new buildings, which includes the energy requirements. In sub-scenario C2 (middle), the dwellings are terraced houses (ground floor + 1 floor) that are organised in the traditional urban blocks, whereas in sub-scenario C3 (right), the dwellings are collective apartment buildings (ground floor + 2 or 3 floors).

3. Method and Assumptions

A method was developed to evaluate the energy consumption of the suburban neighbourhoods and the retrofitting scenarios. The first part of the method, which calculates the energy requirements of the buildings and the assumptions that were used are extensively presented in Marique and Reiter (2012a). The methodology combines a typological classification of buildings (based on the common ownership, the number of level and the surface area of the dwelling; see also Marique and Reiter (2012a) for more details), thermal dynamic simulations and statistical treatments of national censuses to assess the annual energy consumption for space heating, space cooling, ventilation, appliances and domestic hot water. The energy consumption and the primary energy consumption for space heating, cooling and ventilation at the neighbourhood scale are calculated by adding the results from the energy simulations for each type of house according to their distribution in the neighbourhood. The energy consumptions of the appliances, for cooking and domestic hot water are not considered in the framework of this paper. Note also that empirical surveys (ICEDD, 2005; Kint, 2008) show that heating represents the largest portion of the overall energy consumption of Belgian households (76%).

The second part of the energy assessment addresses the energy consumption for daily mobility, which is assessed using a commute-energy performance index that was developed by Boussaux and Witlox (2009) and adapted by Marique and Reiter (2012b) for suburban areas.

Assumptions taken into account for the Belgium context were presented extensively in Marique and Reiter (2012b). This index is expressed in kWh/travel.person and represents the mean energy consumption per territorial unit for travel for one person who lives within a particular neighbourhood. This index considers the travelled distances, the means of transport and its relative consumption rates, which are expressed by equation (1). This index was calculated and mapped for the whole Belgium territory, using a GIS tool, at the "census block" scale. In Belgium, the "census block" (or neighbourhood) is the smaller territorial unit in which statistical data are available.

$$Energy\ performance\ index\ (i) = \sum_{m} \frac{D_{mi} \cdot f_m}{T_i} \tag{1}$$

In equation (1), i is the territorial unit, m is the mean of transport (diesel car, fuel car, train, bus, bike, on foot),*Dmi* is the total distance travelled using the means of transport *m* in the district *i*,*fm* is the consumption factor attributed to the means of transport *m*, and *Ti* is the number of persons in the territorial unit *i*. The consumption factors depend on the consumption of the vehicles (litres of fuel per kilometre) and their occupancy rate. The indices are 0.56 kWh/person.km for a diesel car, 0.61 kWh/p.km for a gasoline car, 0.45 kWh/p.km for a bus, 0.15 kWh/p.km for a train and 0 for non-motorised means of transportation because they do not consume any energy in the following application but can be adapted to each situation and territory because their calculation is entirely parameterised.

The energy consumption for the daily mobility is obtained via equation 2.

$$E_{DM} = Energy\ performance\ index \cdot N \cdot T \tag{2}$$

In equation 2, the energy performance index is multiplied by the number of people *N* and the number of trips *T* in the neighbourhood.

Note that these data only consider the home-to-work and home-to-school travels, but we can use the same methodology for in situ survey data to consider all travel purposes. Although the home-to-work and home-to-school travels are becoming less meaningful in the daily travel patterns in the Western world because of the dramatic growth in other activities (Graham, 2000; Pisarski, 2006), they have more structural power than other travel forms because they are systematic and repetitive.

Using the developed method, the building energy consumption and the transportation energy consumption can be expressed with a common unit (kWh/person.year or kWh/neighbourhood.year), which allows one to consider these two topics together and to include the effect of the location on the daily mobility in the energy balance.

4. Application and Results

Urban sprawl is a concern in a large portion of Wallonia (Belgium). In this region, 52% of the building stock is detached and semi-detached houses (Kints, 2008), and 50% of the census blocks of the region has a mean housing density between five and twelve dwellings per hectare (Vanneste et al., 2007). Suburban neighbourhoods are found everywhere in the region and not only in the suburban municipalities. In this case study, the aforementioned method is applied to one representative suburban neighbourhood of Wallonia. This representative neighbourhood (Figure 3) was selected based on a typological classification of neighbourhoods that was performed to highlight the most representative type of suburban neighbourhoods. Numerous simulations, calculations and sensitivity analyses were performed on several representative neighbourhoods and highlighted that the major trends (highlighted below) remain the same for the suburban neighbourhoods, which shows a built density of 5-12 dwellings per hectare (Marique, 2013).

Figure 3. The selected representative suburban neighbourhood

Currently, the required energy for heatingin buildings is the most important portion of the calculated consumption at the neighbourhood level because the existing suburban building stock in Wallonia is old and poorly insulated. Depending on the available bus services and the distance to the city centre, transportation (only home-to-work and home-to-school travels are considered) represents 11.9-35.9% of the energy consumption of a neighbourhood.

Then, the aforementioned twelve sub-scenarios were applied to this representative neighbourhood to investigate their energy efficiency. Quantitative results are summarized in Table 1 and show that, from an energy viewpoint, all scenarios present interesting results. As stated in Table 1, the energy consumption for heating in buildings is reduced by -7.3% (if only the roofs of the existing buildings are insulated) to -89.8% (if passive retrofitting is promoted). For one fixed insulation level (e.g., the actual fixed energy requirements in the European Directive on the Energy Performance of Buildings as presented in Table 1, although the trends are identical for the low-energy and the passive standards), the most efficient strategies rebuild the neighbourhoods in a more compact urban form (urban blocks or apartment buildings). These scenarios allow a reduction of 68.1% and 70.4%, respectively, in comparison with the reference case (detached houses; related to a reduction of 45.2% only), which highlight the low energy efficiency of this type of urban form, even when the detached houses have better insulation (the result is also true for identical insulation levels). An increase in the built density of the existing neighbourhoodsalso improves the energy efficiency of the existing neighbourhoods by constructing new well-insulated houses (B1 to B3). In B4, the results are better because the insulation of new buildings and the building distribution (terraced houses) are mobilised together. Another interesting scenario, which is assimilated into B4, is the building of new collective dwellings in existing neighbourhoods where large land opportunities remains available (for example, in the centre of suburban blocks that were only urbanised on their perimeter). To optimise the energy consumption reductions of the scenarios that increase the built density, it appears necessary to also improve the insulation of the existing buildings. Beside their interest in terms of the energy efficiency, the scenarios that increase the built density avoid the urbanisation of unoccupied land and the construction of new infrastructures.In these scenarios, the new dwellings are developed by increasing the density of the existing neighbourhoodsinstead of developing new low-density neighbourhoods.

Table 1. Reductions in energy consumption for heating in buildings, which were obtained for twelve retrofitting scenarios

A.INSULATION		B.BUILT DENSITY		C.URBAN FORM	
Scenarios	Energy consumption reductions	Scenarios	Energy consumption reductions	Scenarios	Energy consumption reductions
A1.Insulation in the roofs	-7.3%	B1.Unoccupied plots	-5.2%	C1.Detached houses	-45.2%
A2.Insulation in the roofs + double glazing	-14.8%	B2.Bottom of the plots	-17.4%	C2.Urban blocks	-68.1%
A3.Retrofitting to actual standard	-45.2%	B3.Detached houses between existing houses	-12.9%	C3.Apartment buildings	-70.4%
A4.Retrofitting to the low-energy standard	-59.2%	B4.Terraced houses between existing houses	-30.4%		
A5.Retrofitting to the passive standard	-89,8%				

However, the previous scenarios, particularly those that address the density and the construction of new urban forms, cannot be recommended everywhere in the territory. It is crucial to consider the effect of the location of the neighbourhoods on the travelled distances and the transport energy consumption. For example, the building of a mixed and dense neighbourhood andthe increase in density of an existing neighbourhood that is notably badly located (far from the city centre, shops and other services, with notably low bus services) are obviously counter-productive. Thus, the effect of the location of the neighbourhoods was finally investigated using the commute-energy performance index. Marique et al. (2013a; 2013b) highlighted the huge effect of the structure of the territory on the transport energy consumption (Figure 4). In this work, the territory is interpreted as the system defined by three main elements: i) the location of work places and services (commercial, education, leisure, etc.), ii) the spatial distribution of the population according to the place of residence and iii) the infrastructures (the transport and technical networks). The variation of functions (residences, shops, work places, leisure, etc.) in the neighbourhood and the built density have the strongest effect on the variation of the transport energy consumption. The energy efficiency of home-to-work and home-to-school trips is strongly determined by the travelled distance. The mode choice has a smaller effect on the energy performance of those types of commutes. This result can partly be explained by the relationship between the distance and the mode choice.

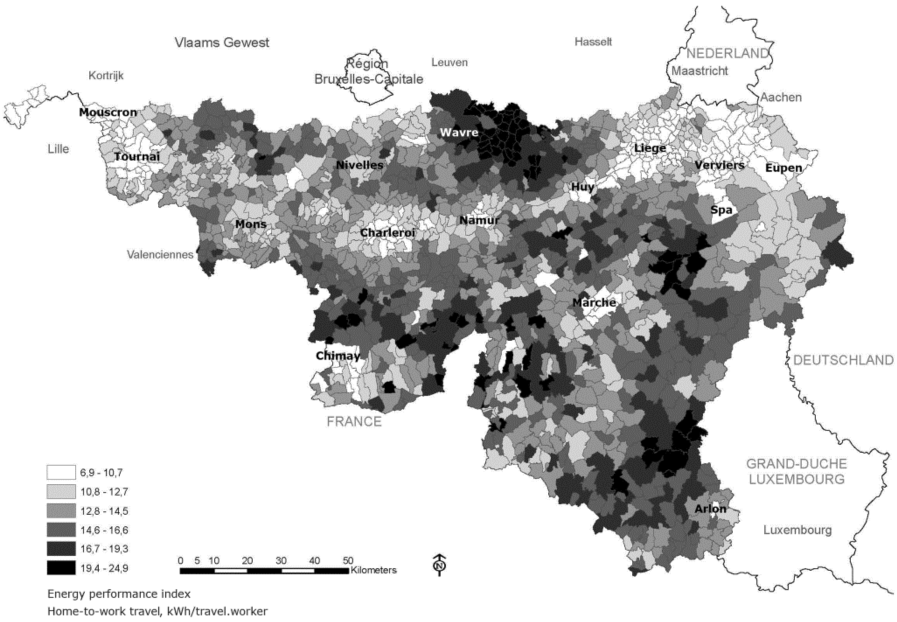

Figure 4. The mapping the commute-energy performance index for home-to-work travel (in kWh/person.travel at the neighbourhood scale shows the variation of the transportation energy consumption (home-to-work travel) according to the location of the neighbourhood.

