Environmental optimization of the public space of cities

Action on urban pavements and elements to support sustainable mobility

By

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A thesis submitted in fulfilment of the requirements for the PhD degree in Environmental Science and Technology

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Bellaterra (Cerdanyola del Vallès), June 2014

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"Así pues, como dice el proverbio:

El camino brillante parece oscuro;

El camino que avanza parece retroceder;

El camino llano parece accidentado;

La virtud superior está vacía como un valle;

El blanco más puro parece manchado;

La vasta virtud parece insuficiente;

La realidad más simple parece cambiar… []…".

Movimiento, Lao-Tse

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…Hoy es siempre todavía. Toda la vida es ahora.

Resumen

El planeamiento urbano empieza a estar fuertemente focalizado en la provisión de redes adecuadas de infraestructuras que estimulen el desarrollo de una movilidad sostenible. Sin embargo, la integración de criterios ambientales en el diseño y gestión de las infraestructuras necesarias para el sustento de la movilidad urbana es mínima. Teniendo en cuenta la enorme extensión y la creciente inversión global en el despliegue de nuevas infraestructuras urbanas para el sustento de la movilidad sostenible, la carga ambiental aportada al espacio público de las ciudades puede ser significativa.

Esta tesis doctoral se centra en la caracterización del comportamiento ambiental del ciclo de vida de diseños convencionales de aceras de hormigón, asfalto y granito e instalaciones para la recarga de vehículos eléctricos de dos ruedas. Las aceras son pavimentos urbanos básicos implementados para el sustento de la actividad peatonal y ciclista como los modos de movilidad urbana más limpios. A su vez, las aceras son la matriz sobre la cual se distribuye un abanico diverso de elementos urbanos relacionados con el soporte de la movilidad sostenible. Las instalaciones para la recarga de vehículos eléctricos son un elemento urbano que se está implementando masivamente en las ciudades para promover la electrificación del parque de vehículos urbanos como una estrategia prometedora para reducir significativamente el consumo de petróleo y las emisiones contaminantes de la movilidad motorizada. A través de la aplicación de la metodología de Análisis del Ciclo de Vida se identifican los diseños ambientalmente más óptimos para reducir la carga ambiental aportada al espacio público y contribuir a incrementar el valor ambiental de promover la movilidad sostenible en las ciudades.

Asimismo, la tesis busca identificar soluciones para mejorar el comportamiento ambiental de aquellos elementos que presentan un alto impacto con el fin de incrementar las ventajas ambientales alcanzadas en la escala urbana. Por un lado, se analiza desde una perspectiva de Ecología Industrial el potencial de producción limpia de losas de granito utilizadas en construcción. Por otro lado, se aplican principios de ecodiseño en la conceptualización de una eco-pergola (mobiliario urbano) que puede contribuir a sustentar una movilidad urbana multimodal (peatonal y bicicleta eléctrica).

Como resultado del desarrollo de la tesis doctoral, se proveen inventarios completos y desagregados de los recursos movilizados (energía, agua y materiales) e impactos ambientales asociados a cada elemento objeto de estudio, se identifican puntos críticos y se definen una serie de criterios y buenas prácticas para la toma de decisiones que conlleven a optimizar el comportamiento del espacio público de las ciudades.

Summary

Urban planning starts to be heavily focused on the provision of adequate networks of urban infrastructures to stimulate a shift towards sustainable mobility in order to alleviate resource consumption and environmental impacts in cities. Nevertheless, the integration of life cycle environmental criteria in the design and management of the urban infrastructures required to support sustainable mobility is usually missing. Given the vast span and increasing global investment in the deployment of new infrastructure, the environmental burden imposed to the urban public space can be significant.

This dissertation concentrates on the characterization of the life-cycle environmental performance of conventional designs of (concrete, asphalt and granite) sidewalks and charging facilities for electric vehicles (two-wheelers). Sidewalks are basic urban pavements implemented to support walking and cycling as the cleanest modes of urban mobility. Sidewalks also represent the matrix for the layout of different urban elements required to support sustainable mobility. Charging facilities for electric vehicles represent one urban element being heavily implemented in cities to encourage the electricification of the urban vehicle fleet as a promising strategy to cut oil consumption and pollutant emissions from motorized mobility. Life Cycle Assessment is applied in order to identify the most environmentally-friendly solutions and best practices to minimize the environmental burden imposed to the urban public space, thereby increasing the value of greening urban mobility.

The dissertation also looks for solutions to improve the environmental performance of those product systems with high environmental footprint in order to achieve major environmental improvements at the urban scale. On the one hand, the potential for cleaner industrial production of granite tiles used in construction is analyzed from an Industrial Ecology approach (technological improvement, rainwater harvesting and by-product synergies). On the other hand, ecodesign principles are applied in the conceptualization of an eco-pergola (street furniture) that can contribute to support multimodal (pedestrian and e-bike) mobility.

As a result, this dissertation provides complete and disaggregated inventory data of the mobilized resources (energy, water, materials) and environmental impacts of the life cycle of each product system, identifies the most relevant hot-spots for environmental improvement and defines a set of criteria and best-practices for sustainability-based decision-making to minimize the environmental burden of the urban public space.

List of acronyms, abbreviations and notation

CP	Conventional Pergola
CP_CCS	Conventional Pergola and Conventional Charging Station
CO_2 eq.	Carbon dioxide equivalent emissions
DfE	Design for Environment
DMWS	Diamond Multi-Wire Saw
DMWS35	Diamond Multi-Wire Saw with 35 wires
DMWS100	Diamond Multi-Wire Saw with 100 wires
DU	Delay in the start of Use of a charging facility
E-BIKES	Electric Bikes
ES	Spanish
EU	European Union
EV	Electric Vehicle
EVCI	Electric Vehicle Charging Infrastructure
EVI	Electric Vehicle Initiative
E2W	Electric two-Wheelers
FR	French
FU	Functional Unit
GHG	Greenhouse Gases
GR	Greek
GS	Granite Sludge
GSR	Granite Sludge Recovery
GWP	Global Warming Potential
ICV	Internal Combustion Vehicle
IE	Industrial Ecology
IEA	International Energy Agency
ISO	International Organization for Standardization
ITeC	Institut de Tecnologia de la Construcció de Catalunya
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LED	Low Energy Demanding lighting equipment
MBGS	Multi-Blade GangSaw

MBGS180	Multi-Blade Gangsaw with 180 steel blades
M&R	Maintenance and Rehabilitation
NC	Normal Conditions
NSC	Natural Stone Council of US
ORP2	Outdoor Recharge Post with two sockets available
ORS6	Outdoor Recharge Station with six sockets available
PED	Primary Energy Demand
QALCC	Qualitative Assessment of Life Cycle Criteria
QR	Quick Renovation of a charging device
RWH	Rainwater Harvesting
SCGP	Spanish Cluster of Granite Producers
SP	Solar Pergola
spE	surplus photovoltaic Electricity
SP_eBike	Solar Pergola with e-bike charging

Preface

This doctoral thesis was developed within the research group on Sustainability and Environmental Prevention (Sostenipra) at the Institute of Environmental Science and Technology (ICTA) of the Universitat Autònoma de Barcelona (UAB) from October 2010 to June 2014. The research presented is the result of a multidisciplinary collaboration between Sostenipra-ICTA-UAB and the Department of Geotechnical Engineering and Geosciences (School of Civil Engineering) from the Technical University of Catalonia-Barcelona Tech (UPC).

This dissertation aims to determine the potential for environmental improvement of the public space of cities, working on the design and management of basic urban pavements, materials, elements and furniture required to support sustainable (pedestrian, cycling and electric) mobility.

The dissertation is essentially based on the following research papers, which have either been published, are under review in international peer-reviewed indexed journals or will be submitted shortly for publication.

- Mendoza JM, Oliver-Solà J, Gabarrell X, Josa A, Rieradevall J, 2012. Life cycle assessment of granite application in sidewalks. *International Journal of Life Cycle Assessment*; 17: 580–592. DOI 10.1007/s11367-012-0391-1.
- Mendoza JM, Oliver-Solà J, Gabarrell X, Rieradevall J, Josa A, 2012. Planning strategies for promoting environmentally suitable pedestrian pavements in cities. *Transportation Research Part D*: *Transport and Environment*; 17:442–450. DOI: 10.1016/j.trd.2012.05.008.
- Mendoza JM, Feced M, Feijoo G, Josa A, Gabarrell X, Rieradevall J, 2013. Life cycle inventory analysis of granite production from cradle to gate. *International Journal of Life Cycle Assessment*, 19: 153-165. DOI: 10.1007/s11367-013-0637-6.
- Mendoza JM, Capitano C, Peri G, Josa A, Rieradevall J, Gabarrell X, 2013. Environmental management of granite slab production from an industrial ecology standpoint. *Journal of Cleaner Production, XX: 1-10. In press.* DOI 10.1016/j.jclepro.2014.03.056.
- Mendoza JM, Josa A, Rieradevall J, Gabarrell X. Environmental significance of the slow-charging infrastructure for electric two-wheelers. *Under review.*

- Mendoza JM, Sanye-Mengual E, Angrill S, García-Lozano R, Feijoo G, Josa A, Gabarrell X, Rieradevall J. Eco-innovation of urban furniture for supporting smart mobility in cities. *Will be submitted shortly.*

In addition, part of the research developed within the dissertation has been also presented in a series of international scientific conferences. The presenter is highlighted in bold letters:

- Mendoza JM, Oliver-Solà J, Arena AP, Moral A, Pablos L, García N, Irusta R, Josa A, **Gabarrell X**, Rieradevall J, 2011. The "CO_2e-graph": an environmental tool for guiding urban planning processes. Application to the public space. ISIE 2011 Conference - Science, Systems, and Sustainability, Berkeley-California 2011. *Oral participation.*
- **Mendoza JM**, Rieradevall J, Gabarrell X, Josa A, 2011. "Environmental optimization of electric vehicles slow-charging infrastructures through a life cycle management approach". ISBN-10: 9400718985. LCM 2011 – Towards Life Cycle Sustainability Management, Berlin 2011. *Oral participation.*
- **Mendoza JM**, Gabarrell X, Rieradevall J, Josa A, 2011. Potential impacts of electro-mobility on the built environment of cities: the needs of comprehensive urban planning for its sustainable deployment. ECOTECH & TOOLS Conference – Environmental and Integrated Assessment of Complex Systems, Montpellier 2011. *Oral participation.*
- Mendoza JM, Rieradevall J, Gabarrell X, Josa A, 2011. Strategies for optimizing the use of electric vehicle charging infrastructures while minimizing the life-cycle environmental impact on the built environment in the city of Barcelona. Smart City Expo World Congress 2011 – Smart Society for Innovative and Sustainable Cities, Barcelona 2011. *Poster.*
- Mendoza JM, Sanyé-Mengual E, Angrill S, Gonzalez-Garcia S, Garcia R, Feijoo G, Moreira MT, Josa A, Gabarrell X, Rieradevall J, 2012. Smart urban furniture for promoting sustainable mobility in cities. Smart City Expo World Congress 2012 – Smart Thinking Solutions, Barcelona, 2012. *Poster.*
- **Mendoza JM**, Sanyé-Mengual E, Angrill S, Gonzalez-Garcia S, Garcia-Lozano R, Feijoo G, Moreira MT, Josa A, Gabarrell X, Rieradevall J, 2013. Promoting sustainable mobility through the ecodesign of multifunctional urban infrastructures

in the context of smart cities. The 6th International Conference on Life Cycle Management - LCM 2013, Gothenburg 2013. *Poster*.

Furthermore, the PhD student has collaborated in teaching activities from 2010 to 2013 within the framework of the ICTA-UAB master's degree in Environmental Studies (MCD 2006-00362) and opportunity has been given to him to conduct a three months research training stay (April 2012 – July 2012) at the Danish Centre for Environmental Assessment (DCEA) in Aalborg University (AAU), Denmark.

Structure of the dissertation

The structure of the dissertation is organized into six main parts and ten chapters. Figure A presents a flow chart that can be used throughout the reading of this manuscript as a *dissertation map*. Below, a brief description of the content of each chapter of the dissertation is presented.

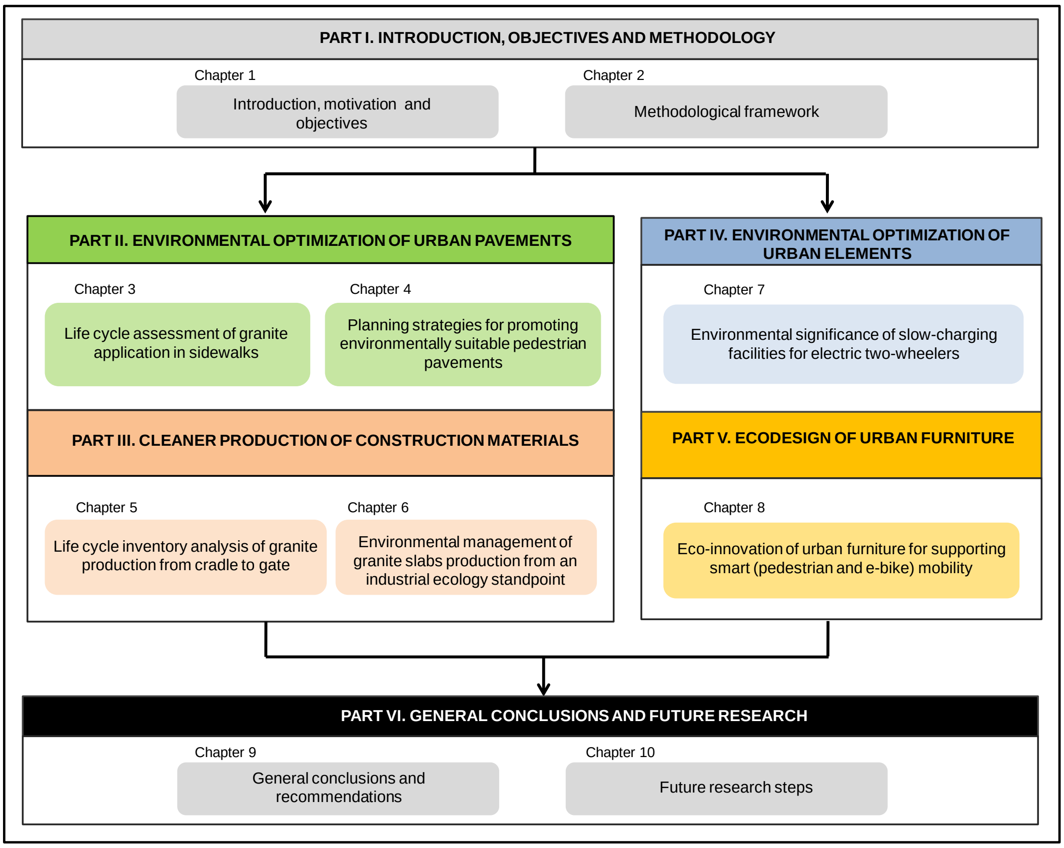

Fig. A Map structure of the dissertation. NOTE: PART VI collects supplementary material (chapter 11: appendices) related to the case studies presented in chapters 5 to 8.