In this work, these results are mobilised to identify the most appropriate suburban neighbourhoods, where an increase in the built density could be favoured without increasing the energy performance index for commuting. Because suburban neighbourhoods are mainly mono-functional and less dense, this simulation is based on the proximity between one suburban neighbourhood and one or more rural or urban cores, which are dense and present a great variety of functions. The urban and rural cores that we used are defined by the National Institute for Statistics (INS, 2006). Figure 5 highlights in yellow the most appropriate suburban neighbourhoods. The green suburban neighbourhoods are located further from the existing urban or rural cores. In those neighbourhoods, an increase in the built density and the construction of new neighbourhoods is not recommended; because of their location and characteristics, the transport energy consumption is expected to be high (longdistances to travel and few or no alternatives to private cars).

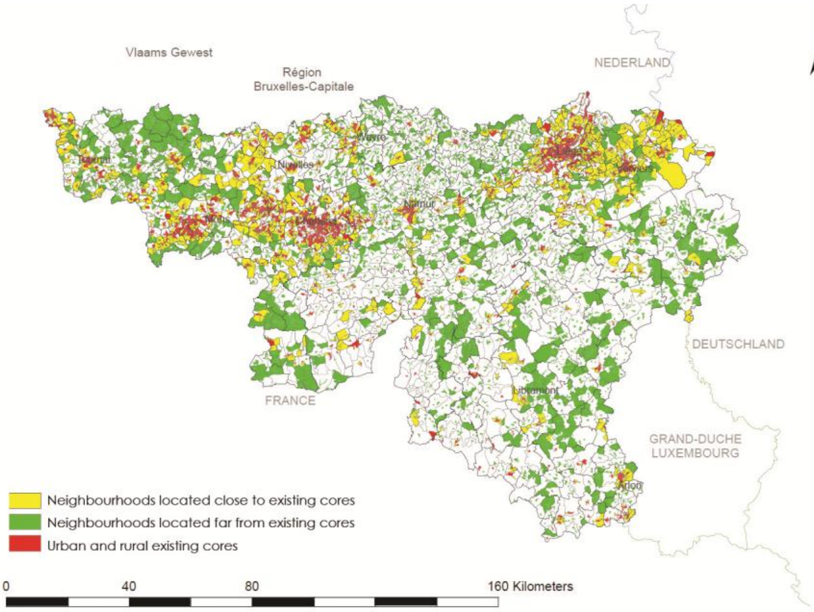

Figure 5. The urban and rural cores (in red), suburban neighbourhoods that are near an urban/rural core (in yellow) and suburban neighbourhoods that are far from the existing cores (in green).

Thus, the scenarios that increase the built density, as well as the building of new neighbourhoods, can be limited to these high-potential areas (neighbourhoods highlighted in yellow on Figure 5). Moreover, these two types of scenarios allow us to recompose locally dense and mixed cores, which have proved their interest in energy efficiency and mode choice in transportation (Marique et al., 2013a, Myung-Jung et al., 2013). This opportunity is interesting particularly because the regional administration has evaluated that 350,000 new dwellings will be built by 2040 to absorb the forecasted demographic growth (+600,000 inhabitants in Wallonia for 2040).

5. Discussion: Retrofitting the Suburbs by Improving Their Energy Efficiency; Key Challenges and Limitations

The results in the first parts of this paper were focused on the energy consumption, which is a crucial topic in the scope of a sustainability transition of suburban areas. This approach is finally completed and moderated by considering the previous study in a broader framework, which considers the economic feasibility of the proposed measures, the regulation framework that allows or does not allow these measures and its societal acceptability.

The cost of the works related to the sub-scenarios that address the insulation of existing buildings increased the insulation level increase (thus, the energy efficiency increase) because of the huge quantity of material to use to reach efficient energy standards. The return on investment must be studied in every particular case to refine this trend. Although there have been financial intensives for several years, this aspect is a major brake to the energy retrofitting of the existing building stock. The division of the existing large plots (mean size = 1,000 m^2) to increase the built density of the existing neighbourhoods allows the owners to sell a part of their plot and gain a considerable amount of money. This option, also investigated in the French

BIMBY research (Miet and Le Foll, 2013) is particularly interesting for households that do not use their entire plot.

We have studied the existing regulation framework (regional and local codes and rules that are related to architecture and urban planning) in Wallonia (Belgium) and this framework is adapted to the scenarios that address the insulation of existing buildings. The only possibly problematic element is the replacement of the facing materials (some colours and materials must be respected according to the local regulations). To increase the built density of existing neighbourhoods is more complicated (except in the sub-scenario B1) because most suburban municipal authorities are reticent to this trend and have adopted specific regulations to avoid increasing the built density of the existing and new suburban neighbourhoods. Because the densification of the existing low-density neighbourhoods is a major preoccupation of the actual regional government (urban planning is a regional matter in Belgium), we can hope for an evolution towards more flexibility in the next few years. Moreover, if the increase in the built density in scenario B1 to scenario B4 can be based on the individual initiatives, scenarios C1 to C3 and the densification of large unoccupied plots in the centre of the existing neighbourhoods request an important intervention of public authorities and private developers to manage the aspects linked to the land properties and build collective development (with various functions, etc.).

Finally, the societal acceptability of the scenarios that increase the built density is also notably problematic. As previously highlighted in the literature, a recent in situ survey in Wallonia (Pierson, 2010) confirms that households in those low-density suburban neighbourhoods are quite reticent to any changes, particularly to increase the built density. Further applied research dedicated to the social representations of housing is necessary to overpass this huge brake.

6. Conclusions and Perspectives

This paper addresses the challenges and conditions of a retrofitting of suburban areas, which was articulated around an increase in the energy efficiency in both the building and the transportation sectors. Two powerful levers were used: (1) urban form, which was considered in addition to the individual building scale, and (2) mobility, to consider the energy used in transportation. Three main types of scenarios (the retrofitting of existing neighbourhoods, increasing the built density and more compact urban forms) and twelve sub-scenarios focused on possible evolutions of the existing suburban building stock were modelled and assessed. The main results of this approach, which were focused on the energy efficiency, were then rethought in a larger framework to highlight the opportunities, the limitations, the constraints and the feasibility of each strategy. These findings show that beyond the traditional polarisation of the debates on energy efficiency of our built environment between the “compact city” and the “sprawled city”, a new pragmatic paradigm, focused on the sustainability transition of suburban areas, particularly by smooth densification in the gardens of existing houses, can make suburban areas evolve towards greater sustainability. However, there are numerous brakes, particularly those that are related to the existing regulation framework and the societal acceptability of an increased density, which should be investigated in further study to be surpassed. These results open avenues for further research on the smooth densification in the suburbs (e.g., energy supply, renewable energy, water heating, ICT).

Acknowledgement

This paper presents the main results of research that was funded by the Walloon region of Belgium in the framework of the "Suburban Areas Favouring Energy efficiency" (SAFE) and the "Solutions for Low Energy Neighbourhoods" (SOLEN) research projects.

References

Berry, B., & Okulicz-Kozaryn, A. (2009). Dissatisfaction with city life: A new look at some old questions. *Cities*. 26, 117-124. http://dx.doi.org/10.1016/j.cities.2009.01.005

Boussauw, K., & Witlox, F. (2009).Introducing a commute-energy performance index for Flanders.*Transportation Research Part A*. 43, 580-591. http://dx.doi.org/10.1016/j.tra.2009.02.005

Couch, C., & Karecha, J. (2006). Controlling urban sprawl: Some experiences from Liverpool. *Cities*. *23*(5). 353-363. http://dx.doi.org/10.1016/j.cities.2006.05.003

CPDT. (2002). *Les coûts de la désurbanisation*. Namur: Conférence Permanente du Développement Territorial.

Dunham-Jones, E., & Williamson, J. (2011).*Retrofitting suburbia. Urban design solutions for redesigning suburbs*. Hoboken: J. Wiley & Sons, Inc.

EEA. (2006). *Urban sprawl in Europe. The ignored* challenge. Final report.Copenhagen: European Environment Agency.

Ewing, R. H. (1994). Characteristics, causes and effects of sprawl: A literature review. *Environmental and Urban Studies*. 2. 1-15.

Ewing, R., Bartholomew, K., Winkelma, S., Walters, J., & Chen, D. (2008). *Growing cooler: The evidence on urban development and climate change*. Washington DC: Urban Land Institute.

Gilbert, R., & Perl, A. (2008). *Transport Revolutions: Moving people and freight without oil*. London: Earthscan.

Gillham, O. (2002). *The Limitless City: A Premier on the Urban Sprawl Debate*. Washington D.C.: Island Press.

Gordon, P., & Richardson, H. (1997). Are compact cities a desirable planning goal? *Journal of the American Planning Association*. *63*(1), 95-106. http://dx.doi.org/10.1080/01944369708975727

Graham, A. (2000). Demand for leisure air travel and limits to growth. *Journal of Air Transport Management*. *6*. 109-118. http://dx.doi.org/10.1016/S0969-6997(99)00031-9

Harmaajärvi, I. (2000). EcoBalance model for assessing sustainability in residential areas and relevant case studies in Finland.*Environmental Impact Assessment Review*. *20*. 373-80.

http://dx.doi.org/10.1016/S0195-9255(00)00048-2

He, J., Bao, C.K., Shu, T.F., Yun, X. Y., Jiang, D., & Brown, L. (2011). Framework for integration of urban planning, strategic environmental assessment and ecological planning for urban sustainability within the context of China. *Environmental Impact Assessment Review. 31*(6), 549-560. http://dx.doi.org/10.1016/j.eiar.2010.09.002

Howley, P. (2009). Attitudes towards compact city living: Towards a greater understanding of residential behavior. *Land Use Policy. 26*. 792-798. http://dx.doi.org/10.1016/j.landusepol.2008.10.004

ICEDD. (2005). *Bilan énergétique wallon 2005. Consommations du secteur du logement 2005*. Namur : MRW, Direction générale Aménagement des Technologies, de la recherché et de l'Energie-Conception et Réalisation ICEDD asbl, Report. Institut de Conseil et d'Etudes en Développement Durable.

INS. (2005). Atlas de Wallonie. Les Hommes > Noyaux d'habitat (INS). http://sder.wallonie.be/ ICEDD/CAP-atlasWallonie2006/pages/atlas.asp?txt=homNoyaux (accessed in September 2013).

Kints, C. (2008). *La rénovation énergétique et durable des logements wallons. Analyse du bâti existant et mise en évidence des typologies de logements prioritaires.* Université Catholique de Louvain-La-Neuve, Architecture & Climat.

Marique, A. F., & Reiter, S. (2012a). A Method to Evaluate the Energy Consumption of Suburban Neighbourhoods. *HVAC&R Research. 18*(1-2), 88-99.

Marique, A. F., & Reiter, S. (2012b).A method for evaluating transport energy consumption in suburban areas.*Environmental Impact Assessment Review. 33*, 1-6. http://dx.doi.org/10.1016/j.eiar.2011.09.001

Marique, A-F. (2013).*Méthodologie d'évaluation énergétique des quartiers périurbains. Perspectives pour le renouvellement périurbain wallon.* (A method to evaluate the energy consumption of suburban neighbourhoods. Prospects for a sustainable suburban renewal in Wallonia).Unpublished Doctoral Thesis, University of Liege, 236p.

Marique, A. F., Dujardin, S., Teller, J., & Reiter, S. (2013a).Urban sprawl, commuting and travel energy consumption.*Proceedings of the Institution of Civil Engineers.Energy. 166*, 1-13.

Marique, A. F., Dujardin, S., Teller, J., & Reiter, S. (2013b). School commuting: the relationship between energy consumption and urban form. *Journal of Transport Geography, 26*. 1-11. http://dx.doi.org/10.1016/j.jtrangeo.2012.07.009

De Meester, T., Marique, A.-F., De Herde, A., & Reiter, S. (2013). Impacts of occupant behaviours on residential heating consumption for detached houses in a temperate climate of the northern part of Europe. *Energy & Buildings, 57*, 313-323. http://dx.doi.org/10.1016/j.enbuild.2012.11.005

Miet, D., & Le Foll, B. (2013). Construire dans mon jardin et résoudre la crise du logement.

Cinq idées-clés pour comprendre la filière BIMBY. *Métropolitiques*.

Modarres, A. (2009). Book Review. *Cities. 27.* 122-125. http://dx.doi.org/10.1016/j.cities.2009.11.010

Modarres, A., & Kirby, A. (2010). The suburban question: Notes for a research program. *Cities 27*, 114-121. http://dx.doi.org/10.1016/j.cities.2009.11.009

Myung-Jun, M. J., Kim, J. I., Kwon, J. H., & Jeong, J. E. (2013). The effects of high-density suburban development on commuter mode choice in Seoul, Korea. *Cities*. *31*, 230-238. http://dx.doi.org/10.1016/j.cities.2012.06.016

Nesamani, K. S. (2010). Estimation of automobile emissions and control strategies in India. *Science of the Total Environment. 408,* 1800-1811. http://dx.doi.org/10.1016/j.scitotenv.2010.01.026

Newman, P., & Kenworthy, J. R. (1989). *Cities and Automobile Dependence: A sourcebook*. Aldershot: Gower Publishing Co.

Newman, P., & Kenworthy, J. R. (1999). *Sustainability and Cities: overcoming automobile dependence*. Washington DC: Island Press.

Phelps, NA. (2010). Suburbs for nations ? Some interdisciplinary connections in the suburban economy.*Cities. 27*, 68-76. http://dx.doi.org/10.1016/j.cities.2009.11.005

Pierson, C. (2010). *Approche sociologique de l'habitat périurbain.*(Societal approach to suburban dwellings).Unpublished master thesis, University of Liège.

Pisarski, A. E. (2006). *Commuting in America III. The third national report on commuting patterns and trends.*Washington D.C.: Transportation Research Board,

Riera Pérez, M. G., & Rey E. (2013). A multi-criteria approach to compare urban renewal scenarios for an existing neighbourhood. Case study in Lausanne (Switzerland).*Building and Environment. 66*, 58-70. http://dx.doi.org/10.1016/j.buildenv.2013.03.017

Rice L. (2012). Retrofitting suburbia: Is the compact city feasible? *Urban Design and Planning. 163*(4), 193-204. http://dx.doi.org/10.1680/udap.2010.163.4.193

Sayce, S., Walford, N., & Garside, P. (2012). Residential development on gardens in England: Their role in providing sustainable housing supply. *Land Use Policy. 29*(4), 771-80. http://dx.doi.org/10.1016/j.landusepol.2011.12.002

Da Silva, A. N. R., Costa, G. C. F., & Brondino, N. C. M. (2007). Urban sprawl and energy use for transportation in the largest Brazilian cities. *Energy for Sustainable Development*. *11*(3), 44-50. http://dx.doi.org/10.1016/S0973-0826(08)60576-1

Steemers, K. (2003). Energy and the city: density, buildings and transport. *Energy and Buildings*. *35*(1), 3-14. http://dx.doi.org/10.1016/S0378-7788(02)00075-0

Tachieva, G. (2010). *Sprawl repair manual*. Washington D.C: Island Press.

UTF. (1999).*Towards an Urban Renaissance*. London: Routledge, Queen's Printer and Controller of HMSO.

Vanneste, D., Thomas, I., & Goosens, L. (2007). *Le logement en Belgique. Report SPF Economie et Statistique*. Brussels : SPF Politique Scientifique.

Whitehand, J. W. R., & Larkham, P. J. (1991). House building in the back garden: reshaping suburban townscapes in the Midlands and South East England. *Area 8*, 57-65.

Williams, K., Gupta, R., Hopkins, D., Gregg, M., Payne, C., Joynt, J., Smith, I., & Bates-Brkljac, N. (2013). Retrofitting England's suburbs to adapt to climate change. *Building Research & Information*. *41*(5), 517-531. http://dx.doi.org/10.1080/09613218.2013.808893

Yaping, W., & Min, Z. (2009). Urban spill over vs. local urban sprawl: Entangling land-use regulations in the urban growth of China's megacities. *Land Use Policy. 26*, 1031-1045. http://dx.doi.org/10.1016/j.landusepol.2008.12.005

Young, W., Bowyer, D., & Naim, R.J. (1996). Modeling the environmental impact of changes in urban structure.*Computers, Environment and Urban Systems. 20*, 313-26. http://dx.doi.org/10.1016/S0198-9715(96)00024-5

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Appendix A.9

The influence of occupation modes on building heating loads: the case of a detached house located in a suburban area

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ABSTRACT: Occupants' behaviour is known to have a great influence on energetic demand, management and consumptions of a building. However, parameters related to inhabitants' lifestyle are often neglected in energetic studies and researches that often focus on insulation, ventilation or climate. In this context, the aim of the paper is to investigate the influence of three parameters related to human behaviour (the family size and the modes of occupations, the management of the heating system and the management of the heated area) on the housing heating loads of a standard dwelling. The case study chosen for this analysis is a detached house located in a suburban area. Five levels of insulation are tested (no insulation, an intermediate level corresponding to 3 cm of insulation, the current standard for new buildings in the Walloon region of Belgium, the low energy standard and the passive house standard) in order to highlight the impact and the interactions between occupation modes and insulation levels. The relevance of the adaptation of the living area of the house according to the evolution of the family size is finally discussed.

Keywords: thermal simulation, energy consumptions, human behaviour, comfort, building performances

1. INTRODUCTION

The use of mathematical models and simulation tools is often presented as the most credible approach to model the comportment of a building and predict the heating consumptions, in a global vision of sustainability. This approach allows to take into account a large number of parameters which are known to act upon energetic behaviour, management and consumptions of a building and to carry out parametric variations in order to test the impact of different strategies. If the level of insulation, the ventilation or the climate are often discussed in the literature, especially as far as retrofit is concerned, the influence of the composition of the household, its evolution through the whole life cycle of a dwelling or the behaviour of the occupants, which evolve over time while the house remains a fixed and unchanged size, are more rarely debated. However, these parameters have a huge impact on the energetic invoice of a household. Building operations and maintenance, occupant's activities and indoor environmental quality, all related to human behaviour, are indeed known to have an influence as great as or even greater than climate, building envelop and energy systems [1].

In the actual context of growing interests in sustainable development and increasing energy prices, more and more households pay attention to their energetic consumptions, especially as far as heating consumptions are concerned [2] while a large part of the population, and namely elderly owners, stay reluctant to undertake heavy renovation works. The age of the occupants seems namely to have a huge impact on heating loads, and particularly on the occupancy rate and the comfort temperature [3]. Moreover, researches have shown that in general, technical improvements were preferred over behavioural measures and especially shift in consumption. Further, home energy-saving measures seemed to be more acceptable than transport energy-saving measures [4]. The behaviour and preferences of inhabitants and the solutions adopted by the households to reduce their consumptions can thus vary in a wide proportion and cannot be apprehended by one only standard type of household in simulations, as it is generally the case.

In this context, the paper aims at comparing the variations of three parameters related to human behaviours and occupation modes: the family size and the modes of occupations, the management of the heating system (thermostat) and the management of the heated area (the inhabitants occupy the ground floor and the first floor or just the ground floor). These three parameters are then used and combined in order to determine the evolution of the occupancy of the house during its life cycle.

The chosen case study for this analysis is a detached house located in a suburban area because this type of house represents a large part of the building stock and of the total energy consumptions related to housing in the Walloon region of Belgium, where urban sprawl is particularly familiar [5, 6].

The methodology, simulation tools and main assumptions used in this research are summarized in section 2. Then, the impact of the three studied parameters on the evolution of heating loads and internal conditions are presented and finally discussed for five significant levels of insulation.

2. METHODOLOGY AND ASSUMPTIONS

2.1. The TAS thermal simulation software

TAS is a software package for the thermal analysis of buildings. It includes a 3D modeller, a thermal/energy analysis module, a systems/controls simulator and a 2D CFD package. CAD links are also provided into the 3D modeller as well as report generation facilities. It is a complete solution for the thermal simulation of a building, and a powerful design tool in the optimisation of a building's environmental, energy and comfort performance. [7]

2.2. The climate

The climate of the northern part of Europe is a temperate climate. The Brussels' meteorological data are used. Data comprise the hourly data of temperature, humidity, global solar radiation, diffuse solar radiation, cloud cover, dry bulb temperature, wind speed and wind direction. In the analysis of the heating consumptions, a whole typical year is used [8]. The maximum and minimum temperatures, for the considered year are 34.9 ℃ and -9,1℃.

2.3. The studied building

The studied building is a detached house with a south-east oriented facade. It is a two-storeyed house, located in a suburban area. Figure 1 shows the plans of the 2 floors of the building. The ground floor is composed of a living room, a kitchen, an office, a hall and a cloakroom. The first floor comprises 4 attic bedrooms and an attic bathroom. The windows are located on the 2 gables. One bedroom has a roof window. The house also includes a cellar and an attic. The house has a surface area of 182 m².

2.4. The thermal characteristics

The analysis presented in this paper take into account 5 levels of insulation of the house: a level without insulation (NI) neither in the walls nor in the roof and the slab [9, 10], a level with 3 cm of insulation in the walls, roof and slab (3cm) [9, 10], the current standard (CS) for new buildings in Belgium [9, 10, 11, 12], a low energy level (LE) [9, 10, 13] and the passive house standard (PHS) [9, 10, 12, 14]. The main thermal characteristics of walls and windows are summarized in the Table 1.

Double-glazed windows are used in the four first cases and replaced by triple-glazed windows in the passive house. The natural ventilation (NV) corresponds to the opening of the windows from 5 pm till 6 pm (30 % of the surface of the window opened). The mixed-mode ventilation (with mechanical exhaust (ME)) and the mechanical ventilation (MV) work when the house is occupied. The ventilation has three speeds. The third and the most substantial one corresponds to the requirements of the Belgian ventilation standard [9]. The first speed, the most applied in practice, is worth 1/3 of the third one and is used in our simulations.