Part I. Introduction, Objectives and Methodological framework

Part I of the dissertation includes two chapters. **Chapter 1** presents a general vision of smart city development and describes the role of the urban public space to accomplish energy and climate sustainability targets. The relevance of urban design in shaping sustainable urban mobility networks is streesed. Emphasis is placed on the description of urban actions dedicated to stimulate walking, cycling and electric mobility. The introduction closes by highlighting the importance related to the provision of environmentally-friendly urban infrastructures to support sustainable modes of mobility. This is the foundation that fuels the motivation and the objectives of the dissertation. Later, **chapter 2** describes the methodological approaches and tools applied throughout the dissertation.

Part II. Environmental optimization of urban pavements

Part II of the dissertation focuses on the characterization of the life-cycle environmental impacts of standard designs of sidewalks with the aim to identify environmentally friendly construction solutions. **Chapter 3** analysis the environmental performance of using granite tiles in sidewalk paving and whether using granite could help to reduce the environmental burden of sidewalks paved with standard (prefabricated) concrete tiles. **Chapter 4** presents and compare the life-cycle embodied energy and greenhouse gas emissions of concrete, asphalt and granite sidewalks. This chapter emphasized the analysis of the variability on the environmental performance of the sidewalks according to changes in their maintenance and repair schedule. In this way, the best environmentally suitable design of sidewalks according to service life planning are identified.

Part III. Cleaner production of construction materials

Part III looks for solutions to improve the environmental performance of the industrial production of granite tiles, which is the material that provides the highest environmental burden to sidewalks. **Chapter 5** presents a comprehensive life cycle inventory (LCI) of the total energy, water and material inputs and waste releases related to the production of granite from cradle to gate. This chapter provides detailed LCI information related to the unit processes of quarrying, sawing, finishing, cutting for the production of polished, flamed, sandblasted and bush-hammered slabs and tiles. The most relevant hot-spots of the industrial production chain are identified. **Chapter 6** analyzes the potential for cleaner production on the stage of granite block sawing into slabs, which is the most environmentally relevant unit process in the entire granite production chain. Cleaner production techniques based on the promotion of technological optimization, implementation of rainwater harvesting systems and material recovery of granite sludge. The environmental improvement of granite production is calculated according to a list of product environmental footprint indicators.

Part IV Environmental optimization of urban elements

Part IV of the dissertation includes **Chapter 7,** which presents a comprehensive characterisation of the life-cycle embodied energy and greenhouse gas emissions of two conventional designs of slow-charging facilities widely implemented in the urban public space for charging electric two-wheelers (e-scooters). The chapter includes the analysis of a series of usage scenarios aimed to determine the relative environmental significance of the charging facilities for the use phase of electric two-wheelers. These scenarios base on the variability on the service ratio (lifetime energy supply) and the effect derived from upgrading the electricity mix towards renewable. The environmentally suitable solution is identified and criteria for life cycle environmental management are provided.

Part V Ecodesign of urban furniture

Part V of the dissertation includes **chapter 8,** which presents the results from the application of ecodesign principles in the development of multifunctional urban furniture that can contribute to support multimodal sustainable mobility. The design of a conventional pergola, which provides diurnal shadow and nocturnal light for pedestrian comfort, is reconceptualised towards the development of a solar pergola (eco-product) that can support pedestrian and e-bike mobility with zero environmental cost. Different scenarios based on the variability on solar radiation, nocturnal lighting requirements and carbon intensity of the electricity grid mix are used to determine of the variability on the environmental performance of the product systems.

Part VI General conclusions and future research

Part VI includes **Chapter 9** that presents the general conclusions and recommendations from the dissertation. The chapter also describes some of the limitations encountered during the development of the research and the transfer of knowledge. **Chapter 10** presents a list of future research lines that can be followed to complement and extend this dissertation.

Part VII Supplementary material

Part VII includes chapter 11, which presents a series of appendices with further descriptions and data related to the case studies presented in chapters 5 to 8.

[Note: Chapters from 3 to 8 of the dissertation presents an article that is either published (chapter 3-6), under review (chapter 7), or soon to be submitted to a peer-reviewed indexed scientific journal (chapter 8). For this reason, an abstract and a list of keywords are presented at the beginning of each chapter, followed by the main body of the article].

Part I. Introduction, Objectives and Methodological framework

Chapter I. Introduction

Chapter 1 presents a general vision of smart sustainable cities and describes the role of the urban public space to accomplish energy and climate sustainability targets. Emphasis is placed on the description of those urban interventions aimed to stimulate walking, cycling and the use of electric vehicles as clean and energy-efficient modes of mobility. The introduction is closed by highlighting the importance related to the provision of environmentally-suitable urban infrastructures to support sustainable modes of mobility with minimal environmental cost for the urban public space. This is the foundation that fuels the motivation and the objectives of the dissertation.

1- Chapter 1. Introduction

1.1.A vision for smart sustainable cities

Cities play a crucial role as engines of the socio-economic growth however they are places of high environmental pressure (European Union, 2011). Globally, with a population share of just above 50% but occupying less than 2% of the earth's surface, cities concentrate 80% of economic output, over 75% of the world´s resources use, between 60% to 80% of total energy consumption, and approximately 75% of global greenhouse gas (GHG) emissions (Ash et al., 2008; Kamal-Chaoui and Robert, 2009; Pacione, 2009; UN Population Division, 2010; Lazaroiu and Roscia, 2012). This pattern reflects the concentration of particular activities within individual cities and urban areas. Predominantly, buildings, transport, and industry contribute 22% to 25% each to global GHG emissions (Herzog, 2009; UNEP, 2011a).

Given the scale of resource consumption, energy use and contribution to climate change driven by rapid urbanization, there is an emerging consensus on the importance of promoting integrated strategies for making cities thriving centres of sustainable development and innovation (UN, 2013). In Europe, particularly, cities are considered instrumental elements for the successful achievement of the headline targets defined by the European 2020 strategy (European Commission, 2010a) through which it is aimed at contributing to transition the European Union (EU) into a smart, sustainable and inclusive economy. The European 2020 energy and climate targets for sustainable growth are aimed at reducing GHG emissions by 20 % from 1990 levels; increasing the input from renewable energy sources in the EU's overall final energy consumption to 20 %; and moving towards a 20% increase in energy efficiency.

In order to achieve a decarbonised and energy efficient Europe today's urban planning has to drastically change (European Union, 2011). Many governments have started to argue that a holistic model for sustainable urban development requires the adoption of "smart city planning". According to the European Innovation Partnership on Smart Cities and Communities (European Commission, 2013a), "Smart Cities" should be regarded as systems of people interacting with and using flows of energy, materials, services and financing to catalyse sustainable economic development, resilience, and high quality of life. A smart city is considered a well performing city in 6 principle components (Fig. 1.1), built on the smart combination of endowments and activities of self-decisive, independent and aware citizens (Centre of Regional Science, 2007). Tools, methods and processes developed in this context should differentiate themselves by a holistic approach linking planning, design and operation while keeping in mind citizens' needs.

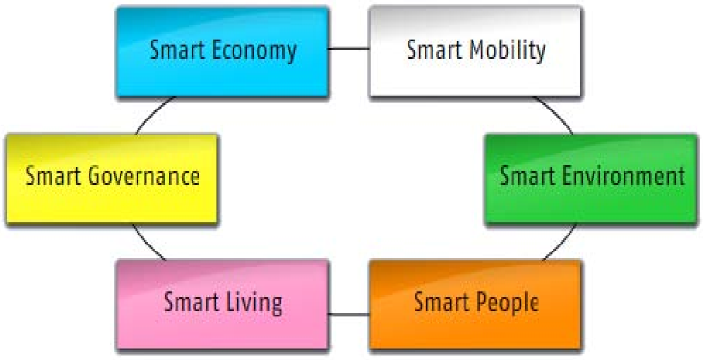

Fig. 1.1 Main components of a smart city model. Source: Centre of Regional Science, (2014) (http://www.smart-cities.eu/model.html).

According to the European Innovation Partnership on Smart Cities and Communities (European Commission, 2013a), the achievement of the energy and climate sustainability targets for Europe 2020 (European Commission, 2010a), requires the wide-reaching roll-out of integrated, scalable, sustainable smart city solutions, specifically in areas where energy production and use; mobility and transport; and information and communication technologies (ICT) are intimately linked. In this sense, plans for the development of smart cities concentrates on the following three vertical areas:

- Sustainable urban mobility – alternative energies, public transport, efficient logistics and planning;
- Sustainable districts and built environment – improving the energy efficiency of buildings and districts, increasing the share of renewable energy sources used and the liveability of the citizen;
- Integrated infrastructures and processes across energy, ICT and transport – connecting infrastructure assets to improve the efficiency and sustainability of cities.

In this process, a sustainable spatial planning, urban design and logistics deployment is essential and drives the attention to the urban public space as a key scale for intervention to support such integrated solutions that lead to the development of smart sustainable cities.

1.2.The role of urban public space

According to UN-HABITAT (2013a; 2013b; 2013c; 2013d), for promoting socially and economically vibrant and environmentally sustainable cities across the world, attention should be mostly focused to the need for better spatial planning related to public spaces and, particularly, streets:

- Firstly, the street system provides the connectivity matrix for the city, which is fundamental for urban mobility. The efficiency of this mobility is a determinant for urban economic productivity and environmental performance.
- Secondly, the street pattern also provides the matrix for the layout of urban basic services, mainly energy, water supply and sanitation, drainage, transportation, parking slots, and diverse urban elements, including street furniture, which support daily life within cities.
- Thirdly, the street pattern, including plazas and public gardens, is the key element of personal interaction and communication between the citizens. In that sense, it defines the cultural and political quality of city life.
- Fourthly, the walkability and bikeability of the spaces, the safety of the sidewalks and the form and location of shops along the street determines the quality and quantity of street life.

The urban public space represents therefore a system of systems, where layers of functional networks intersect and complement each other in a mutually reinforcing and beneficial way (UN-HABITAT, 2014). Nevertheless, if no environmental criteria are applied in the planning, design and management of the constructive solutions and elements that make up the structure and form and define the function of the urban public space, important environmental burdens can be imposed to the urban system (Oliver-Solà et al., 2009a; 2009b; 2009c; 2011; Petit-Boix et al., 2014; Rieradevall et al., 2011; Sanjuan-Delmás et al., 2014).

The World Wide Fund for Nature (WWF) in a report entitle "reinventing the city" (WWF, 2008), indicated that $350 trillion will be spent on urban infrastructure and usage during the next three decades that will contribute to around 465 Gt of GHG emissions under business-as-usual (BAU) global projections (Fig. 1.2).

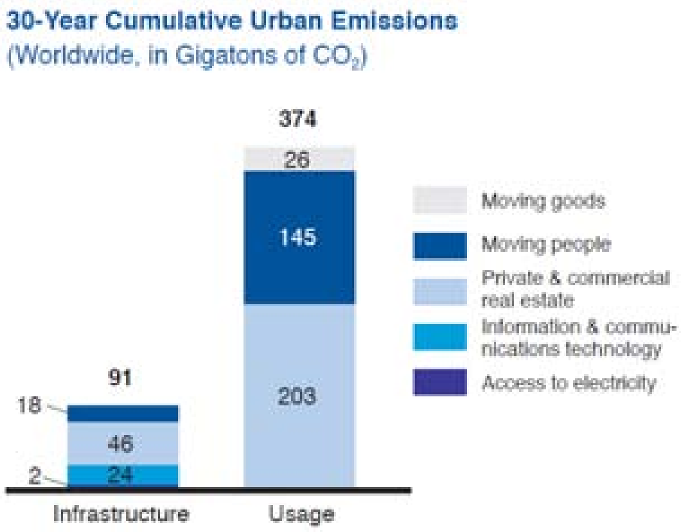

Fig. 1.2 Urban infrastructure and usage GHG emissions under BAU projections. Source: WWF (2008).

This huge expenditure on new urban infrastructure either can cause the environmental impact of cities to become more pronounced or can be a relevant opportunity to mitigate environmental impacts. The promotion of urban management practices can contribute to reduce GHG emissions stemming from the usage of existing urban infrastructure whereas the application of best practices in urban planning and design can provide sustainability into the development of new urban infrastructure (WWF, 2008). Thus, any decision taken at the level of the planning, design and management of the urban public space can actively contribute to a step forward in the improvement of the environmental performance of cities (Engel-Yan et al., 2005; Farreny et al., 2011a). And this consideration is specially relevant to tackle energy consumption and greenhouse gas emissions from urban mobility.