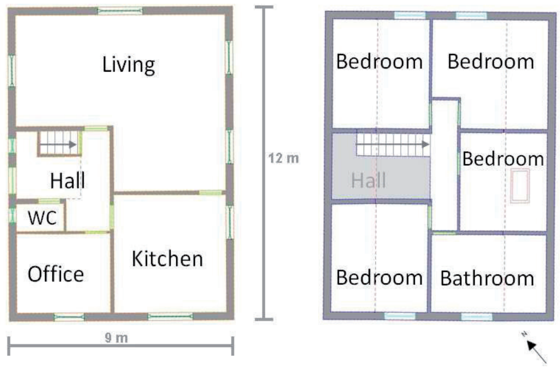

Figure 1: Plans of the ground floor and the attic floor of the studied house

2.5. The internal gains

The more the building is efficient, the more internal conditions have an influence on the heating consumptions of the building. The modelling of internal gains must be representative of the reality. Thanks to the multizone modelling adopted in the analysis, internal gains can be adjusted in each room, according to the moment of the day and the occupation mode.

The following heat emissions are used in the simulations [9, 13] :

- Occupation: 80W per person (the number of person varies from 0 to 5 according to the occupation mode)
- Fridge and deep freeze: 0.85 kWh/day
- Washing-up: 0.3*1.1 kWh/use (65 uses/(year.person))
- Appliances: 50kWh/(year.person)
- Television : 150W (1, 2 or 3hours/day)
- Computer: 70W (0, 1, 2 or 10hours/day)
- Cooking: 912W (0.5, 1 or 1.5hours/day)
- Lighting: 6W/m²
- Shower: 1486W/shower (0, 24 or 48 minutes/day)

Table 1: Main thermal properties of the 5 studied levels of insulation.

Levels of insulation	Roof (W/m²K)	External walls (W/m²K)	Ground floor (W/m²K)	Windows (W/m²K)	Airtightness (vol/h)	Ventilation	Annual heating requirement (exigency)
NI	3.586	1.757	1.874	1.22	0.6	NV	-
3cm	0.972	0.758	0.880	1.22	0.6	NV	-
CS	0.3	0.4	0.4	1.22	0.39 (7.8h^{-1} under 50Pa)	NV	-
LE	0.265	0.326	0.395	1.22	0.1 (2h^{-1} under 50Pa)	ME	≤ 60 kWh/(m² a)
PHS	0.129	0.147	0.199	0.774	0.03 (0.6h^{-1} under 50Pa)	MV with heat recovery	≤ 15 kWh/(m² a)

Total internal gains used in each thermal simulation depend on the chosen occupation mode and thus on combinations of the treated parameters. The reference value comes from a monitoring and is worth 2.57 W/m² [15].

2.6. The parametric variations

The study presented in this paper aims at comparing the influence of three parameters related to human behaviour and occupation mode on the heating loads. The studied parameters and their variations are presented below.

The first parameter deals with the family size and the corresponding occupation mode. Two types of family composition are considered and allow to target and to characterize the four following occupation modes.

- Occupation mode 1 (OM1): an active couple works outside the house during the day while their three children go to school.
- Occupation mode 2 (OM2): a self-employed or unemployed couple works/stays at home during the day while their three children go to school.
- Occupation mode 3 (OM3): an active couple without children works/stays outside during the day. Five cases are discussed.
- Occupation mode 4 (OM4): a retired couple, not very active, spends a lot of time at home. Two cases are discussed.

The second parameter deals with the management of the heating system. This modelling is based on three types of management of the thermostat, that depend on the occupation mode. The three studied cases are :

- T1: 20 ℃ in the occupied rooms with a drop to 16 ℃ at night and during the day. The heating season begins the first of October and ends the first of May
- T2: 20 ℃ in the occupied rooms with a drop to 16 ℃ at night. The heating season begin the first of October and ends the first of May.
- T3: 21℃ in the occupied rooms, all over the year , during day and night.

The last parameter is the management of the heated area. The size of a family and its activities evolve over time while the house has a fixed and unchanged size but sometimes, people remove in a part of the house which became too big for them (after the departure of children for example, facing the difficulty of climbing stairs,...). In the simulations, the house is occupied either completely (ground floor and the first floor (GF)) or only partially (just the ground floor (G)). In this case, we consider that the office is transformed into a bedroom.

2.7. The studied cases

Several cases can be arised from the combination of the parameters presented in the previous section. The nine studied cases are summarized in Table 2 (OM is the occupation mode, T1, T2 and T3 are the temperature settings, a cross in the GF column means that both the ground floor and the first floor are occupied (totally or partially) while a cross in the G column means that only the ground floor is occupied).

Table 2: The 9 case studied in the simulations

	OM	GF	G	T1	T2	T3
Case 1.1	1	x		x		
Case 2.2	2	x			x	
Case 3.3	3	x		x		
Case 3.4	3	x			x	
Case 3.5	3		x		x	
Case 3.6	3	x				x
Case 3.7	3		x			x
Case 4.8	4	x				x
Case 4.9	4		x			x

3. RESULTS

The results are presented in 4 parts:

1. the analysis of the 2 cases representing a family with children (case 1.1 and case 2.2),
2. the analysis of the 5 cases representing an active couple without children (cases 3.3 to 3.7),
3. the analysis of the 2 cases representing a retired couple (case 4.8 and case 4.9) and
4. the analysis of the 3 extreme cases representing 3 of the 4 modes (the cases 1.1, 3.4 and 4.9).

Table 3 presents the heating loads of the 9 simulated cases for the 5 levels of insulation. In the first part of the table (part A), the total heating loads calculated for the house are divided by the total surface area of the house (182m²) in each case because if the occupied and heated area changes, the position of the insulation stays the same in each case. In the second part (part B), the total heating loads calculated are divided by the occupied and heated area (182m² if the house is totally occupied by a family (the cases 1.1 and 1.2), 138m² if the ground floor and the first floor are partially occupied by a couple (the cases 3.3, 3.4, 3.6 and 4.8) and 91m² if only the ground floor is occupied by a couple (the cases 3.5, 3.7 and 4.9)).

3.1. OM 1 and 2 : couple with 3 children

Table 3 shows that case 1.1 is more energy-efficient than case 2.2 for all the levels of insulation tested, excepted for the passive case. Proportionally, the biggest difference between these two cases is observed at this passive level: the difference in heating loads between cases 1.1. and 1.2 reaches 2.28 kWh/(m².year) (28.73%). For the other levels of insulation, the difference between the two cases is contained in a range between 0.75% and 8.28% (from 0.45 to 14.98 kWh/(m².year)). This table also reveals the importance of the level of insulation. The change from one level of insulation to another permits a huge reduction in heating loads. Moreover, for both considered cases, the greatest energy reductions are visible when the passive standard is reached. In general, the change from one level of insulation to the higher one is very interesting and has a greater impact than the benefit gained from occupation modes case 1.1 on case 2.2.

3.2. OM3 : active couple without children

If heating loads are divided by the heated area (Part B of Table 3), 4 of the 5 cases relating to the

Table 3: The heating loads of the 9 studied cases (in kWh/m²). The first part of the table (A) presents the total heating loads divided by the total surface area of the house (182m²). The second part (B) presents the heating loads divided by the occupied area (182m², 138m² or 91m² according to the corresp onding occupation mode).

	Case 1.1	Case 2.2	Case 3.3	Case 3.4	Case 3.5	Case 3.6	Case 3.7	Case 4.8	Case 4.9
A.) kWh/m² (Heating loads are divided by the total surface area of the house (182m²))									
NI	180.13	195.11	154.78	170.70	132.19	231.00	178.71	214.71	175.43
3 cm	96.46	101.30	92.94	101.35	88.25	132.15	115.16	122.76	111.96
CS	59.53	59.08	60.50	64.92	59.69	80.75	74.54	74.88	71.62
LE	28.46	31.03	30.18	36.19	31.99	44.82	39.74	40.69	36.99
PHS	7.25	5.16	11.88	13.28	12.76	15.93	15.39	13.54	13.15
B.) kWh/m² (Heating loads are divided by the occupied area (182, 138 or 91m²))									
m²	182	182	138	138	91	138	91	138	91
NI	180.13	195.11	205.40	226.53	265.46	306.55	358.88	310.73	352.28
3 cm	96.46	101.30	123.34	134.50	177.22	175.37	231.25	177.67	224.83
CS	59.53	59.08	80.29	86.15	119.87	107.16	149.68	108.37	143.82
LE	28.46	31.03	40.05	48.02	64.24	59.48	79.79	58.89	74.29
PHS	7.25	5.16	15.76	17.62	25.61	21.14	30.91	19.59	26.41

third occupation mode do not meet the passive house standard. If the heating loads for cases 3.3 to 3.7 are divided by the total surface area of the house, the passive standard is respected. The values of cases 3.6 and 3.7 are indeed nearly beyond the bounds, especially since these cases are considered only with a "speed 1" ventilation rate.

The low energy standard is not reached for case 3.5 and 3.7 (Table 3B) if the occupied area is considered but is reached when the total surface is used (Table 3A).

The heating demands vary a lot according to the occupation mode (Table 3A). The two extreme cases are case 3.5 and case 3.6, The differences between these two cases vary from 98.81 kWh/(m^2.year) for the non insulation case (42.77%) to 3.17 kWh/(m^2.year) for the passive house standard (19.93%). The average of the differences is worth 30.10%. In general, the more the building is insulated, the more the difference between the cases decreases. The impact of behaviour becomes thus less huge and less marked. These two cases develop opposite behaviours. According to Table 3B, the two extreme cases are cases 3.3 and 3.7. The differences between heating loads are contained in a range between 153.18 kWh/(m^2.year) for the non insulated case and 15.15 kWh/(m^2.year) for the passive house standard. The average of the differences is worth 46.89%, which means that a couple, living in a house with 3cm of insulation, with a behaviour similar to case 3.7, can consume as much as a couple living in a non-insulated house with a more responsive and better managed behaviour. In general, if the building has a good insulation, the impact of the behaviour, compared with heated squared meters, can be proportionately as high as the impact of changing from a level of insulation to a better one.

This result highlights the very low equilibrium between comfort and good energy management. If people have very different schedules, it is quite interesting to be able to switch on by remote control the heating and the ventilation which allows to trigger the revival of the heating system. Lowering the day temperature from 20 °C to 16 °C can make a saving of about 10%, by comparing cases 3.3 and 3.4.

A very good insulation will reduce the consequences of the carelessness of people or of their no energy-efficient behaviour. But the reduction of consumptions remains and is thus easily improvable!

3.3. OM4: retired couple not very active

The occupation mode related to retired couple that is not very active and stays at home during the day is less energy-efficient because the house is more often occupied which means more heat, more light, more cooking times. Moreover, thermal comfort is the basis of the notion of comfort for elderly households. This occupation mode requires a great need for heat and that is not negotiable. Note that heating loads predicted by these simulations are low compared to real consumptions generated by some elderly households' behaviours, for example maintaining indoor air temperature at 26℃ all over the year during day and night.

Occupying just a part of the house (here the ground floor), is energetically more interesting. According to Table 3A, if the house is not insulated, the difference between cases 4.8 (the ground floor and the first floor are partially occupied) and 4.9 (the ground floor, only, is occupied) is worth 39.28 kWh/(m^2.year) (18.29%) but this difference is only worth 0.38 kWh/(m^2.year) (2%) in the passive house. According to Table 3B, the average of the differences between these 2 cases is about 21% (contained in a range between 6.83 and 47.16 kWh/(m^2.year)). But these 2 cases do not concern the same surface area and thus the most consumers in terms of kWh/(m².year), the case 4.8, gives the impression to consume less than the case 4.9. It might be interesting to bring in a density factor. Once again, the impact of the occupation mode in terms of kWh/m².year decreases if the insulation of the house is better.

3.4. Comparison between 3 representative occupation modes: synthesis

This section aims at comparing the heating loads results related to 3 extreme occupation modes. The 3 selected cases are case 1.1. (an active couple working outside the house during the day with three children going to school), case 3.4 (an active couple without children working outside the house during the day), and case 4.9 (a retired couple not very active, staying at home with a higher comfort temperature).

The more the building is insulated, the more the occupation mode is marked. The comparison between case 1.1 and case 3.4 (Table 3A) highlights that the difference between heating loads is contained in a range between 5.24% (9.44 kWh/(m^2.year)) for a non-insulated house and 45.42% (6.03 kWh/(m^2.year)) for the passive house standard. The difference in heating loads between the two modes related to a couple without children (cases 3.4 and 4.9) are relatively low. The average of the differences is indeed worth 5.74%. Figure 2 shows that if the building is not insulated, the occupation mode related to the family with three children is the higher consumer of energy. But this occupation mode with children becomes more efficient than the two others modes if the house is insulated. That also reveals the importance of internal gains.

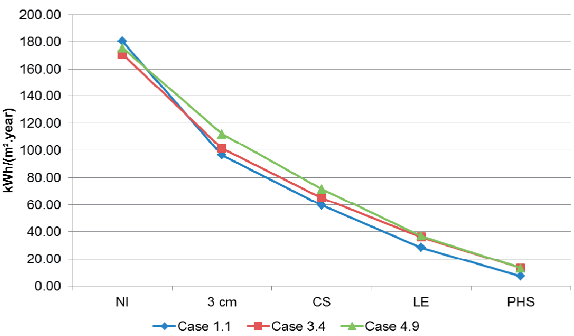

Figure 2: Heating loads (kWh/(m².year)) based on the 5 levels of insulation tested for cases 1.1, 3.4 and 4.9 (In this figure, heating loads are divided by the total surface area of the house (182m²)).

If we consider now the second part of Table 3 (where heating loads are divided by the occupied area), the differences between the three studied cases are more important. The average of the differences between case 1.1 and case 3.4 (range from 10.38 to 46.39 kWh/(m^2.year)) and between case 3.4 and case 4.9 (range from 8.79 to 125.76 kWh/(m^2.year)) are worth 36%. Case 1.1 remains the most interesting one for any level of insulation thanks to the largest heated area, to the numerous internal gains and to the better management of the heating system.

The differences between the cases increase with the level of insulation even if the difference of heating load between cases 3.4 and 4.9 and case 1.1 is more marked if heating loads are divided by the occupied area, as it can be seen on Figure 3.

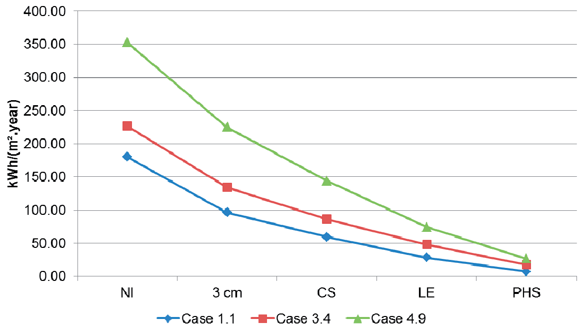

Figure 3: Heating loads (kWh/(m².year)) based on the 5 levels of insulation tested for cases 1.1, 3.4 and 4.9 (In this figure, heating loads are divided by the occupied area).

4. DISCUSSION

This section aims at discussing the impact of these occupation modes during the life cycle of the house. Indeed, several occupation modes can follow one another during the life of a house. To assess their impact on the life expectancy of the studied house, 4 assumptions of occupation are established for a period of time of 100 years and summarized in Table 4. For example, in A1, the house is occupied during 45 years by a family with 3 children (case 1.1) then by an active couple without children (case 3.4) during 30 years and finally by a retired couple (case 4.9) during 25 years.

Table 4 : Years of occupation of each occupation mode, for a life cycle of 100 years : 4 assumptions

	A1	A2	A3	A4
Case 1.1	45	25	60	25
Case 3.4	30	50	25	55
Case 4.9	25	25	15	20
Total	100	100	100	100

Average heating loads calculated for the four scenarii of occupation presented in Table 4, and divided by the heated area, are summarized in Table 5. In two cases (A2 and A4), the requirements of the passive house standard are not met. The more the building is insulated, the more the difference of heating in % increases between the two cases. In the passive house standard, this difference reaches 26.18% (4.51 kWh/(m^2.year)) between A2 and A3, that are the 2 extreme cases.

If the size of family evolves over time, the size of the house and its occupation modes should also be adapted. This strategy would allow to reduce the heating consumptions during the whole life cycle of the building. The aim is to maximize the occupation of the house. But that can lead to significant works of adaptation (extra kitchen, independent entrances, etc.). The insulation and possibilities of thermal improvement of the building must also be taken into account in order to choose the best option.

Table 5 : Average heating loads (in kWh/(m².year)) of a house on his life (100 years) based on the assumptions of occupation modes presented in Table 4.

	A1	A2	A3	A4
NI	237.09	246.37	217.55	240.08
3 cm	139.96	147.57	125.22	143.05
CS	88.59	93.91	78.83	91.03
LE	45.78	49.70	40.22	48.38
PHS	15.15	17.23	12.72	16.79

5. CONCLUSION

Nine types of occupancy of a standard detached house located in a Belgian suburban area have been determined by combining several representative types of households, occupation modes and thermal preferences (management of the thermostat). Thanks to multi-zone thermal simulations performed with a dynamic thermal simulation software (TAS), heating loads have been calculated for these nine case studies and for four combinations of the most representative ones during the life cycle of the building (100 years).

These analyses have highlighted the importance of internal gains related to the different modes of occupation, their influence on heating loads for the studied levels of insulation and the significance to take into account several types of households and occupation modes in thermal studies.

These analyses have particularly highlighted that the more the building is insulated, the more the lifestyle, namely through internal gains, influence proportionally the heating loads even if, in terms of kWh, this impact decreases. These results emphasize that the number of inhabitants and their presence in the house can reduce the heating loads. However, insulation is paramount and increasing the insulation of the house always gives better results than just adapting the occupation mode.

For the studied building, the model that presents the lower heating loads is the active couple working outside with three children, because, in this case, the number of inhabitants is quite adapted to the size of the house. The balance between optimal comfort and good management of the energy is very low and particularly if people have varied schedules. It is thus quite interesting to be able to switch on by remote control the heating and ventilation systems which allows to trigger the revival of the heating.

Last but not least, a more responsible behaviour can easily improve the energy balance of a house. Buildings thermal improvements are also very efficient but take more time and money to be realized. To heighten public awareness of the impact of their lifestyle is thus crucial and can quickly lead to significant reductions in the total energy consumptions of a family.

6. ACKNOWLEDGEMENTS

This research is funded by the Walloon Region of Belgium in the framework of the “Suburban Areas Favouring Energy efficiency”, project (SAFE). The authors express their thanks to the research team of Architecture et Climat, at the Université catholique de Louvain.

7. REFERENCES

[1] W. Hilderson, E. Mlecnik, J. Cré, Potential of Low Energy Housing Retrofit: insights from building stock analysis, Belgian Science Policy, 2010. www.lehr.be.

[2] L. Mettetal, La question énergétique dans l'habitat privé: le profil déterminant des ménages, Note rapide; n°476, IAU Ile-de-France, juin 2009.

[3] L. Mettetal, Les pratiques énergétiques des ménages du périurbain, Note rapide, n°485, IAU Ile-de-France, novembre 2009.

[4] W. Poortinga, L. Steg, C. Vlek, G. Wiersma, Household preferences for energy-saving measures : A conjoint analysis, Journal of Economic Psychology 24, 49–64, 2003.

[5] C. Kints, La rénovation énergétique et durable des logements wallons. Analyse du bâti existant et mise en évidence des typologies de logements prioritaires, LEHR, Architecture & Climat, UCL, septembre 2008. www.lehr.be.

[6] A-F. Marique, S. Reiter, A method to assess global energy requirements of suburban areas at the neighbourhood scale. Proc. of the 7th International IAQVEC Conference on Indoor Air Quality, Ventilation and Energy Conservation in Buildings, Syracuse, New York, 2010.

[7] A.M., Jones, EDSL Ltd., TAS, Software package for the thermal analysis of buildings. 13/14 Cofferidge Close, Stony Stratford, Milton Keynes, Mk11 1BY, United Kingdom, 2010.

[8] IWEC Weather Files (International Weather for Energy Calculations) from ASHRAE, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc, Atlanta, USA, 2009.

[9] W. Feist, Logiciel de conception de maison passive 2007 PHPP2007, Passivhaus Institut, Darmstadt, novembre 2007.

[10] NORME NBN D50-001, Dispositifs de ventilation dans les bâtiments d'habitation, Bruxelles, NBN, 2008.

[11] NORME NBN B 62-002, Performances thermiques de bâtiments. Calcul des coefficients de transmission thermique (valeurs U) des composants et éléments de bâtiments. Calcul des coefficients de transfert de chaleur par transmission (valeur HT) et par ventilation (valeur Hv), Bruxelles, NBN, 2008.

[12] C. Delmotte, Réglementation sur la performance énergétique des bâtiments : du nouveau à Bruxelles et en Wallonie, Les Dossiers du CSTC, N°4, Cahier n°1, 2008.

[13] www.ibgebim.be, May 2010.

[14] www.maisonpassive.be, May 2010.

[15] A. De Herde, M. Bodart, Les conclusions de Pléiade, Université catholique de Louvain, Architecture et Climat, 1994.

Appendix B: Pierre Dewallef

Appendix B.0

Assessing the cost of electricity

Prof. Pierre Dewallef

January 2013

1 Introduction

In today's mostly liberalized electricity market, the economics of a power plant are evaluated as any other industrial investment. Typically, an investor is looking to satisfy a certain level of return for his investment. Example target can be the return on equity (ROE) or the internal rate of return (IRR). However, both indexes depend upon:

- the market price of electricity and
- the production cost of electricity including the interest and amortization cost, the fuel cost and the operation and maintenance cost.