1.2.1.Sustainable mobility

One of the most critical aspects of the planning, design and management of the urban public space is that it finally sculpts the urban form which has significant consequences for urban mobility and the sustainability of cities. Kenworthy (2006) suggests that sustainable urban form and transport should be at the core of developing an eco-city. These factors form the shell or basic framework in which everything else about the city is embedded and must operate, and if they are not addressed only marginal changes in urban sustainability can be made. This concern has been also pointed out by Marshall (2008) who states that although much attention on mitigating global climate change has usually focused on alternative fuels use, vehicles technological improvement, and low-carbon electricity generation, better urban design (land-use patterns and the layout of transportation infrastructure) represents an important yet undervalued opportunity. The author suggests that long-term savings in carbon emissions from shifts in urban form could be comparable to those from vehicle technological innovation.

In Europe, half of all road transportation fuel is combusted in cities (European Commission, 2007a), where traffic is responsible for at least 40% of GHG emissions and more than two-thirds of local noxious emissions arising from this mode of transport (European Commission, 2007b). The European 2020 Strategy (European Commission, 2010a) stresses therefore the importance to address the urban dimension of mobility in order to shape a modernised transport system that contributes to achieve the energy and climate sustainability targets. In this sense, the European White Paper on Transport (European Commission, 2011a) calls to take significant action in urban mobility planning in order to reach a 60% GHG emission reduction target by 2050 with respect to 1990 levels for the transport sector.

New approaches to ensure best-practices in clean and energy-efficient urban mobility planning are emerging based on the need to shift towards more environmentally-friendly modes of mobility such as walking, cycling and public transport and greening a share of the urban motorized vehicle fleet (UNEP, 2011b; European Commission, 2013b).

Walking and cycling mobility

Advocating increased ratios in walking and cycling should become an integral component of urban mobility and infrastructure design (European Commission, 2011a). Walking and cycling are the cleanest, highest resource-efficient and healthier ways for the individuals to travel in urban areas. Cities with higher percentages of walking and cycling mobility trips have lower per capita energy use (Fig. 1.3), which translates into less dependence on fossil fuels, less pressure on other scarce resources such as land, and less emissions of GHG and air pollutants (UNEP, 2010).

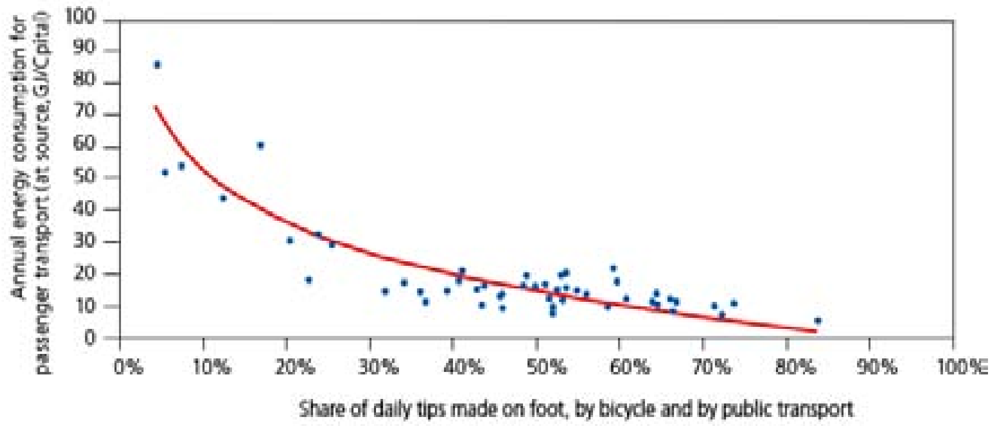

Fig. 1.3 Energy consumption for passenger transport versus modal share. Source: IEA (2008).

According to the IEA (2009), improving the provision and accessibility of walking and cycling infrastructure through the design of integrated urban mobility networks can help to create cities and towns that are conducive to walking and cycling. On the one hand, connecting sidewalks and cycling paths to public transport stations expands the possible range of resource-efficient travel and increase ridership of public transport (UNEP, 2010). On the other hand, increased walking and cycling ratios has the added value of fostering a more physical active lifestyle with many health benefits for citizens, such as a decrease in obesity and related heart diseases (European Commission, 2011b; UN-HABITAT 2013c). Fig. 1.4 presents the cycle for walkable and bikeable cities.

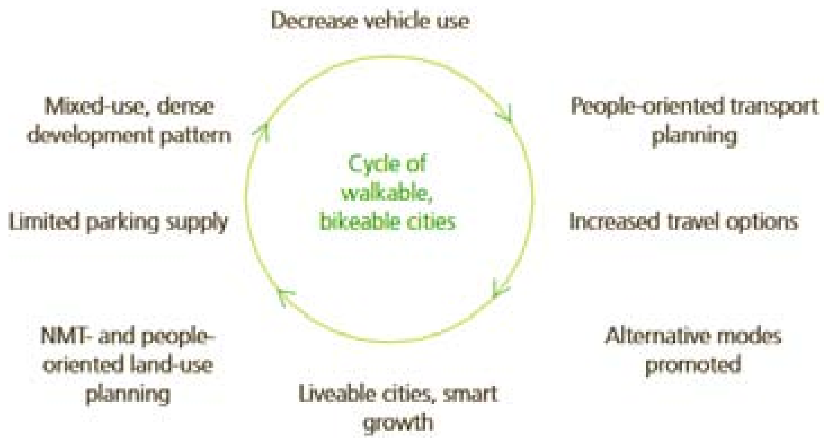

Fig. 1.4 Cycle for walkable and bikeable cities. Source: UNEP (2010). Acronyms – NMT: Non-motorized transport.

Many cities around the world have recognised such structural opportunities for sustainable urban development. For instance, Copenhagen, Oslo, Amsterdam, Madrid and Stockholm (EIU, 2009), together with Curitiba, Vancouver and Portland in the Americas, have all prioritised compact urban development, creating walkable and bikeable urban neighbourhoods supported by accessible public transport systems. Particularly in Barcelona (one of the most densely populated cities in Europe) efforts by the City Council and local metropolitan administrations look to 'democratise' streets and public spaces, with action taken to improve accessibility, affordability and efficiency of the public transport network, promote cycling, walking and other alternative forms of transport (European Union, 2011). Barcelona's public bicycle service (Bicing) is an example of a successful sustainable mobility programme which has been rapidly adopted by the targeted population (Fig. 1.5).

Fig. 1.5 Map of Barcelona´s bicing stations. Source: www.bicing.cat.

Well-designed streetscape (i.e. street connectivity and safety, complete sidewalk provisions and well-suited pedestrian and cycling routes of exemplary quality) is essential to draw city residents to the use of sidewalks and public spaces. In this sense, the model of "complete streets", an acknowledgement that streets serve numerous purposes, not just moving cars and trucks, is gaining steam throughout Europe, much of North America and in parts of Eastern Asia. Many cities have started to reclaim land once given over to motorways and freeways to pedestrians, cyclists and public transport to ensure eco-efficiency of their infrastructural systems (UN-HABITAT, 2013b). However, greening the urban motorised vehicle fleet is a fundamental issue to be addressed in order to achieve a clean and energy-efficient urban mobility.

Electric mobility

The gradual phasing out of conventional petrol-fuelled cars by the deployment of cleaner and energy-efficient vehicles represents a major challenge to achieve significant reduction of oil dependence, GHG emissions and local air and noise pollution in cities (European Commission, 2009a). The European White Paper on Transport (European Commission, 2011a) set the goal to halve the use of petrol-fuelled cars in urban mobility by 2030 and phase them out in cities by 2050 in order to achieve essentially CO_2-free city logistics. In this sense, the European Green Cars Initiative (European Commission, 2008) launched a few years ago has the purpose of supporting research and development on clean and energy-efficient vehicles with a main focus placed on the electrification of mobility because electric vehicles (EVs) represent one of the most promising technology pathways for cutting oil use and GHG emissions on a motorized per-kilometre basis (IEA, 2012). Battery-powered EVs use an electric motor for propulsion with batteries for electricity storage. EVs offer the prospect of zero tailpipe emissions of GHGs and air pollutants, as well as very low noise and vibration. Another important advantage of EVs over conventional ICVs is the substantial energy efficiency (Fig. 1.6). EVs have up to three times the engine and drive-train efficiency of conventional ICVs (IEA, 2011).

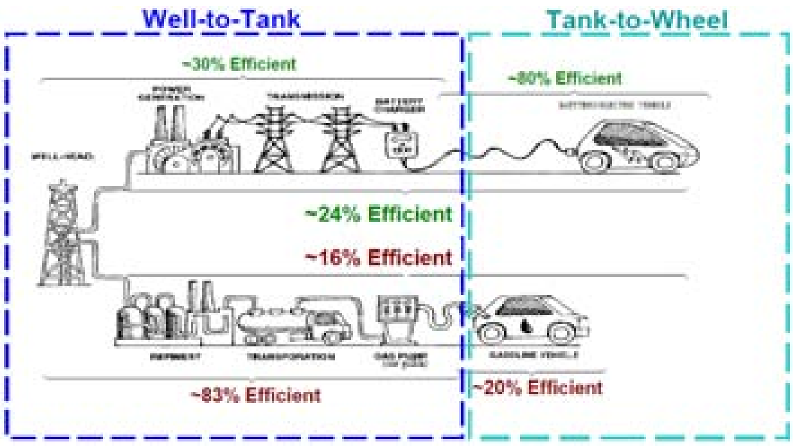

Fig. 1.6 Well-to-wheel energy efficiency of EVs and ICVs. Source: Berry et al. (2009).

Within the last few years the promotion of electric mobility has been given first priority in the EU, US, Japan, China, and Korea, where the convergence with the use of renewable energy sources for electricity production appears the most appealing strategy for reducing environmental impacts from urban motorized mobility (ERTRAC, EPoSS and SmartGrids, 2010). It is worth noticing that electrification of road transport refer to vehicles of many kinds including bikes, scooters and motorbikes, passenger cars, delivery vans, light and heavy-duty freight vehicles and vehicles for public transport (i.e. buses). However, light EVs such electric two-wheelers (E2Ws) (e-bike, e-scooters and e-motorbikes) and small passenger e-cars are expected to have a rapidly rising market share that may facilitate the market entry of electric mobility in its entirety for the pervasive electrification of motorized urban vehicle fleets (ERTRAC, EPoSS and SmartGrids, 2012).

The vision of the Electric and Plug-in Hybrid (EV/PHEV) Vehicles Roadmap developed by the IEA (2011) is to achieve by 2050 the widespread adoption and use of EVs and PHEVs (EV from now on), which together represent more than 50% of annual light duty vehicle (LDV) sales worldwide in order to contribute approximately a 30% reduction in LDV global GHG emissions. However, GHG reductions depend heavily on the carbon intensity of the electricity grid mix. Thus, GHG targets are based on the expected decarbonisation of global electricity generation. The initial deployment of electric mobility should be particularly encouraged therefore in urban areas of regions with available low carbonized electricity generation systems. However, the provision of adequate planned and designed public charging facilities is essential.

1.2.2. Urban infrastructure for urban mobility

Infrastructure shapes mobility therefore no major changes in transport sustainability will be possible without the deployment of a properly planned and designed network of urban infrastructures and elements with the encouragement of an intelligent use of it (European Commission, 2011). The choice of infrastructure investments is central for cities to make up a significant share of urban traffic sustainable (European Commission, 2013b).

Urban pavements for supporting walking and cycling mobility

In order to stimulate comfortable walking and cycling activities, the provision of adequate sidewalks and other urban pavements (squares, pathways, rides, plazas) is essential. A sidewalk refers to a paved space running along the side of a carriageway with the main purpose of carrying pedestrian (and cycling) traffic. In the compact city of Barcelona (Spain) the urban public space accounts for 25.7% (25.9 km^2) of the total urban area (101 km^2). Streets alone represent 16.5 km^2 that accounts for 16.3% of the total urban area and around two thirds of the entire urban public space, from which over 5.6 km^2 are sidewalks (FAD, 2009). Sidewalks alone account for a notable share of the paved surfaces of the urban public space and their relevance is significantly increasing due to the growing investment related to urban development and refurbishment plans committed to support sustainable mobility in cities. Fig. 1.7 presents an overview of a sidewalk as a key basic element of the street system of cities.

Fig. 1.7 Overview of a sidewalk. Numbers: 1 – frontage zone; 2 – pedestrian through zone; 3 – street furniture/curb zone; 4 – enhancement/buffer zone. Source: NACTO (2013).

The consideration of user needs is a significant prerequisite in the design of sustainable street spaces (Mateo-Babiano and Ieda, 2007). In this process, a “user-need hierarchy” (Fig. 1.8) is applied to define the basic attributes to be considered in the design of suitable construction solutions to meet the demands of pedestrians and cyclists.

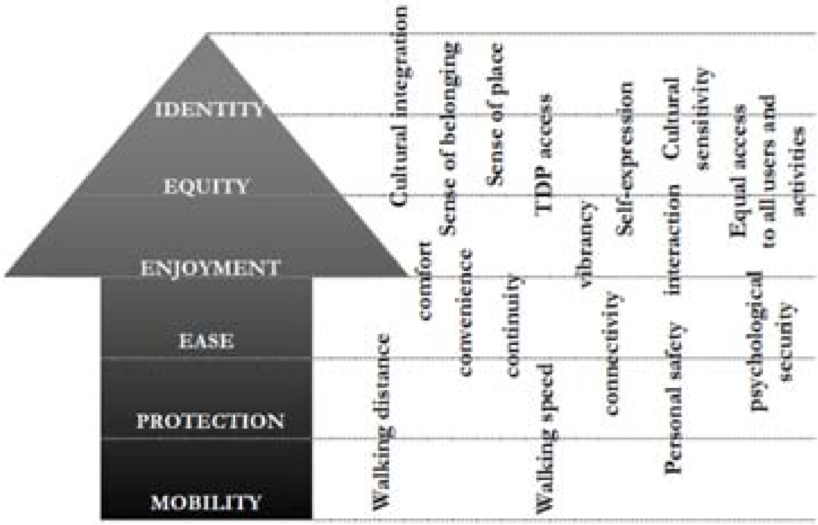

Fig. 1.8 A pedestrian-need hierarchy. Acronyms: TDP - transport-disadvantaged persons. Source: Mateo-Babiano and Ieda (2007).