While some uncertainties remain on the fuel cost, the bigger risk is certainly on the market price of electricity as, in a liberalized economy, this price can fluctuate widely.

When a technology is new, the construction cost can be significantly more important than for well established technology. High construction cost combined with uncertain electricity prices is often an important barrier to convince investors to spend some money in new technologies. This is especially the case in the actual framework for reduction of green house gases emissions where new (yet costly) technologies must be put in place to deal with the climate change. In order to ensure the development of these new technologies, active policies must be put in place to promote *clean power generation*.

A possible way to promote clean power generation is to allocate subsidies to guarantee a minimum value for the market price of electricity. Doing so, it is easier for investors to decide whether or not to invest in a given technology. As the technology develops, production cost goes down and efficiency and reliability go up allowing the cost of electricity to go down and to become compatible, on the long term with the market price of electricity.

It is therefore of paramount interest for policy makers to update their knowledge about production cost of electricity so as to guarantee that subsidies are well allocated at all time.

2 Production cost of electricity

The production cost of electricity (COE) is usually expressed in € per MWh[1] and depends upon:

- the capital cost of the project itself made of
  - the power plant construction cost,
  - the interest rate and return on equity (the balance between interest rate and return of equity depends upon the financing structure),
  - the equivalent utilization time of the plant at rated output,
- the fuel cost,
- the operation and maintenance cost.

The interest rate is the return expected by the financing organism (i.e., the bank) and the return on equity is the return expected by investors in his capital. Both are linked to the risk of the project and the weighted average cost of capital (WACC). For sake of simplicity, an average discount rate is defined which takes into account the WACC, the risk of the project and the financing structure.

The equivalent utilization time of the plant at rated output is the electrical energy generated by a plant in a period of time divided by the electrical energy which could be produced by the plant working at rated output during a year. This definition allows correction to be made for part load operation in order to compare different projects on a similar basis.

The fuel cost per unit of electricity produced is proportional to the specific price of the fuel and inversely propotional to the average electrical efficiency of the installation (which must not be confused with the efficiency at rated output).

Operation and maintenance costs consist of fixed costs of operation, maintenance and administration (staff, insurance,...), and the variable costs of operation and maintenance (cost of repair, consumables, spare parts,...).

The cost of electricity is assessed by adding the capital cost, fuel cost and operation and maintenance costs. However, as the various costs are incurred at different times, they have to be corrected to a single reference time for financial calculation. The conversion used is referred to as the present value.

The cost of electricity expressed in € /MWh is calculated as:

$$COE = \frac{C \cdot \psi}{P \cdot T_{eq}} + \frac{Y_F}{\bar{\eta}} + \frac{U_{fix}}{P \cdot T_{eq}} + u_{var} \text{ and } \psi = \frac{d}{1-(1+d)^{-N}} \quad (1)$$

where:

- C is the total capital requirements to be written off (€),

[1] A MWh (mega watt-hour) represents the energy corresponding to a power of one mega watt produced during one hour. It corresponds to 3,6 billion J.

- ψ is the annuity factor used to take into account the interest rate and return on equity (correction based on the present value method),
- d is the average discount rate in percent per annum,
- N is the amortization in years that is often taken as the life time of the power plant (typically 20 years),
- P is the rated power output (MW),
- T_{eq} is the equivalent utilization time at rated power output in hours par annum,
- Y_F is the price of fuel expressed in € per MWh of primary energy (based on the lower heating value),
- $\bar{\eta}$ is the average net plant efficiency in percent,
- U_{fix} is the fixed cost of operation, maintenance and administration,
- u_{var} is the variable cost of operation expressed in € per MWh.

It is interesting to note that the cost of electricity is made of fixed costs (capital costs, interest costs, fixed cost of operation) and variable costs (fuel cost, variable cost of operation). If the market price of the electricity is falling below the variable cost, the power plant must be shut down because no contribution to the fixed costs can be generated.

3 Cost data

This section presents a series of standard data whose purpose is to constitute a starting point for the study. They can be completed by data gathered in the literature and on the internet.

The power plant net efficiencies mentioned below refer to the fuel lower heating value (LHV) while fuel costs and specific CO_2 emissions refer to higher heating values (HHV).

Type of plant	P (MW)	C (€/kW)	$\bar{\eta}$ (%)	T_{eq} (h/a)	u_{var} (€/MWh)	U_{fix} (€/kW/a)
NGCC [2]	(800 MW)	550-650	55-59	5000	2-3	8 - 10
IGCC [3]	(800 MW)	1300-1500	42-47	5000	4-6	10 - 12
PCSPP [4]	(800 MW)	1200-1400	42-47	6000	2,5-3,5	15 - 19
Nuclear (PWR [5])	(1250 MW)	2000-3000	35	7000	2	30 - 50
CCS [6] on NGCC	(450 MW)	800-950	50-55	5000	4-5	10 - 12
CCS on PCPP	(450 MW)	1800-2100	35-40	5000	5-7	20 - 25
CCS on IGCC	(450 MW)	1600-1900	37-42	5000	4-6	15 - 20
Biomass	(30 MW)	2500-3000	28-32	5000	5-7	30 - 35
Photovoltaic	(1 MW)	2500-3000	-	1500	2-3	15 - 20
Solar tower	(60 MW)	2500-3000	-	2500	10-20	100 - 120
CSP [7]	(1 MW)	6000-7000	-	2000	5-10	15 - 20
Stirling Dish	(1 MW)	4000-5000	-	2000	5-10	15 - 20
Off-shore Wind Turbine	(5 MW)	1500-2000	-	2500	15-18	35 - 40
On-shore Wind Turbine	(3 MW)	1200-1500	-	2000	12-15	30 - 35
OTEC [8] Power Plants	(60 MW)	6000-7000	-	5000	15-18	50 - 60
Natural gas cogeneration (Gas Turbine)	(20 MW)	600-800	-	5000	5-8	10 - 12
Natural gas cogeneration (Reciprocating engine)	(1 MW)	800-1000	-	4000	10-12	10 - 12
Tidal Power Plants	(60 MW)	5000-9000	-	3000	20-30	60 - 70

Table 1: Specific price, net efficiency, equivalent utilization time, fixed and variable costs for operation and maintenance of various power plants

[2] Natural Gas Combined Cycle
[3] Integrated coal Gazeification Combined Cycle
[4] Pulverized Coal Steam Power Plant
[5] Pressurized Water Reactor
[6] Carbon Capture and Storage
[7] Concentrated Solar Photovoltaic
[8] Ocean Thermal Energy Conversion

Type of fuel	density ($kg\,m^{-3}$)	LHV ($MJ\,kg^{-1}$)	HHV ($MJ\,kg^{-1}$)	Y_F (€/MWh)	CO_2 (kgCO2/MWh)
Natural gas	0.8	50	55	30	251
Coal	800	32.5	32.5	10	378
Nuclear fuel	-	-	-	1.5	0
Wood chips	320	12	20	25	0 - 20
Wood pellets	600	16	20	35	30

Table 2: Density, lower and higher heating value, specific price and specific CO_2 emissions of various fuels

Appendix B.1

Status of Concentrated Solar Photovoltaic (CSP) technology for electricity production

Academic year 2012-13

1 Context

A group of policy makers working for public authorities is looking for an update regarding the different technologies for electricity production. Their scope is to obtain synthetic information for electricity production cost, energy yield, potential CO_2 emissions reduction and technological status (under development, tested, mature,...) in order to best allocate subsidies for clean power generation.

2 Problem

You have been contacted by this group to make a 15 minutes presentation on the status of **concentrated solar photovoltaic technology**. Your intervention must present the main aspects of the technology and mention the principal advantages and drawbacks in terms of potential production for the European Union, intermittency, security of supply and technological maturity.

Your presentation must contain an assessment of the electricity production cost together with a prospective of the calculated cost (decreasing, stable, increasing). The potential CO_2 emissions reduction resulting from the development of the technology must be presented as well. The reference case will be a natural gas combined cycle.

For your cost calculations you will assume an amortization time equal to the duration of the installation (i.e., 20 years) and a weighted average cost of capital of 7%.

3 Practical information

The presentation must be done in English and must not last more than 15 minutes. Due to the time restriction, the length of the presentation should not exceed 15 to 20 slides.

A document is available on the website (entitled *Assessing the cost of electricity*) which explains in details the methodology to be used for the calculation of the electricity production cost. This document is considered as a starting point and completing the cost information supplied by additional information gathered from the literature of from the internet is welcome.

When writing your presentation, you can suppose that your audience has a solid technical background in energy production and already knows the methodology for the assessment of the cost of electricity. Always mention your source when you present cost information and, at the end of the presentation, you will supply a list of references.

For further information, you can contact Prof. Pierre Dewallef (p.dewallef@ulg.ac.be).

Appendix B.2

Status of Solar Tower Power Plant technology for electricity production

Academic year 2012-13

1 Context

A group of policy makers working for public authorities is looking for an update regarding the different technologies for electricity production. Their scope is to obtain synthetic information for electricity production cost, energy yield, potential CO_2 emissions reduction and technological status (under development, tested, mature,...) in order to best allocate subsidies for clean power generation.

2 Problem

You have been contacted by this group to make a 15 minutes presentation on the status of **solar tower power plant technology**. Your intervention must present the main aspects of the technology and mention the principal advantages and drawbacks in terms of potential production for the European Union, intermittency, security of supply and technological maturity.

Your presentation must contain an assessment of the electricity production cost together with a prospective of the calculated cost (decreasing, stable, increasing). The potential CO_2 emissions reduction resulting from the development of the technology must be presented as well. The reference case will be a natural gas combined cycle.

For your cost calculations you will assume an amortization time equal to the duration of the installation (i.e., 20 years) and a weighted average cost of capital of 7%.

3 Practical information

The presentation must be done in English and must not last more than 15 minutes. Due to the time restriction, the length of the presentation should not exceed 15 to 20 slides.

A document is available on the website (entitled *Assessing the cost of electricity*) which explains in details the methodology to be used for the calculation of the electricity production cost. This document is considered as a starting point and completing the cost information supplied by additional information gathered from the literature of from the internet is welcome.

When writing your presentation, you can suppose that your audience has a solid technical background in energy production and already knows the methodology for the assessment of the cost of electricity. Always mention your source when you present cost information and, at the end of the presentation, you will supply a list of references.

For further information, you can contact Prof. Pierre Dewallef (p.dewallef@ulg.ac.be).

Appendix B.3

Status of off-shore wind power technology for electricity production

Academic year 2012-13

1 Context

A group of policy makers working for public authorities is looking for an update regarding the different technologies for electricity production. Their scope is to obtain synthetic information for electricity production cost, energy yield, potential CO_2 emissions reduction and technological status (under development, tested, mature,...) in order to best allocate subsidies for clean power generation.

2 Problem

You have been contacted by this group to make a 15 minutes presentation on the status of **off-shore wind power technology**. Your intervention must present the main aspects of the technology and mention the principal advantages and drawbacks in terms of potential production for the European Union, intermittency, security of supply and technological maturity.

Your presentation must contain an assessment of the electricity production cost together with a prospective of the calculated cost (decreasing, stable, increasing). The potential CO_2 emissions reduction resulting from the development of the technology must be presented as well. The reference case will be a natural gas combined cycle.

For your cost calculations you will assume an amortization time equal to the duration of the installation (i.e., 20 years) and a weighted average cost of capital of 7%.

3 Practical information

The presentation must be done in English and must not last more than 15 minutes. Due to the time restriction, the length of the presentation should not exceed 15 to 20 slides.

A document is available on the website (entitled *Assessing the cost of electricity*) which explains in details the methodology to be used for the calculation of the electricity production cost. This document is considered as a starting point and completing the cost information supplied by additional information gathered from the literature of from the internet is welcome.

When writing your presentation, you can suppose that your audience has a solid technical background in energy production and already knows the methodology for the assessment of the cost of electricity. Always mention your source when you present cost information and, at the end of the presentation, you will supply a list of references.

For further information, you can contact Prof. Pierre Dewallef (p.dewallef@ulg.ac.be).

Appendix B.4

Status of biomass combustion power plant technology for electricity production

Academic year 2012-13

1 Context

A group of policy makers working for public authorities is looking for an update regarding the different technologies for electricity production. Their scope is to obtain synthetic information for electricity production cost, energy yield, potential CO_2 emissions reduction and technological status (under development, tested, mature,...) in order to best allocate subsidies for clean power generation.

2 Problem

You have been contacted by this group to make a 15 minutes presentation on the status of **biomass combustion power plant technology**. Your intervention must present the main aspects of the technology and mention the principal advantages and drawbacks in terms of potential production for the European Union, intermittency, security of supply and technological maturity.

Your presentation must contain an assessment of the electricity production cost together with a prospective of the calculated cost (decreasing, stable, increasing). The potential CO_2 emissions reduction resulting from the development of the technology must be presented as well. The reference case will be a natural gas combined cycle.

For your cost calculations you will assume an amortization time equal to the duration of the installation (i.e., 20 years) and a weighted average cost of capital of 7%.

3 Practical information

The presentation must be done in English and must not last more than 15 minutes. Due to the time restriction, the length of the presentation should not exceed 15 to 20 slides.

A document is available on the website (entitled *Assessing the cost of electricity*) which explains in details the methodology to be used for the calculation of the electricity production cost. This document is considered as a starting point and completing the cost information supplied by additional information gathered from the literature of from the internet is welcome.

When writing your presentation, you can suppose that your audience has a solid technical background in energy production and already knows the methodology for the assessment of the cost of electricity. Always mention your source when you present cost information and, at the end of the presentation, you will supply a list of references.

For further information, you can contact Prof. Pierre Dewallef (p.dewallef@ulg.ac.be).

Appendix B.5

Status of tidal power plant technology for electricity production

Academic year 2012-13

1 Context

A group of policy makers working for public authorities is looking for an update regarding the different technologies for electricity production. Their scope is to obtain synthetic information for electricity production cost, energy yield, potential CO_2 emissions reduction and technological status (under development, tested, mature,...) in order to best allocate subsidies for clean power generation.

2 Problem

You have been contacted by this group to make a 15 minutes presentation on the status of **tidal power plant technology**. Your intervention must present the main aspects of the technology and mention the principal advantages and drawbacks in terms of potential production for the European Union, intermittency, security of supply and technological maturity.

Your presentation must contain an assessment of the electricity production cost together with a prospective of the calculated cost (decreasing, stable, increasing). The potential CO_2 emissions reduction resulting from the development of the technology must be presented as well. The reference case will be a natural gas combined cycle.

For your cost calculations you will assume an amortization time equal to the duration of the installation (i.e., 20 years) and a weighted average cost of capital of 7%.

3 Practical information

The presentation must be done in English and must not last more than 15 minutes. Due to the time restriction, the length of the presentation should not exceed 15 to 20 slides.

A document is available on the website (entitled *Assessing the cost of electricity*) which explains in details the methodology to be used for the calculation of the electricity production cost. This document is considered as a starting point and completing the cost information supplied by additional information gathered from the literature of from the internet is welcome.

When writing your presentation, you can suppose that your audience has a solid technical background in energy production and already knows the methodology for the assessment of the cost of electricity. Always mention your source when you present cost information and, at the end of the presentation, you will supply a list of references.

For further information, you can contact Prof. Pierre Dewallef (p.dewallef@ulg.ac.be).

Appendix B.6

Status of ocean thermal energy conversion (OTEC) power plant technology for electricity production

Academic year 2012-13

1 Context

A group of policy makers working for public authorities is looking for an update regarding the different technologies for electricity production. Their scope is to obtain synthetic information for electricity production cost, energy yield, potential CO_2 emissions reduction and technological status (under development, tested, mature,...) in order to best allocate subsidies for clean power generation.

2 Problem

You have been contacted by this group to make a 15 minutes presentation on the status of **ocean thermal energy conversion power plant technology**. Your intervention must present the main aspects of the technology and mention the principal advantages and drawbacks in terms of potential production for the European Union, intermittency, security of supply and technological maturity.

Your presentation must contain an assessment of the electricity production cost together with a prospective of the calculated cost (decreasing, stable, increasing). The potential CO_2 emissions reduction resulting from the development of the technology must be presented as well. The reference case will be a natural gas combined cycle.

For your cost calculations you will assume an amortization time equal to the duration of the installation (i.e., 20 years) and a weighted average cost of capital of 7%.

3 Practical information

The presentation must be done in English and must not last more than 15 minutes. Due to the time restriction, the length of the presentation should not exceed 15 to 20 slides.

A document is available on the website (entitled *Assessing the cost of electricity*) which explains in details the methodology to be used for the calculation of the electricity production cost. This document is considered as a starting point and completing the cost information supplied by additional information gathered from the literature of from the internet is welcome.

When writing your presentation, you can suppose that your audience has a solid technical background in energy production and already knows the methodology for the assessment of the cost of electricity. Always mention your source when you present cost information and, at the end of the presentation, you will supply a list of references.

For further information, you can contact Prof. Pierre Dewallef (p.dewallef@ulg.ac.be).

Appendix B.7

Status of Stirling dish power plant technology for electricity production

Academic year 2012-13

1 Context

A group of policy makers working for public authorities is looking for an update regarding the different technologies for electricity production. Their scope is to obtain synthetic information for electricity production cost, energy yield, potential CO_2 emissions reduction and technological status (under development, tested, mature,...) in order to best allocate subsidies for clean power generation.

2 Problem

You have been contacted by this group to make a 15 minutes presentation on the status of **Stirling dish power plant technology**. Your intervention must present the main aspects of the technology and mention the principal advantages and drawbacks in terms of potential production for the European Union, intermittency, security of supply and technological maturity.

Your presentation must contain an assessment of the electricity production cost together with a prospective of the calculated cost (decreasing, stable, increasing). The potential CO_2 emissions reduction resulting from the development of the technology must be presented as well. The reference case will be a natural gas combined cycle.

For your cost calculations you will assume an amortization time equal to the duration of the installation (i.e., 20 years) and a weighted average cost of capital of 7%.

3 Practical information

The presentation must be done in English and must not last more than 15 minutes. Due to the time restriction, the length of the presentation should not exceed 15 to 20 slides.

A document is available on the website (entitled *Assessing the cost of electricity*) which explains in details the methodology to be used for the calculation of the electricity production cost. This document is considered as a starting point and completing the cost information supplied by additional information gathered from the literature of from the internet is welcome.

When writing your presentation, you can suppose that your audience has a solid technical background in energy production and already knows the methodology for the assessment of the cost of electricity. Always mention your source when you present cost information and, at the end of the presentation, you will supply a list of references.

For further information, you can contact Prof. Pierre Dewallef (p.dewallef@ulg.ac.be).

Appendix B.8

Status of Natural Gas Combined Cycle (NGCC) technology for electricity production

Academic year 2012-13

1 Context

A group of policy makers working for public authorities is looking for an update regarding the different technologies for electricity production. Their scope is to obtain synthetic information for electricity production cost, energy yield, potential CO_2 emissions reduction and technological status (under development, tested, mature,...) in order to best allocate subsidies for clean power generation.

2 Problem

You have been contacted by this group to make a 15 minutes presentation on the status of **Natural Gas Combined Cycle power plant technology**. Your intervention must present the main aspects of the technology and mention the principal advantages and drawbacks in terms of potential production for the European Union, intermittency, security of supply and technological maturity.

Your presentation must contain an assessment of the electricity production cost together with a prospective of the calculated cost (decreasing, stable, increasing). The potential CO_2 emissions reduction resulting from the development of the technology must be presented as well. The reference case will be a natural gas combined cycle.

For your cost calculations you will assume an amortization time equal to the duration of the installation (i.e., 20 years) and a weighted average cost of capital of 7%.

3 Practical information

The presentation must be done in English and must not last more than 15 minutes. Due to the time restriction, the length of the presentation should not exceed 15 to 20 slides.

A document is available on the website (entitled *Assessing the cost of electricity*) which explains in details the methodology to be used for the calculation of the electricity production cost. This document is considered as a starting point and completing the cost information supplied by additional information gathered from the literature of from the internet is welcome.

When writing your presentation, you can suppose that your audience has a solid technical background in energy production and already knows the methodology for the assessment of the cost of electricity. Always mention your source when you present cost information and, at the end of the presentation, you will supply a list of references.

For further information, you can contact Prof. Pierre Dewallef (p.dewallef@ulg.ac.be).

Appendix B.9

Status of Nuclear power plant technology for electricity production

Academic year 2012-13

1 Context

A group of policy makers working for public authorities is looking for an update regarding the different technologies for electricity production. Their scope is to obtain synthetic information for electricity production cost, energy yield, potential CO_2 emissions reduction and technological status (under development, tested, mature,...) in order to best allocate subsidies for clean power generation.

2 Problem

You have been contacted by this group to make a 15 minutes presentation on the status of **Nuclear power plant technology**. Your intervention must present the main aspects of the technology and mention the principal advantages and drawbacks in terms of potential production for the European Union, intermittency, security of supply and technological maturity.

Your presentation must contain an assessment of the electricity production cost together with a prospective of the calculated cost (decreasing, stable, increasing). The potential CO_2 emissions reduction resulting from the development of the technology must be presented as well. The reference case will be a natural gas combined cycle.

For your cost calculations you will assume an amortization time equal to the duration of the installation (i.e., 20 years) and a weighted average cost of capital of 7%.