The user-needs criteria are aimed to increase the level of satisfaction that can influence user loyalty towards the use of the street space and, particularly, sidewalks. At the base of these needs is the desire for movement (mobility). Aside from this, pedestrians (and cyclists) have other physiological or psychological and sociological needs such as protection, ease, enjoyment or leisure, equity and identity. In this sense, a user (pedestrian/cyclist) need-hierarchy reflects both movement and non-movement as contributory towards increasing user satisfaction and comfort (Mateo-Babiano, 2009). In order to fulfil each criterion a series of basic attributes or parameters are considered.

The criteria applied in sidewalk design, construction and management is mainly based therefore on the consideration of technical, economic and social factors, such as ergonomics, comfort, safety, durability, aesthetics, and price. The application of environmental criteria is missing.

Charging facilities to support electric mobility

Governments across the world are providing different economic stimuli to accelerate the deployment of an extensive publicly accessible urban charging network, which is considered one of the key milestones and challenges in the widespread adoption of EVs (Hacker et al., 2009; RAE, 2010; IEA, 2011; Eurelectric, 2012; Zubaryeva and Thiel, 2013). The deployment of EV charging facilities is taking place by means of offering different charging alternatives in private and public spaces across different urban locations.

Charging alternatives include slow and fast charging pilots and stations, inductive (wireless) and contact-running charging systems, battery swapping stations and wind and solar-powered charging parking (ERTRAC, 2012). Definitions of charging alternatives attempt to capture the range of charging times typically experienced by EVs according to the maximum amount of power provided and the way that the energy is delivery to their batteries (Eurelectric, 2011). Fig. 1.9 shows an illustration of an urban charging network for EVs.

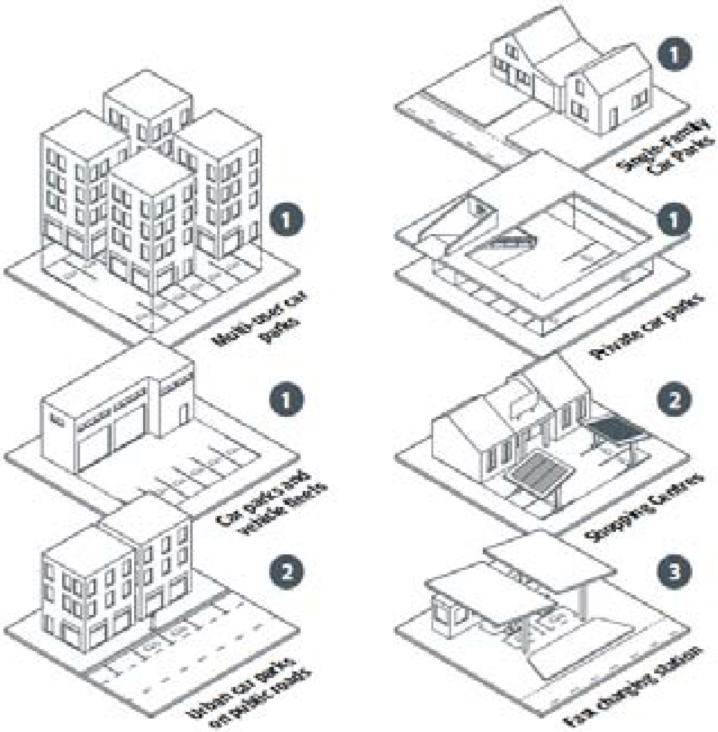

Fig. 1.9 An urban charging network for EVs. Numbers: 1 – charging cabinets; 2 – charging posts; 3 – fast charging stations. SOURCE: CIRCUTOR (2013).

The Global EV Outlook (IEA, 2013) provides useful descriptions and information to understanding the present and future EV world landscape in the 18 membership countries of the Electric Vehicle Initiative (EVI), which seeks to facilitate the global deployment of at least 20 million EVs by 2020 (http://www.ieahev.org/). EVI countries have cumulative targets for the implementation of approximately 2.4 million of public slow chargers and 6,000 fast chargers by 2020. Meanwhile, in the EU, the recently released proposal for a European Directive on the deployment of alternative fuels infrastructure (European Commission, 2013c) sets out a minimum coverage for the implementation of EV charging facilities mandatory to be implemented by each Member

State for 2020. The urban recharging EV networks range from 12,000 to up to 1,500,000 charging points, where at least 10% should be publicly accessible. However, guidance provided by government agencies on the implementation of charging facilities is focused mainly on their technical, economical and regulatory aspects, without incorporating environmental criteria for life cycle management (i.e. ETEC, 2009; TfL, 2010; BEAMA, 2012; CEA, 2013). Fig. 1.10 presents a schematic view of the main criteria considered for the implementation of EV charging facilities in the urban public space.

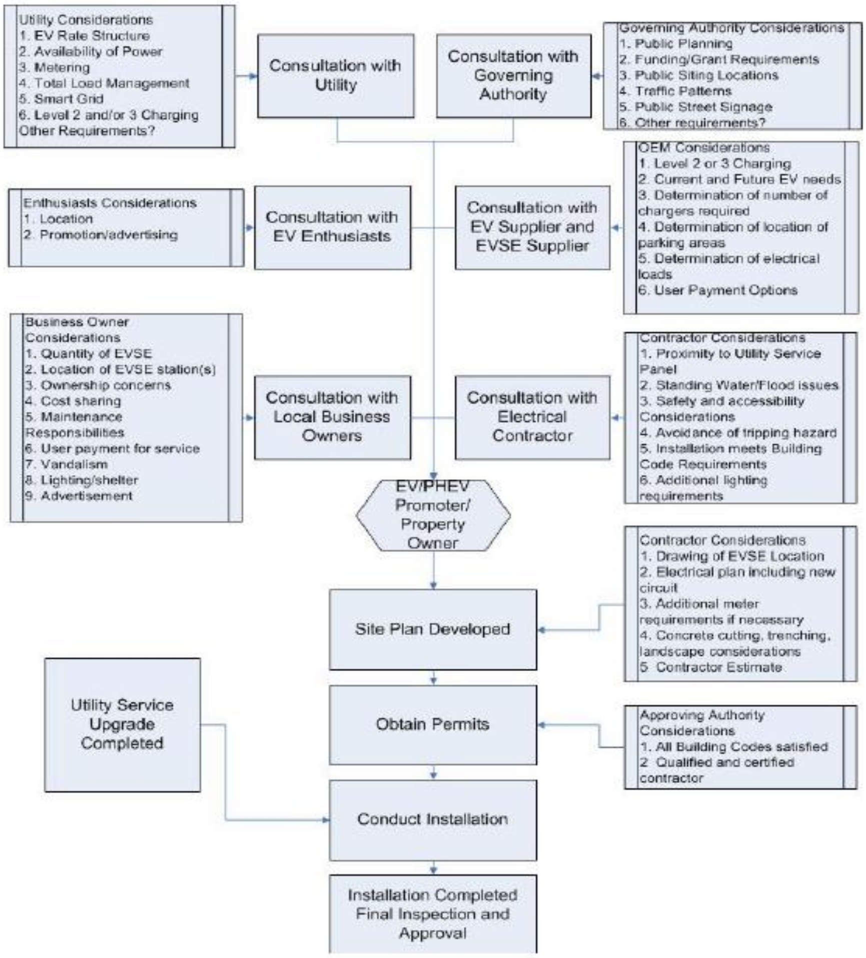

Fig. 1.10 Installation flowchart for public charging facilities. Acronyms: EVSE – Electric Vehicle Supply Equipment. Source: ETEC (2009).

The application of environmental considerations in the design, deployment and management of EV charging facilities is also missing.

1.3.Motivation of the dissertation

The provision of adequate planned and deployed urban infrastructures and elements are essential to stimulate a shift towards sustainable mobility. However, decisions should not be made based on partial data acting as indicators for whole system performance. In order to effectively mitigate environmental impacts from transportation modes, life-cycle environmental performance should be considered including both the direct and indirect processes, services and supporting infrastructures required for the development of mobility (Chester and Horvath, 2009). Access to life cycle environmental information is crucial in order to encourage the implementation of environmentally-friendly solutions that contribute to reduce the environmental burden provided to the built public space, thereby increasing the value of greening urban mobility.

A massive input of a variety of construction materials is ubiquitous across cities and stored as part of the huge network of paths, passages, broadways, squares and other pedestrian and cycling spaces. Given the vast span of these pavements and the increasing global annual investment in related construction and maintenance works, there is enough reason to believe that the pedestrian and cycling urban network itself represents an interesting opportunity for significant environmental improvement in cities. The relevance of this issue has been demonstrated by Oliver-Solà et al. (2009) who have analyzed the life cycle environmental impact of standard designs of concrete sidewalks. The results provided by the authors indicated that the life cycle environmental impact per square meter of concrete sidewalks can range from 19.7 kg CO_2 eq. to 74.3 kg CO_2 eq. (+ 277%), depending on the design implemented with regard to the function to be fulfilled (i.e. pedestrian traffic only, underground services and pedestrian traffic, motorized traffic and pedestrian traffic or motorized traffic plus pedestrian traffic plus underground services). As a consequence, "one-size-fits-all" solutions can entail a significant environmental burden to the urban public space. However, the quantitative research on the global environmental impacts of these urban infrastructures is still in its early stages. There is a need to promote the characterization of the life-cycle environmental performance of different standard designs of sidewalks and other equivalent urban pavements in order to define criteria for its potential environmental improvement. In this process, a careful consideration of the type of construction materials chosen for sidewalk paving is critical. These studies will allow urban planners to identify the most environmentally-friendly construction solutions and best-practices in urban management to minimize the environmental burden imposed to the urban public space.

It is worth noticing that the space dedicated to sidewalks also represent the matrix for the layout of an extent and diverse spectrum of urban elements that provide specific functions and services to support urban mobility. These elements include traffic signals, street lighting lamps, traffic lights, bus canopies, pergolas, benches, to name a few. Each of these elements provides also a specific environmental burden to the urban public space that may be relevant if no environmental criteria are applied in their planning, design and management. This concern has been pointed out by Rieradevall et al. (2011) and González-García et al. (2011; 2012a; 2012b) who demonstrated the potential environmental savings resulted from the application of ecodesign principles in the development of an environmentally friendly street lamp and wooden-based urban furniture. For instance, the attributes of the eco-street lamp rely on energy and material efficiency. The use of a highly efficient light bulb and photovoltaic energy sources with a decrease in light pollution provide 71% reduction of the environmental impacts related to the use phase of the conventional product system and the dematerialization of the aerial structure and urban setting with the use of recycled materials contribute to around 60% reduction of environmental impacts related to the materials inputs. EV public charging facilities represent one urban element of particular interest. These elements are expected to gain mass presence in the urban environment in the near future. Hundreds to thousands of EV charging facilities have been already implemented in the public space of many cities worldwide to encourage and support the use of EVs. However, the scientific literature based on the analysis of the life cycle environmental performance of EVs is usually focused on considering their operation stage or their entire life cycle (vehicle production, operation and disposal) but without integrating the comprehensive characterization of the environmental significance of the charging facilities required to operate them (Hacker et al. 2009; Nemry and Brons 2010; Howey et al. 2011; MacPherson et al. 2012; Hawkins et al. 2013). Thus, little is known about the potential environmental burden that the EV charging facilities can place on the public space of cities and their relative environmental significance to the operation stage of EVs. In this early stage of deployment of electric mobility, it is fundamental to start analyzing the life-cycle environmental performance of different designs of EV charging facilities in order to minimize long-term environmental burdens.

1.4.Objectives of the dissertation

The main objective of this dissertation is to determine the potential for environmental improvement of the public space of cities by taking action on the design and management of basic urban pavements and elements **required to support sustainable (pedestrian and electric) mobility.**

This general objective involves two particular interests:

A. Identification of the most **environmentally-suitable solutions to minimize the environmental burden on the built urban space** (chapters 3, 4, and 7). This particular interest involves the following specific objectives:

I. Characterization of the **life-cycle environmental impact of standard designs of (concrete, asphalt and granite) sidewalks** and comparison of their environmental performance according to changes in their service lives.

II. Characterization of the **life-cycle environmental performance of conventional designs (post vs. station) of public charging facilities for electric two-wheelers** and analysis of their relative environmental significance for the operation stage of vehicles according to changes in the service ratio, usage conditions and electricity grid mix.

B. Identification and analysis of alternatives **to improve the environmental performance of those elements and product systems with the highest environmental footprint in order to achieve major environmental improvements at the urban scale** (chapter 5, 6 and 8). This particular interest involves the following specific objectives:

III. Analysis of the **potential for cleaner production of construction materials with poor environmental performance (granite)** based on the promotion of technological optimization and the implementation of water management (rainwater harvesting) and waste management (by-product synergies) alternatives from an industrial ecology perspective.

IV. Demonstration of the usefulness of the application of **ecodesign principles and smart decision-making in the conceptualization and development of a CO_2-free multifunctional urban furniture (pergola)** to support multimodal sustainable (pedestrian and e-bike) mobility in cities.

In order to achieve the main aim of the dissertation and give response to its particular interests, **a series of transversal goals are outlined**:

- Provision of **complete and disaggregated inventory data** of the mobilized resources (energy, water and materials) and waste releases along the life cycle of each product system analyzed.
- Identification of the **most environmentally relevant hot-spots** of the life-cycle of the different product systems, paying particular attention on the indicators of global warming potential and primary energy demand.
- Definition of **variables and parameters to be considered in life cycle inventory modelling and environmental impact assessment** (sensitivity analysis) in order to get an accurate picture of the environmental performance and potential for environmental improvement of the different product systems analyzed.
- Definition of **criteria and proposal of best-practices for the environmental optimization and life-cycle management** of the different product system to contribute actively to the environmental improvement of the urban public space.

Chapter II. Methodological framework

Chapter 2 presents an overview of the general methodological frameworks and tools applied in this dissertation. In addition, it briefly presents the research framework that has been followed according to the results obtained in the different case studies.