3 Practical information

The presentation must be done in English and must not last more than 15 minutes. Due to the time restriction, the length of the presentation should not exceed 15 to 20 slides.

A document is available on the website (entitled *Assessing the cost of electricity*) which explains in details the methodology to be used for the calculation of the electricity production cost. This document is considered as a starting point and completing the cost information supplied by additional information gathered from the literature of from the internet is welcome.

When writing your presentation, you can suppose that your audience has a solid technical background in energy production and already knows the methodology for the assessment of the cost of electricity. Always mention your source when you present cost information and, at the end of the presentation, you will supply a list of references.

For further information, you can contact Prof. Pierre Dewallef (p.dewallef@ulg.ac.be).

Appendix B.10

Status of Integrated coal Gazeification combined cycle (IGCC) power plant technology for electricity production

Academic year 2012-13

1 Context

A group of policy makers working for public authorities is looking for an update regarding the different technologies for electricity production. Their scope is to obtain synthetic information for electricity production cost, energy yield, potential CO_2 emissions reduction and technological status (under development, tested, mature,...) in order to best allocate subsidies for clean power generation.

2 Problem

You have been contacted by this group to make a 15 minutes presentation on the status of **Integrated coal Gazeification combined cycle power plant technology**. Your intervention must present the main aspects of the technology and mention the principal advantages and drawbacks in terms of potential production for the European Union, intermittency, security of supply and technological maturity.

Your presentation must contain an assessment of the electricity production cost together with a prospective of the calculated cost (decreasing, stable, increasing). The potential CO_2 emissions reduction resulting from the development of the technology must be presented as well. The reference case will be a natural gas combined cycle.

For your cost calculations you will assume an amortization time equal to the duration of the installation (i.e., 20 years) and a weighted average cost of capital of 7%.

3 Practical information

The presentation must be done in English and must not last more than 15 minutes. Due to the time restriction, the length of the presentation should not exceed 15 to 20 slides.

A document is available on the website (entitled *Assessing the cost of electricity*) which explains in details the methodology to be used for the calculation of the electricity production cost. This document is considered as a starting point and completing the cost information supplied by additional information gathered from the literature of from the internet is welcome.

When writing your presentation, you can suppose that your audience has a solid technical background in energy production and already knows the methodology for the assessment of the cost of electricity. Always mention your source when you present cost information and, at the end of the presentation, you will supply a list of references.

For further information, you can contact Prof. Pierre Dewallef (p.dewallef@ulg.ac.be).

Appendix B.11

Status of Natural Gas cogeneration power plant technology for combined heat and electricity production

Academic year 2012-13

1 Context

A group of policy makers working for public authorities is looking for an update regarding the different technologies for electricity production. Their scope is to obtain synthetic information for electricity production cost, energy yield, potential CO_2 emissions reduction and technological status (under development, tested, mature,...) in order to best allocate subsidies for clean power generation.

2 Problem

You have been contacted by this group to make a 15 minutes presentation on the status of **Natural Gas cogeneration power plant technology**. Your intervention must present the main aspects of the technology and mention the principal advantages and drawbacks in terms of potential production for the European Union, intermittency, security of supply and technological maturity.

Your presentation must contain an assessment of the electricity production cost together with a prospective of the calculated cost (decreasing, stable, increasing). The potential CO_2 emissions reduction resulting from the development of the technology must be presented as well. The reference case will be a natural gas combined cycle.

For your cost calculations you will assume an amortization time equal to the duration of the installation (i.e., 20 years) and a weighted average cost of capital of 7%.

3 Practical information

The presentation must be done in English and must not last more than 15 minutes. Due to the time restriction, the length of the presentation should not exceed 15 to 20 slides.

A document is available on the website (entitled *Assessing the cost of electricity*) which explains in details the methodology to be used for the calculation of the electricity production cost. This document is considered as a starting point and completing the cost information supplied by additional information gathered from the literature of from the internet is welcome.

When writing your presentation, you can suppose that your audience has a solid technical background in energy production and already knows the methodology for the assessment of the cost of electricity. Always mention your source when you present cost information and, at the end of the presentation, you will supply a list of references.

For further information, you can contact Prof. Pierre Dewallef (p.dewallef@ulg.ac.be).

Appendix B.12

Status of Carbon Capture and Storage applied on natural gas combined cycle power plants for electricity production

Academic year 2012-13

1 Context

A group of policy makers working for public authorities is looking for an update regarding the different technologies for electricity production. Their scope is to obtain synthetic information for electricity production cost, energy yield, potential CO_2 emissions reduction and technological status (under development, tested, mature,...) in order to best allocate subsidies for clean power generation.

2 Problem

You have been contacted by this group to make a 15 minutes presentation on the status of **carbon capture and storage applied on natural gas combined cycle**. Your intervention must present the main aspects of the technology and mention the principal advantages and drawbacks in terms of potential production for the European Union, intermittency, security of supply and technological maturity.

Your presentation must contain an assessment of the electricity production cost together with a prospective of the calculated cost (decreasing, stable, increasing). The potential CO_2 emissions reduction resulting from the development of the technology must be presented as well. The reference case will be a natural gas combined cycle.

For your cost calculations you will assume an amortization time equal to the duration of the installation (i.e., 20 years) and a weighted average cost of capital of 7%.

3 Practical information

The presentation must be done in English and must not last more than 15 minutes. Due to the time restriction, the length of the presentation should not exceed 15 to 20 slides.

A document is available on the website (entitled *Assessing the cost of electricity*) which explains in details the methodology to be used for the calculation of the electricity production cost. This document is considered as a starting point and completing the cost information supplied by additional information gathered from the literature of from the internet is welcome.

When writing your presentation, you can suppose that your audience has a solid technical background in energy production and already knows the methodology for the assessment of the cost of electricity. Always mention your source when you present cost information and, at the end of the presentation, you will supply a list of references.

For further information, you can contact Prof. Pierre Dewallef (p.dewallef@ulg.ac.be).

Appendix B.13

Status of Carbon Capture and Storage applied on coal power plants for electricity production

Academic year 2012-13

1 Context

A group of policy makers working for public authorities is looking for an update regarding the different technologies for electricity production. Their scope is to obtain synthetic information for electricity production cost, energy yield, potential CO_2 emissions reduction and technological status (under development, tested, mature,...) in order to best allocate subsidies for clean power generation.

2 Problem

You have been contacted by this group to make a 15 minutes presentation on the status of **carbon capture and storage applied on coal power plants**. Your intervention must present the main aspects of the technology and mention the principal advantages and drawbacks in terms of potential production for the European Union, intermittency, security of supply and technological maturity.

Your presentation must contain an assessment of the electricity production cost together with a prospective of the calculated cost (decreasing, stable, increasing). The potential CO_2 emissions reduction resulting from the development of the technology must be presented as well. The reference case will be a natural gas combined cycle.

For your cost calculations you will assume an amortization time equal to the duration of the installation (i.e., 20 years) and a weighted average cost of capital of 7%.

3 Practical information

The presentation must be done in English and must not last more than 15 minutes. Due to the time restriction, the length of the presentation should not exceed 15 to 20 slides.

A document is available on the website (entitled *Assessing the cost of electricity*) which explains in details the methodology to be used for the calculation of the electricity production cost. This document is considered as a starting point and completing the cost information supplied by additional information gathered from the literature of from the internet is welcome.

When writing your presentation, you can suppose that your audience has a solid technical background in energy production and already knows the methodology for the assessment of the cost of electricity. Always mention your source when you present cost information and, at the end of the presentation, you will supply a list of references.

For further information, you can contact Prof. Pierre Dewallef (p.dewallef@ulg.ac.be).

Appendix B.14

Status of Carbon Capture and Storage applied on integrated coal gasification combined cycle (IGCC) power plants for electricity production

Academic year 2012-13

1 Context

A group of policy makers working for public authorities is looking for an update regarding the different technologies for electricity production. Their scope is to obtain synthetic information for electricity production cost, energy yield, potential CO_2 emissions reduction and technological status (under development, tested, mature,...) in order to best allocate subsidies for clean power generation.

2 Problem

You have been contacted by this group to make a 15 minutes presentation on the status of **carbon capture and storage applied on integrated coal gasification combined cycle power plants**. Your intervention must present the main aspects of the technology and mention the principal advantages and drawbacks in terms of potential production for the European Union, intermittency, security of supply and technological maturity.

Your presentation must contain an assessment of the electricity production cost together with a prospective of the calculated cost (decreasing, stable, increasing). The potential CO_2 emissions reduction resulting from the development of the technology must be presented as well. The reference case will be a natural gas combined cycle.

For your cost calculations you will assume an amortization time equal to the duration of the installation (i.e., 20 years) and a weighted average cost of capital of 7%.

3 Practical information

The presentation must be done in English and must not last more than 15 minutes. Due to the time restriction, the length of the presentation should not exceed 15 to 20 slides.

A document is available on the website (entitled *Assessing the cost of electricity*) which explains in details the methodology to be used for the calculation of the electricity production cost. This document is considered as a starting point and completing the cost information supplied by additional information gathered from the literature of from the internet is welcome.

When writing your presentation, you can suppose that your audience has a solid technical background in energy production and already knows the methodology for the assessment of the cost of electricity. Always mention your source when you present cost information and, at the end of the presentation, you will supply a list of references.

For further information, you can contact Prof. Pierre Dewallef (p.dewallef@ulg.ac.be).

Appendix C: Manakari Vageesh

Appendix C.1

[1] - https://eur-lex.europa.eu/resource.html?uri=cellar:c7e47f46-faa4-11e6-8a35-01aa75ed71a1.0014.02/DOC_1&format=PDF

Appendix C.2

[2] - https://eur-lex.europa.eu/resource.html?uri=cellar:c7e47f46-faa4-11e6-8a35-01aa75ed71a1.0014.02/DOC_2&format=PDF

Appendix C.3

[3] - https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52016PC0861R(01)&from=EN

Appendix C.4

[4] - http://cadmus.eui.eu/bitstream/handle/1814/57264/RSCAS_2018_TechnicalReport.pdf?sequence=1

Appendix C.5

[5] - https://www.ipcc.ch/sr15/

Appendix C.6

[6] - https://electricity.network-codes.eu/network_codes/

Appendix C.7

[7] - https://electricity.network-codes.eu/network_codes/cacm/

Appendix C.8

[8] - https://fsr.eui.eu/eu-electricity-network-codes/

Appendix C.9

[9] - https://docstore.entsoe.eu/Documents/TYNDP%20documents/TYNDP2018/Scenario_Report_2018_Final.pdf

Appendix C.10

[10] - http://fsr.eui.eu/wp-content/uploads/QM-AX-18-017-EN-N.pdf

Appendix C.11

[11] - https://www.gasforclimate2050.eu/files/files/Ecofys_Gas_for_Climate_Feb2018.pdf

Appendix C.12

[12] - http://www.grtgaz.com/fileadmin/medias/communiques/2018/EN/Etude-mix-gaz-100-pourcent-renouvelable
pdf