2- Chapter 2. Methodological framework

2.1.Methodological approaches and tools

Fig. 2.1 shows an overview of the methodological approaches and tools applied in the dissertation.

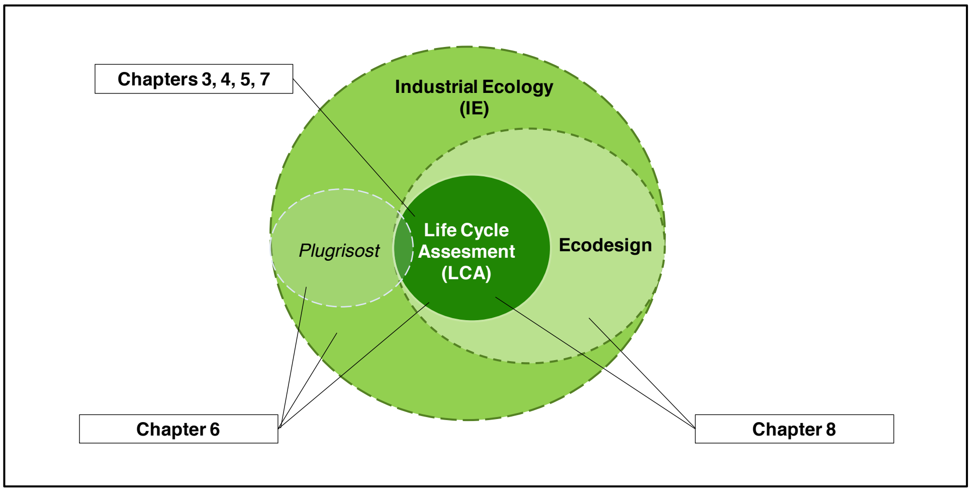

Fig. 2.1. Methodological approaches and tools applied throughout the dissertation.

Life Cycle Assessment (LCA) is the core methodological tool used in the development of the dissertation. Ecodesign and Industrial Ecology (IE), including the plugrisost® analytical model, are wider frameworks applied to solve specific questions and goals arising in the research. Below, the general characteristics of the different methodological approaches and tools are described, starting from the broader to the more specific. Further information and descriptions can be found in chapters 3 to 8 of the dissertation, including the corresponding appendices with supplementary material.

2.1.1.Industrial ecology

As argued in the seminal publication by Frosch and Gallopoulos (1989), IE looks to ecosystems as models for industrial activity to optimize resource efficiency ("the biological metaphor"). Many biological ecosystems are especially effective at recycling resources and thus are held out as exemplars for efficient cycling of energy and material resources in industry (Lifset and Graedel, 2002; Chertow, 2004). The concept requires that an industrial (and socio-economic) system be viewed not in isolation from its surrounding systems, but in concert with them. It is a systems view in which one seeks to optimize the total materials cycle from virgin material, to finished material, to component, to product, to obsolete product, and to ultimate disposal (Graedel and Allenby, 2010).

IE has a primary focus on manufacturing processes and product design. It views firms as agents for environmental improvement because they possess the technological expertise that is critical to the successful execution of environmentally informed design of products and processes (Lifset and Graedel, 2002). The IE concept is made practical by operating at three basic levels (Fig. 2.2): at the firm or unit process level, at the inter-firm, district or sector level and finally at the regional, national or global level, where a range of different approaches, methods and tools for sustainability decision-making apply (Chertow, 2000; Ehrenfeld and Chertow, 2002).

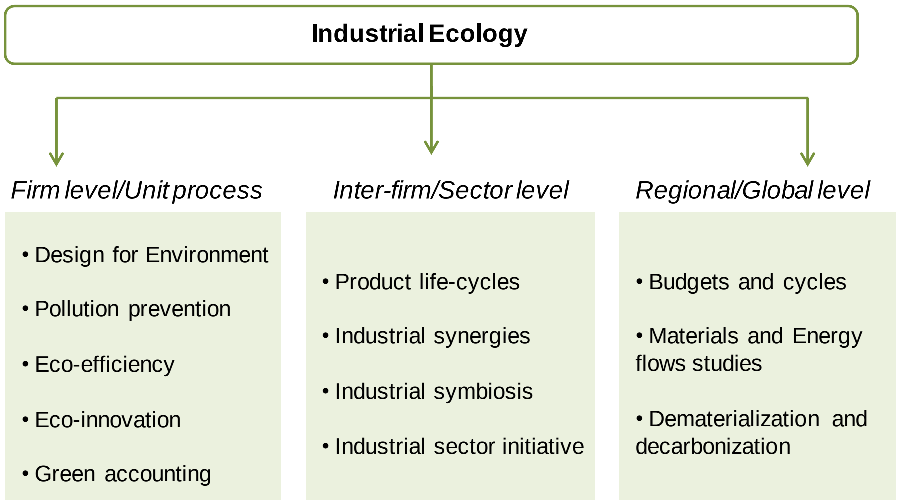

Fig. 2.2 Basic elements of IE seen as operating at different levels. Source: Chertow (2000) and Ehrenfeld and Chertow (2002).

A key element of IE is that it takes a systemic approach to analyse environmental problems in order to avoid narrow, partial analyses that can overlook important variables and, more importantly, lead to unintended consequences. Life cycle thinking (UNEP/SETAC, 2012) is therefore one basic approach which provide systems orientation.

- **The IE tools of LCA (chapters 3 to 8) and ecodesign (chapter 8) have been applied in the dissertation. Nevertheless, a wider IE approach is applied in chapter 6 in order to solve a series of specific research questions raised in that particular case**

study. It includes the use of the Plugrisost® analytical model, which is briefly described below.

Plugrisost analytical model

The software Plugrisost® (Morales-Pinzón et al., 2012a) is an IE analytical simulation tool based on system dynamics that facilitates and support the technical, economic and environmental evaluation of alternative water supplies (rainwater harvesting (RWH) and greywater systems) to contribute to the sustainable management of water resources.

Plugrisost® software analyses the optimal design variables and performance of RWH and greywater systems, using tap water production and use as the reference system for comparison. Tap water production includes water catchment (lake, river and ground), treatment and distribution. RWH includes the catchment, storage, processing and distribution of rainfall. Greywater systems include catchment, treatment and reuse of wastewater. Fig. 2.3 presents a diagram of the basic components of Plugrisost® software.

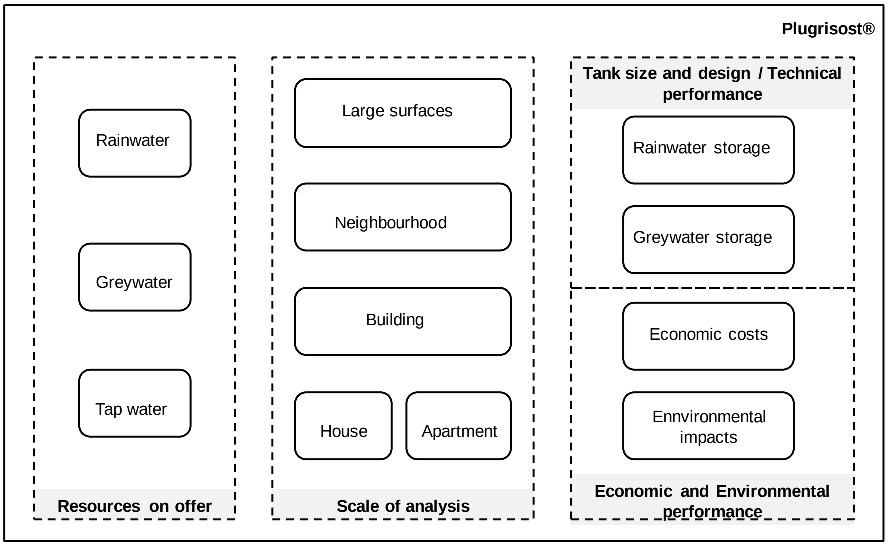

Fig. 2.3 basic components of Plugrisost® software.

The software, although developed primarily to analyze the sustainability performance of the design and implementation of alternative supply systems at different urban scales (neighborhood, building, house and apartment), integrates the assessment of RWH and greywater supply systems for non-residential large surfaces such as industrial facilities and industrial areas. In this sense, the Plugrisost® software has been applied to determine the potential for RWH and use in the industrial production of granite, which is a high water-intensive construction material (see chapter 6). Fig. 2.4 presents and illustration and a diagram of the relationship between determining factors in the optimal design of RWH systems.

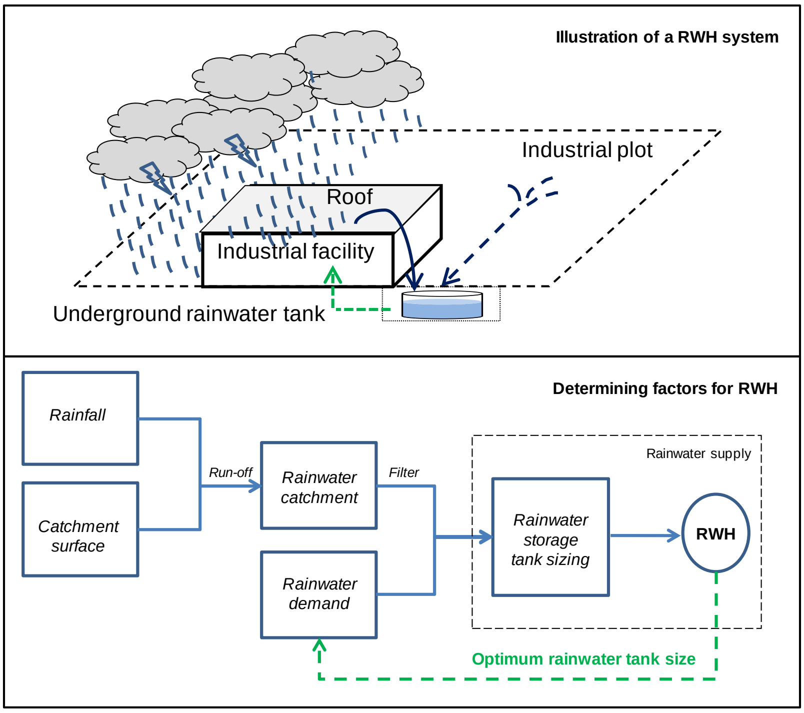

Fig. 2.4 Determining factors for RWH and use in industrial facilities.

The sizing of rainwater storage tanks is central factor to be considered in building the RWH system. The optimal sizing of rainwater storage tanks is a function of rainwater catchment and rainwater demand. Rainwater catchment, in turn, is a function of the useful catchment surfaces available (roofs and/or paved areas) and rainfall. The criteria applied are meant to achieve a share of rainwater supply according to the daily water requirements of the system under consideration (Gabarell et al., 2013a). Following, a brief description of each determining factor in the optimal design of RWH systems is provided:

Rainfall The first methodological step in modeling the potential for RWH consists of collecting historical daily rainfall records from the bioclimatic geography of interest. Historical rainfall records are inputs that reproduce past climate conditions, which, under certain assumptions, can be considered representative of future local conditions. The value captured by the model is the daily rainfall recorded by weather stations or estimated by stochastic models.

Catchment surface The catchment surface corresponds to the useful space that could be dedicated for rainwater collection. When modelling a large area, it is assumed that the whole catchment area is connected and that rainwater can be captured in the same tank. Because not all of the rain can be harvested, a runoff coefficient and filter coefficient should be applied.

Rainwater demand It corresponds to the defined amount of water to be daily satisfied by using rainwater inputs. Water demand can be modelled as either a constant or variable depending on the day or month of the year. However, in the absence of data, the daily average value is used unless indicated otherwise.

Rainwater storage tank sizing The analytical model allows for determining the potential for RWH according to the variability in rainwater storage tank size using a dynamic balance between daily rainwater availability and demand. In this way, the statistically average potential for RWH can be defined. In this process, the yield for each volume of a rainwater tank is estimated according to the different scenarios previously defined.

Rainwater harvesting According to the criteria used to determine the potential for RWH, the software model a large number of scenarios a by the combination of calculation variables and parameters in order to determine the optimum rainwater storage tank size. After obtaining an adequate volume for the rainwater tank, the Plugrisost program allows to perform a statistical analysis of the system using simulated rainfall through the application of probabilistic models. This analysis contributes to observe the variability on the percentage of the water demand met with rainwater supplies.

Finally, the software can be used to model the economic and environmental performance of each particular scenario in order to determine the potential cost savings and environmental savings regarding the use of tap water inputs. Detailed descriptions about the Plugrisost® analytical model and software can be found in Morales-Pinzón et al. (2012a) and Gabarrell et al. (2013a). The software and a manual for users can be directly downloaded at http://sostenipra.ecotech.cat/.

2.1.2. Ecodesign

Ecodesign (also called "Design for Environment") is a conspicuous element of IE. More than 80% of the environmental impacts of products are determined at the design stage (European Commission, 2012). Experience has shown therefore that pollution prevention and waste reduction through the early action in process and product design can be much more effective than "end-of-pipe" (corrective) environmental decisions (Hendrickson et al., 2002). Ecodesign has a product, process or service orientation, focusing on the reduction in the use of hazardous substances, decline in resource consumption, and facilitation of end-of-life management through re-use and recycling. By incorporating systematic environmental considerations into product, process and service design *ex ante*, industrial designers seek to avoid or minimize environmental pressures and impacts (Tukker et al., 2000; Lifset and Graedel, 2002). In this way, the environmental attributes of a product are given the same status as the more traditional product values considered right from the earliest stage of product design such as functionality, safety, ergonomics, endurance, image, quality, aesthetics and cost.

Implicitly, ecodesign entails detailed consideration of the life cycle of products by taking (preferable) a cradle-to-grave approach, from the extraction and use of raw materials and natural resources, manufacturing processes, packaging systems, transport operations, product usage and end-of-life management (European Commission, 2012). Ecoodesign aims to prevent the shift of environmental burdens from one life cycle stage to another. In addition, ecodesign efforts can be concentrated at the level of those product´s hot-spots with high potential for significant environmental improvement in order to find suitable solutions that contribute to the development of environmentally-friendly products.

- **Fig. 2.5 introduces a diagram of the ecodesign framework applied to solve the specific research questions raised in chapter 8 from the dissertation.** A brief description of each basic methodological step is presented below. Further step-by-step descriptions can be found in chapter 8 and appendix IV.

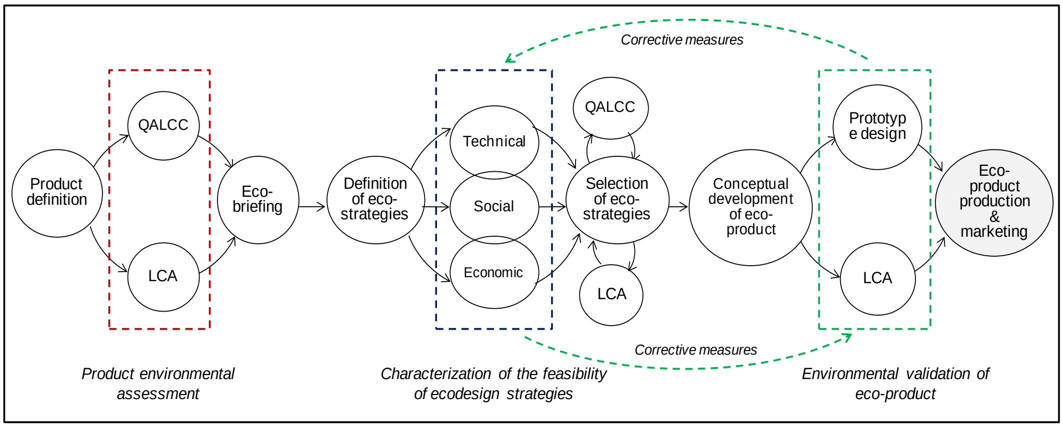

Fig. 2.5 Ecodesign methodological framework. Source: adapted from González-García et al. (2012a; 2012b) and Sanyé-Mengual et al. (2014). Acronyms: QALCC - Qualitative Assessment of Life Cycle Criteria; LCA- Life Cycle Assessment.

This ecodesign methodological framework is based on the approaches proposed by González-García (2012a; 2012b) and Sanyé-Mengual et al. (2014), which have been successfully applied for the eco-innovation of urban furniture and the development of eco-products.

Product definition Product definition is a basic stage to approach the goals of the ecodesign process. In this first stage, a market study can be performed to observe the design trends (insights and norms and technological development) that can contribute to the ecodesign thinking process. A multidisciplinary team should be previously created to cover all the fields of knowledge implied in ecodesign. The multidisciplinary team should include industrial designers and engineers, environmental scientists, marketing managers, and other relevant agents involved in the product´s supply chain. The team will be responsible of taking thoughtful choices for the design and development of an environmentally-friendly product.

Product environmental assessment It is performed through the application of a Qualitative Assessment of Life Cycle Criteria (QALCC) and Life Cycle Assessment (LCA). QALCC (CPRAC, 2012) is a qualitative evaluation that provides a first environmental diagnosis of a product´s life cycle. As a result, the life-cycle stages that have the largest potential for environmental improvement can be identified. The QALCC method consists of three main steps: first, definition of the life cycle stages and system boundaries of the product of interest; second, definition of environmentally relevant criteria for each life-cycle stage; and third, weighting of the environmental criteria provided for each life-cycle stage. A spider diagram can be used to represent the qualitative environmental valuation of the life cycle stages of the product using single (statistically averaged) scores. It enables the identification of the environmentally best and worst product´s life-cycle stages. QALCC results are then complemented with quantitative environmental data generated through LCA (ISO 14040, 2006) in order to complete the identification and characterization of the environmentally relevant hotspots for environmental improvement. LCA consists of the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its entire life cycle.

Ecobriefing The eco-briefing (Smith and Wyatt, 2006) compiles the outcomes from the QALCC and LCA studies in a valuation matrix of product environmental performance. It shows, in a concise and clear way, the most environmentally relevant hot-spots (life-cycle stages and elements) and ecodesign requirements for the environmental improvement of a given product. It is at this stage where a complete picture of the critical environmental attributes of a conventional product is provided to the multidisciplinary team in order to build ideas for ecodesign.

Definition and selection of eco-design strategies As a result from the ecobriefing, a series of eco-design strategies can be defined and selected to improve the product´s environmental performance. Ecodesign strategies can be based on acting at the level of product conceptualization, materials use, product manufacture and packaging, product distribution, usage and maintenance, and end-of-life management. Once a series of eco-design strategies are defined, two selective steps are addressed. First, a feasibility assessment is performed to detect technical, economic and social constrains. Subsequently, those feasible eco-design strategies are classified according to their priority of implementation. This step enables a first selection of the most interesting eco-design strategies. Second, the pre-selected eco-design strategies are assessed from a qualitative (QALCC) and quantitative (LCA) environmental perspectives in order to characterize their potential for environmental improvement. As a result, the multidisciplinary team selects the most suitable eco-design strategies to be integrated in the conceptual development of the eco-product, its prototyping and the subsequent industrial production and marketing.

Conceptual development of eco-product, validation and production and marketing The conceptual development of the eco-product must insure that the marketed eco-product will excel in environmental performance and all other aspects that lead to customer satisfaction and product profitability (Rose, 2000). In this way, previous to the eco-product production and marketing, two interactive steps are addressed. First, a prototype of the eco-product is designed and developed. Second, the environmental performance of the prototype is validated through LCA. Both steps interact in order to optimize the final eco-product design. In this stage, design problems may be found but re-design solutions be proposed to avoid or minimizing costly and time consuming industrial and marketing interventions.

2.1.3. Life cycle assessment

LCA represents one of the core elements of the IE discipline. LCA is a tool for the systematic compilation and evaluation of the environmental aspects and the potential environmental impacts of products systems throughout their life cycle, from raw material acquisition through use until final disposal (UNEP/SETAC, 2012). All processes related to a product during its whole life cycle are together called the "product system". It also includes services which provide a given function. Fig. 2.6 presents the complete life cycle of a given product system.

Fig. 2.6 Life cycle stages of a product system. Source: UNEP/SETAC (2007).

Requirements and guidelines

The LCA methodological framework is standardized by the ISO 14040-44 (2006) series, which defines four basic steps (Fig. 2.7):

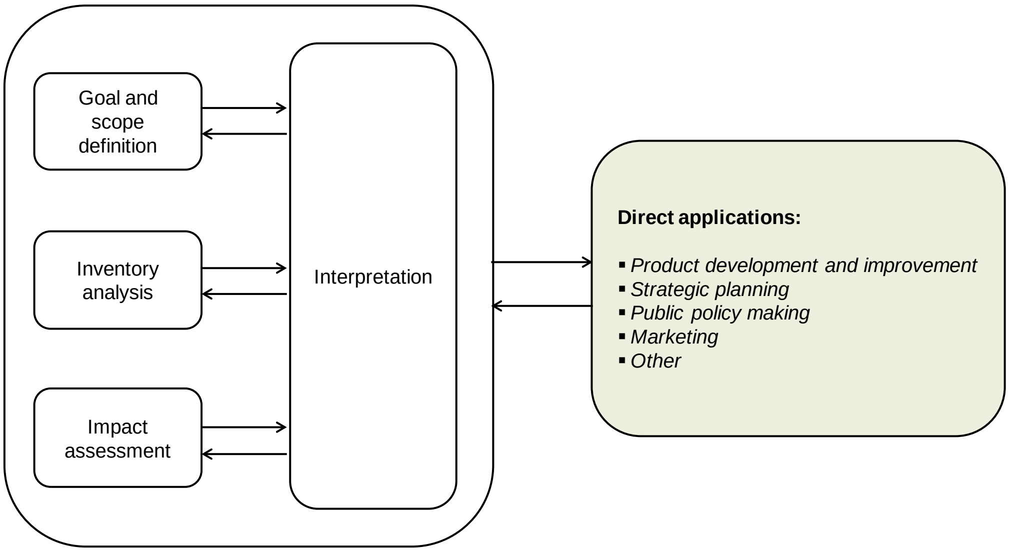

Fig. 2.7 Methodological stages of an LCA study. Source: ISO 14040 (2006).

From the fig. 2.7 it is apparent that LCA is not a linear process. Instead it follows an iterative procedure, in which the level of detail is subsequently increased in order to generate more accurate and comprehensive results.

Goal and scope definition The goal of an LCA should include the intended application, the reasons for carrying out the study, the intended audience, and whether the results are intended to be used in comparative assertions intended to be disclosed to the public. The scope should be sufficiently well defined to ensure that the breadth, depth and detail of the study are compatible and sufficient to address the stated goal. It should include a description of the product system to be studied, the functions of the product system or, in the case of comparative studies, the systems, the functional unit, the system boundary, the allocation procedures, impact categories selected and methodology of impact assessment, and subsequent interpretation to be used, data requirements, assumptions, limitations, initial data quality requirements, type of critical review (if any), and type and format of the report required for the study.

Inventory analysis The life cycle inventory (LCI) analysis phase involves data collection and calculation procedures to quantify relevant inputs (energy, raw materials, water, ancillary elements, and other physical flows) and outputs (products, co-products and waste, pollutant releases to air, water and soil, and other relevant environmental aspects) of a product system to meet the goals of the study. The process of conducting an LCI analysis is iterative. As data are collected and more is learned about the system, new data requirements or limitations may be identified that require a change in the data collection procedures so that the goals of the study will still be met. A first validation of the quality and representativeness of the data is carried out in this phase.

Impact assessment The life cycle impact assessment (LCIA) phase is aimed at evaluating the environmental significance of the LCI results of the product system of interest. In general, this process involves associating inventory data with specific environmental impact categories and category indicators, thereby attempting to understand the environmental effects. Issues such as choice, modelling and evaluation of impact categories can introduce subjectivity into the LCIA phase. Therefore, transparency is critical to the impact assessment to ensure that assumptions are clearly described and reported. The basic elements of the LCIA phase consist of: selection of impact categories, categories indicators and characterization models, assignment of LCI results (classification), calculation of category indicator results (characterization). The normalization, grouping and weighting of environmental impacts are optional elements.

Interpretation phase In the interpretation phase, the LCI and LCIA results are summarized and discussed as a basis for conclusions, recommendations and decision-making. The interpretation should reflect the fact that the LCIA results are based on a relative approach, that they indicate potential environmental effects, and that they do not predict actual impacts on category endpoints, the exceeding of thresholds or safety margins or risks. The interpretation phase may involve the iterative process of reviewing and revising the scope of the LCA, as well as the nature and quality of the data collected and calculated in a way which should be consistent with the defined goal.

Modelling approaches in LCA

It is worth noticing that there are two main approaches to LCA and, particularly, LCI modelling. These approaches are namely the *attributional approach* and the *consequential approach* (Fig. 2.8).

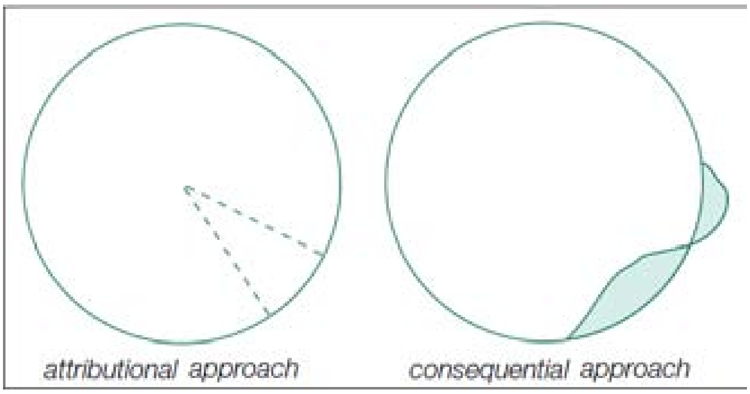

Fig. 2.8 Conceptual differences between attributional and consequential LCA modelling approaches. The circles represent total environmental exchanges. Source: Weidema (2003).

According to the Global Guidance Principles for Life Cycle Assessment Databases developed by UNEP/SETAC Life Cycle Initiative (UNEP/SETAC, 2011), *attributional LCA* is defined as a system modelling approach in which inputs and outputs are attributed to the functional unit of a product system by linking and/or partitioning the unit processes of the system according to a normative rule. *Consequential LCA* is defined as a system modelling approach in which activities in a product system are linked so that activities are included in the product system to the extent that they are expected to change as a consequence of a change in demand for the functional unit. Both approaches are therefore theoretically associated with different objectives and research questions, and hence aim to provide different information to the end user of the LCA studies. Different objectives of the two approaches have repercussions on the models used in the LCA. These differences are usually (but in theory not exclusively) reflected in the LCI phase which subsequently affects therefore the LCIA results:

- *Attributional LCA approach* (also called "accounting" or "descriptive approach") uses data on actual suppliers or average data (technology mix) and commonly uses allocation as a means to deal with multifunctional processes or systems.
- C*onsequential LCA approach* (also called "change-oriented approach") uses data on actual supplier as long as this supplier is not constrained (i.e., insofar as it is flexible to respond to an increase in demand with an equal increase in supply), otherwise uses data representing marginal technology (i.e., suppliers that will actually respond to a change in demand); and uses a system expansion approach to deal with multifunctional processes to expand the analysed system with additional processes.

➢ **The *attributional LCA* approach has been applied to address the different research questions and goals arising from this dissertation.** LCA results attempt to provide information on what portion of global burdens can be imputed to each product systems using normative rules. The environmental performance of each product systems is characterized according to the consideration of the actual processes that are directly linked by (physical, energy, and service) flows to the life-cycle stages of the products with regard to their functional units. No changes in the demand of products are considered.

Indicators for environmental impact assessment

Another important distinction in LCA relates to the use *of midpoints and endpoints indicators* to interpret the life cycle emissions and resource consumption in terms of their contribution to environmental impacts (LCIA) for the so-called "Areas of Protection" (AoP). AoP are divided into Human Health, Natural Environment and Natural Resources (European Commission, 2010b). According to ISO 14044 (2006), the indicator of an impact category can be chosen anywhere along the impact pathway, which links inventory data to environmental impacts on the AoP:

- *Characterisation at midpoint level* models the impact using an indicator located somewhere along (but before the end of) the mechanism.
- *Characterisation at the endpoint* level requires modelling all the way to the impact on the entities described by the AoPs.

Fig. 2.9 shows the framework for LCIA modelling at midpoint and endpoint levels.

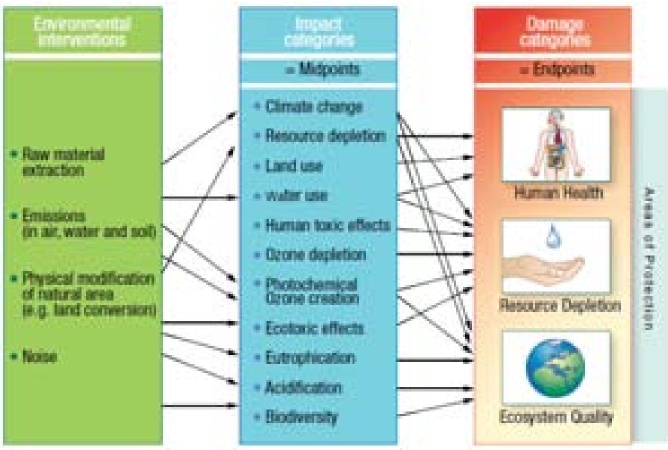

Fig. 2.9 Basic diagram of the life cycle impact assessment midpoint-damage framework. Source: UNEP/SETAC (2012).

The midpoint-damage framework conceptualizes the linkages between a product's environmental aspects (environmental interventions/LCI results) and their ultimate damage caused to the AoP (UNEP/SETAC 2012). Impact categories at the midpoint level are defined at the place where a common mechanism for a variety of substances within that specific impact category exists. Although there are uncertainties associated with each type of environmental impact modelling, it is considered that, in general, the results at the midpoint level are more accurate and precise compared to the endpoint assessment (European Commission, 2010b).

- **The environmental impact categories used in this dissertation correspond to midpoint indicators based on the CML 2001 baseline environmental characterisation method (Guineè et al., 2001).** According to the ILCD Handbook (European Commission, 2010b), the aim of the CML method is to provide best practice for midpoint indicators, operationalising the ISO 14040-44 (2006) series of Standards. **Special attention has been given to the analysis of the environmental indicators of global warming potential (GWP)**, expressed as GHG emissions measured in tons of carbon dioxide equivalent (tn CO2-eq [100 years]) according to the IPCC (2006) approach **and the primary energy demand (PED)** indicator, expressed in equivalent gigajoules (GJ-eq from renewable and non-renewable resources [net cal. value]) measured according to Hischier et al. (2010) approach. However, other methods and environmental indicators are also used (see chapter 6 for specific information). The **GaBi software and datasets** (PE-International, 2013) and **ecoinvent LCI database** (SCLCI, 2010) were used as supporting analytical tools. Besides, **all the LCI dataset produced throughout the development of the dissertation has been uploaded into the LCADB.sudoe tool**, which is briefly described below.

LCADB.sudoe tool

The representativeness and reliability of the outcomes from LCA studies, and consequently ecodesign and IE projects, aimed to improve the environmental performance of products, processes and services depend directly of the quality of the dataset used in calculations. The Life Cycle Assessment DataBase in SUDOE

(LCADB.sudoe) is the outcome from an initiative promoted within the framework of the ECOTECH ("International Network in Life Cycle Assessment and Ecodesign for Environmental Innovation of Technologies) SUDOE Project (SOE2/P1/E377) with the aim to create and implement a common database for the development of LCA and IE studies in South-West Europe (France, Portugal and Spain). The LCADB.sudoe has the aim to provide a specific high quality LCI datasets for the SUDOE area focus on topics with special importance for the region in order to reduce uncertainty through the use of general data (Gabarrell, 2013b; 2013c). The topics covered in the database include agriculture, construction, energy Production, manufacture process, services, transport, use and consumption, waste treatment, water and forest and forestry products. The LCADB.sudoe is an online free tool (Fig. 2.10), which can be found in the following site: http://lcadb.sudoe.ecotech.cat/.

Fig. 2.10 Screenshot of the LCADB.sudoe website. Source: http://lcadb.sudoe.ecotech.cat/.

Users of the LCADB.sudoe can directly consult the LCI dataset for the development of their own LCA and IE research projects or contribute with the provision (uploading) of new LCI datasets. An user´s manual can be found at: http://icta.uab.es/ecotech/sudoe/reports/GT3/manual_usuario.pdf.

The database format developed by Sostenipra Resarch Group (http://www.sostenipra.cat) in partnership with the Universidad de Aveiro, Ecole des

Mines d'Alès, Montepellier SupAgro, INRA, UdG, IRSTEA and CATAR Agro Resources. The LCI data collection and provision sheets follow the ISO 14040-44 guidelines and are compatible with the ILCD system and Ecoinvent. All the datasets published in the LCADB.sudoe are previously validated by an external expert committee of editors and reviewers (Sostenipra, 2013). Fig. 2.11 presents a diagram of the basic steps for the creation and validation of a LCI dataset.

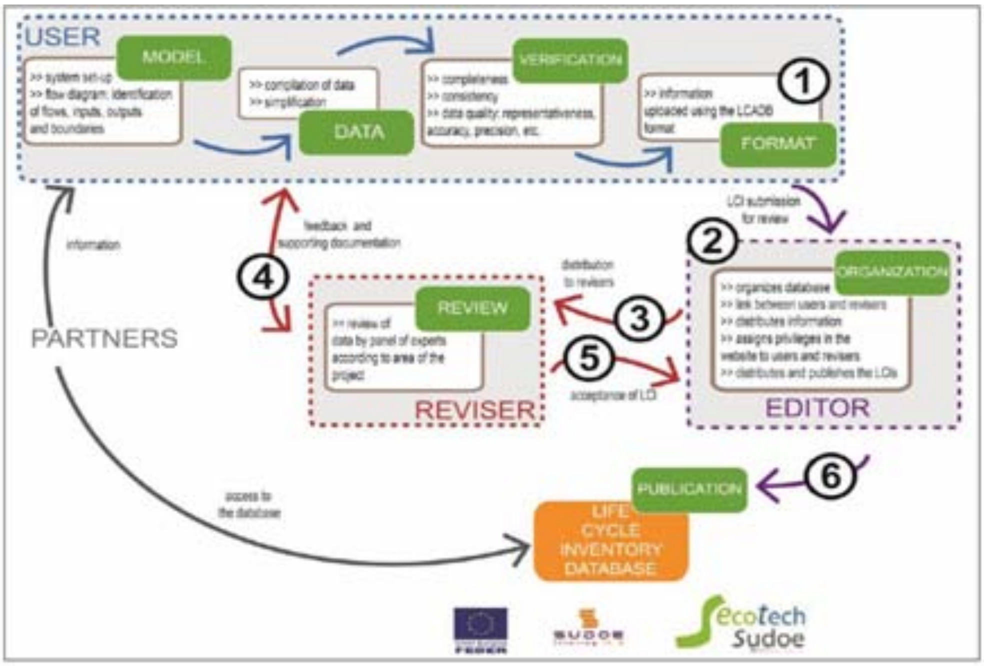

Fig. 2.11 Basic steps for the creation and validation of a LCI dataset to be published in LCADB.sudoe. Source: Sostenipra (2013).

This iterative online free tool allows researchers from academy, industrial producer and urban planners to share knowledge and expertise for the development of comprehensive and high quality LCA, DfE and IE studies in the context of Southwest Europe.

2.2.Schematic overview of the research framework

The Fig. 2.12 shows a schematic overview of the complete research framework addressed in the dissertation according to main results obtained from the development of the different case studies (chapters 3 to 8).

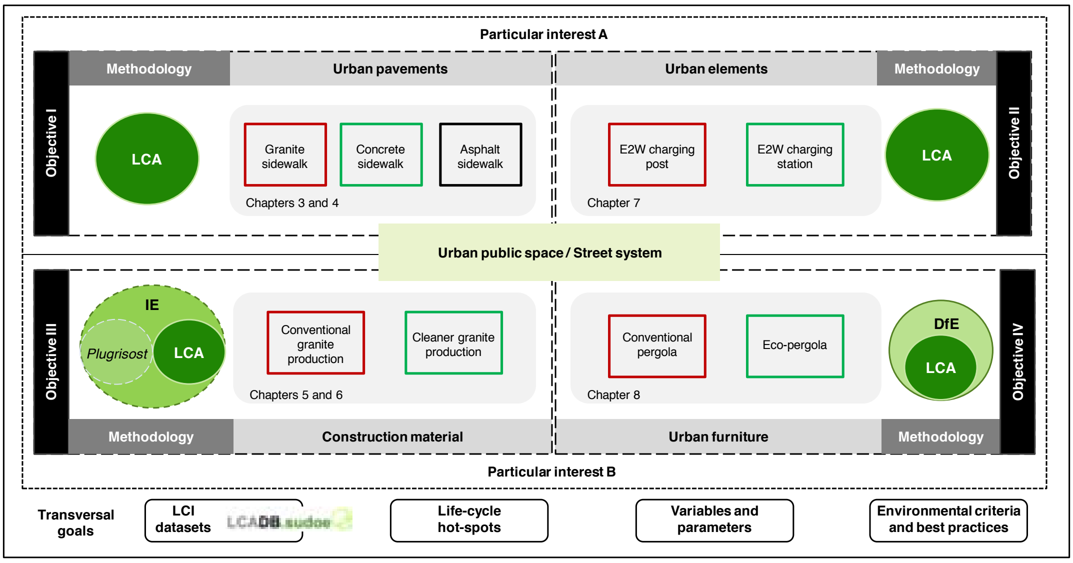

Fig. 2.12 Schematic overview of the research framework addressed in throughout dissertation.

Consistent with the main objective and interests of the dissertation, the research presented in chapters 3, 4 and 7 is aimed to identify the most environmentally friendly designs of urban pavements and elements to support sustainable mobility (pedestrian and electric) with a minimum environmental cost to the public space of cities (highlighted in green boxes). Besides, the dissertation is also intended to find solutions to improve the environmental performance of those products systems with high environmental footprint (highlighted in red boxes) in order to contribute to achieve major environmental improvements at the urban scale. This is the purpose of the research presented in chapters 5, 6 and 8. The transversal goals apply to all the case studies addressed in the dissertation.

Part II. Environmental optimization of urban pavements.

Chapter III. Life cycle assessment of granite application in sidewalks

3- Chapter 3. life cycle assessment of granite application in sidewalks

This chapter is based in the following paper:

Mendoza, J.M., Oliver-Solà, J., Gabarrell, X., Josa, A., Rieradevall, J., 2012. Life cycle assessment of granite application in sidewalks. Int. J. Life Cycle Assess. 17, 580-592. DOI 10.1007/s11367-012-0391-1.

Reference to article

Abstract

Purpose Sidewalks are important built areas for promoting environmental sustainability in cities since they support walking as a zero emission form of transportation protecting the environment and the health of individuals. However, sidewalk management is typically focused on assessing their suitability for users without applying any environmental criteria on the infrastructure design. The paper aims to quantify the environmental impact that sidewalks can contribute to the urban space if no environmental criteria are applied in sidewalk design.

Methods This study focuses on the environmental assessment of a very common sidewalk system found in cities to support pedestrian and light motorized traffic for over 45 years. The constructive solution consists of granite slabs (top layer) fixed on a mortar layer (3 cm thick) that is settled on a base of concrete (15 cm thick). The life cycle methodology was employed to conduct the environmental assessment of the system. The results are compared with the environmental outcomes of a sidewalk system that has the same function but is paved with concrete slabs to identify the environmentally optimal sidewalk design. The impact assessment method was CML Baseline 2001, and the inventory data were compiled from manufacturers associations, local authorities and literature review.

Results and discussion Construction materials have the highest environmental impact (48%-87%) in the sidewalk life cycle, where the granite top layer is the first contributor, although the amount of granite in the sidewalk system represents the 30% of the total weight of the construction materials used. A granite sidewalk has from 25% to 140% higher impact than a concrete one. The energy required to produce slabs is the key factor that characterizes the environmental impact of granite. Electricity and diesel consumption in stone-cutting and moving represent over the 70% of the environmental burden of granite. The transportation of granite slabs is also relevant to the environmental impact. The use of imported granite could account for up to 76%-177% of the total environmental impact of the sidewalk life cycle.

Conclusions Although granite is a natural material, using granite slabs is not an environmentally suitable alternative over using concrete ones for paving sidewalks. The results have shown that if no environmental criteria are applied during sidewalk design and management, urban planners may be unconsciously contributing to an important environmental burden on the built environment. The ecodesign of pedestrian networks is a strategic opportunity to promote environmentally suitable urban infrastructures that contribute to sustainability in cities.

Recommendations Energy efficiency techniques, water management and well-considered transportation management should be developed and implemented in the granite industry to minimize the environmental impact of using it for paving. Additionally, further research is needed to quantify the environmental performance of other construction materials used in sidewalk construction in order to identify the best environmental alternatives and design improvements by optimizing the use of materials to the sidewalks functions.

Keywords: Sidewalks, Granite, Slabs, City, Urban, Pavement, LCA, Sustainability.

Chapter IV. Planning strategies for promoting environmentally suitable pedestrian pavements in cities

4- Chapter 4. Planning strategies for promoting environmentally suitable pedestrian pavements in cities.

This chapter is based in the following paper:

Mendoza JM, Oliver-Solà J, Gabarrell X, Rieradevall J, Josa A, 2012. Planning strategies for promoting environmentally suitable pedestrian pavements in cities. ***Transportation Research Part D: Transport and Environment*, 17, 442-450. DOI: 10.1016/j.trd.2012.05.008.**

Reference to article

Abstract

This paper examines the relevance of incorporating comprehensive life-cycle environmental data into the design and management of pedestrian pavements to minimize the impact on the built environment. The overall primary energy demand and global warming potential of concrete, asphalt and granite sidewalks are assessed. A design with a long functional lifetime reduces its overall primary energy demand and global warming potential due to lower maintenance and repair requirements. However, long-lived construction solutions do not ensure a lower life-cycle primary energy demand and global warming potential than for shorter-lived designs; these values depend on the environmental suitability of the materials chosen for paving. Asphalt sidewalks reduce long-term global warming potential under exposure conditions where the functional lifetime of the pavements is less than 15 years. In places where it is known that a concrete sidewalk can have a life of at least 40 years, a concrete sidewalk is the best for minimizing both long-term primary energy demand and global warming potential. Granite sidewalks are the largest energy consumers and greenhouse gas contributors.

Keywords. Pedestrian Pavement, Service Life, Life Cycle Assessment, Concrete, Asphalt, Granite.

Part III. Cleaner production of construction materials.

Chapter V. Life cycle inventory analysis of granite production from cradle to gate

5- Chapter 5. Life cycle inventory analysis of granite production from cradle to gate.

This chapter is based in the following paper:

Mendoza JM, Maria F, Feijoo G, Josa A, Gabarrell X, Rieradevall J, 2014. Life cycle inventory analysis of granite production from cradle-to-gate. ***International Journal of Life cycle Assessment*****, 19, 153-165. DOI: 10.1007/s11367-013-0637-6**

Reference to article

Abstract

Purpose Granite is a traditional high-quality material that is widely used in construction. A key strategy that is increasingly promoted to highlight the competitiveness of materials is life cycle environmental performance. Due to the lack of comprehensive life cycle inventories (LCIs), the environmental characterisation of granite products has received little attention in scientific literature. In this paper, a complete LCI of the production chain of intermediate and finished granite products is provided and analysed.

Method The Spanish granite production industry, which is the second major European producer and the seventh worldwide, is examined. The reference unit is defined as 1 m^2 of finished granite tiles with dimensions 60 cm x 40 cm x 2 cm used for indoor and outdoor applications. Input and output data were collected through the distribution of technical data collection surveys to quarries and processing facilities, and via on-site visits. During data calculation and validation, technical support was provided by technicians from the Spanish Cluster of Granite Producers (SCGP). The LCI data describe the industrial activity in baseline year 2010 that corresponds to a total production volume of 48,052 m^3 of quarried granite and a net of 881,406 m^2 of processed granite.

Results and discussion The production of 1 m^2 of polished granite tiles requires 28.3 kWh of electricity, 23 MJ of diesel, 103 litres of water, and 7 kg of ancillary materials. Sandblasted, flamed or bush-hammered finishes applied to granite tiles have a minimal effect on their total energy and material requirements but significantly affect their water consumption. Electrical energy, cooling water, and steel are the major industrial requirements, in which granite sawing is the most demanding process. The resource efficiency of the production chain is 0.31. Approximately 117 kg of granite are wasted per m^2 of granite tiles that are produced (53 kg). Seventy-four percent of granite waste is

composed of granite scrap, which becomes a marketable by-product. The predominant source of granite waste is the sawdust that is generated during stone-cutting operations.
Conclusions LCIs provide the relevant information required to characterise the environmental performance of granite production and products. LCI data can be easily managed by users due to the disaggregation into unit processes. LCI data can be used to analyse the environmental burden associated with intermediary granite products, such as granite blocks, sawn granite slabs and finished granite slabs, and to analyse the environmental burden of finished granite tiles according to the corresponding net production volumes.
Recommendations LCI dataset of granite production should be extended to include alternative production technologies, such as multi-diamond wire machines for sawing granite, which is an increasingly competitive production technology with interesting properties for cleaner production. Strong competitive granite industries, such as the industries in China, India, and Brazil, should also provide LCIs of granite products to transparently compare different product chains, identify environmental strategies on the sector level, and promote the green procurement of granite products.
Keywords: Natural stone, granite, quarrying, sawing, slabs, resource efficiency, environmental performance, LCI.

Chapter VI. Environmental management of granite slabs production from an industrial ecology standpoint.

6- Chapter 6. Environmental management of granite slabs production from an industrial ecology standpoint.

This chapter is based in the following paper:

Mendoza JM, Capitano C, Peri G, Josa A, Rieradevall J, Gabarrell X, 2014. Environmental management of granite slab production from an industrial ecology standpoint. ***Journal of Cleaner Production*****, XX, 1-10.** ***In press*****.** DOI: 10.1016/j.jclepro.2014.03.056.

Reference to article

Abstract

The granite production chain is high energy and water intensive with very low resource efficiency. Granite block sawing into slabs is the most environmentally relevant unit process. The promotion of cleaner production alternatives is essential to improving the industry's competitiveness and the life cycle environmental performance of granite products. This paper focus on characterizing the potential for environmental improvement of the entire granite production chain by promoting the optimization of sawing technology, the implementation of rainwater harvesting (RWH) systems and the material recovery of wasted granite (sludge).

The environmental performance of multi-blade gangsaw (MBGS) and diamond multi-wire saw (DMWS) technologies is characterized and compared by mean of life cycle assessment. Results demonstrate that the implementation of DMWS technology can contribute almost 30% of water savings, 40% of energy savings and 80% of material savings per square meter of polished granite tiles (60 cm x 40 cm x 2 cm) production. These resource savings contribute together to reduce the product´s environmental footprint by 35% to 80%, depending on the indicator considered.

The potential for RWH is analyzed using Plugrisost® simulation software based on system dynamics. RWH depends on the relationship between rainfall, catchment surface and tank size according to the industrial process's water demand. The results demonstrate major potential to satisfy over 50% of the systems´ daily water requirements using rainwater supply stored in rainwater tanks of varying capacity. RWH is presented as a sustainable strategy to be included in industrial water cycle management.

A comprehensive review of scientific literature reveals a range of technically feasible alternatives to promote material recovery of granite sludge. The ceramic industry appears to be one of the most promising industrial endpoints with which to avoid waste landfilling and contribute to important mineral, energy and water savings. This by-product synergy could also potentially serve as starting point for springboarding exchanges with other industrial agents, becoming a global extension of resource efficiency through joint environmental management.

Keywords. Granite sawing, life cycle assessment, rainwater harvesting, waste recovery, by-product synergy, cleaner production.

Part IV. Environmental optimization of urban elements.

Chapter VII. Environmental significance of slow-charging facilities for electric two-wheelers.

7- Chapter 7. Environmental significance of slow-charging facilities for electric two-wheelers.

This chapter is based in the following paper:

Mendoza, J.M., Josa, A., Rieradevall, J., Gabarrell, X., 2014. Environmental significance of public charging facilities for electric two-wheelers. ***Under review in an international scientific journal.***

Abstract

The environmental characterization of the charging infrastructure required to operate electric vehicles (EVs) is usually overlooked in the literature. Only small life cycle inventories of EV charging facilities are publicly available. This lack of information is especially noticeable in environmental studies of the environmental performance of electric two-wheelers (E2Ws), none of which have included an analysis of charging facilities, even though they constitute the most successful electric-drive market in the world.

This paper focus on characterizing the life-cycle global warming potential (GWP) and primary energy demand (PED) of two conventional charging facility designs that are widely implemented for charging E2Ws in the public space. The relative environmental significance of charging facilities per kWh consumed by E2Ws is determined by considering a range of use scenarios (variability in the service ratio) and the effect of upgrading the electricity mix to include more renewable energy sources. Savings of over 3 tn of CO_2-eq emissions and 56 GJ-eq. can be achieved by implementing optimized charging system designs. The internalization of the relative environmental burden from the charging facility per kWh consumed by E2Ws can increase the GWP of E2Ws' use phase from 1% to 20% and the PED from 1% to 13%.

Although the article focuses on a particular case scenario, the research is intended to provide complementary criteria for further research on the life cycle management of electric mobility systems. Thus, a series of factors that can influence the potential environmental significance of EV charging network at the macro scale are discussed.

Keywords. Electric mobility, charging infrastructure, electricity mix, global warming potential, life cycle assessment, industrial ecology.

7.1. Introduction

7.1.1. Urban charging infrastructure for electric vehicles

The mass deployment of electric vehicles (EVs) that rely on low-GHG-emission electricity generation represent one of the most promising technology pathways for reducing oil use and CO_2 emissions on a per-kilometer basis (IEA, 2011). The vision of the EV technology roadmap developed by the IEA (2011) is to achieve more than 50% of annual EV sales worldwide in order to contribute approximately a 30% reduction in road-transport CO_2 emissions by 2050. Consistent with this vision, the Electric Vehicles Initiative (EVI) provides a forum for global cooperation on the sustainable deployment of EVs and their associated infrastructure. The goal of the EVI is that the electric drive is the predominant motorized transportation mode in sustainable urban mobility systems (http://www.ieahev.org/). In this sense, the EVI membership seek to facilitate the global deployment of at least 20 million of EVs by 2020 (Clean Energy Ministerial, 2010) that would account for over 80% of EV sales worldwide (IEA, 2013).

One of the key challenges in the widespread adoption of electric mobility is the deployment of diverse, extensive and reliable urban charging network (RAE, 2010; Contestabile et al., 2012). Charging EVs at home overnight is considered the best option to deliver the greatest environmental and economic system´s performance (Hacker et al., 2009; DfT, 2011; REE, 2011). However, the provision of a pervasive public urban charging network is essential to alleviate "range anxiety" and make the use of EVs more flexible between drivers with lack of access to domestic electricity supplies (Nemry et al., 2010; ERTRAC, 2012). A large publicly-accessible EV charging infrastructure (EVCI) is being implemented in many cities around the world (Eurelectric, 2012; Zubaryeva and Thiel, 2013). According to the IEA (2013), the global publicly-accessible EVCI stock by 2012 in EVI countries accounted for over 47,400 slow charging points and above 1,900 fast charging stations for a total stock of about 180,000 EVs. Definitions of slow and fast charging attempt to capture the range of charging times typically experienced by EVs according to the maximum amount of power provided to their batteries (Eurelectric, 2011; IEA, 2013). By 2020, EVI countries have cumulative targets for the implementation of approximately 2.4 million public slow charging and 6,000 public fast charging points (IEA, 2013). In the European Union (EU), the proposal for a European Directive on the deployment of alternative fuels infrastructure (European Commission, 2013) establish that EVs further need to have at least two charging points per vehicle available for full recharging of batteries, and a certain number of publicly accessible charging points for intermittent topping-up charging to overcome range anxiety. Thus, the proposal sets out a minimum EVCI coverage to be implemented by each Member State for 2020. The urban charging EV networks range from 12,000 to up to 1,500,000 charging points, which at least 10% should be publicly accessible.

The Fig. 7.1 provides an overview of the basic (slow and fast) and complementary charging alternatives available, and under research and development (i.e. inductive and contact energy supply), for charging different types of EVs in cities. A summary of the present (2012-2013) and future (2020 horizon) extent and diversity of public EV charging networks related to EVI and EU countries among a brief description of each charging alternative indicated in Fig. 7.1 are presented in sections A.1, A.2 and A.3, respectively, from appendix III.

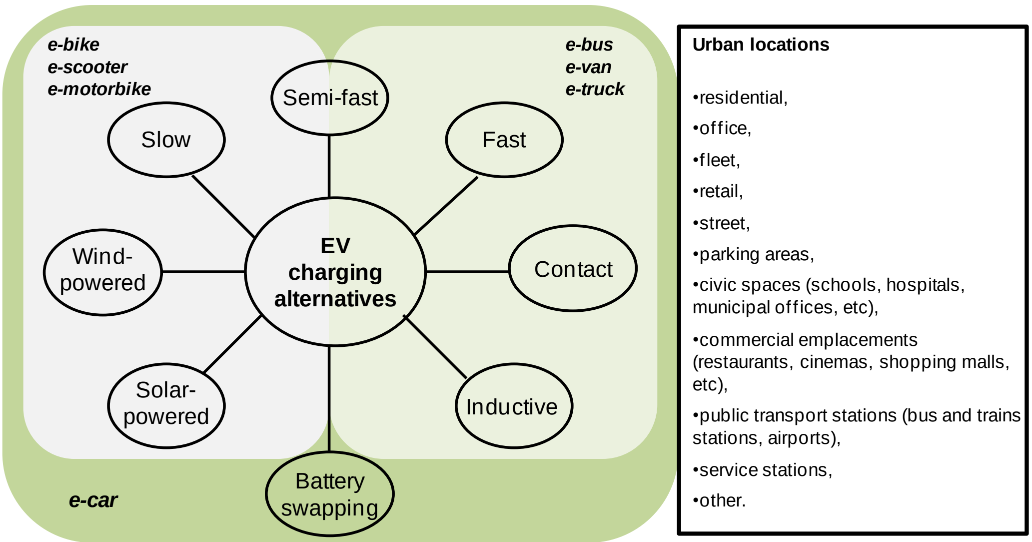

Fig. 7.1 Overview of EV charging alternatives available in public and private urban locations.

In the last few years, a wide range of scientific literature has focused on the life cycle assessment (LCA) of EVs. There is a consensus between researchers that the environmental performance of EVs is highly dependent on the carbon intensity of the electricity grid mix (Hacker et al., 2009; Nemry and Brons, 2010; MacPherson et al., 2012). Nevertheless, some authors started to demonstrate that accounting for vehicle´s production environmental impacts is important when comparing vehicles technologies with significantly different powertrains. MacPherson et al. (2012), Hawkins et al. (2013)

and Cooney et al. (2013) proved that the EV production phase is substantially more environmentally intensive than that of internal combustion vehicles (ICVs). However, the assessment of the environmental significance of the EVCI required to support EVs´ operation, has received little attention. Nevertheless, in order to effectively mitigate the environmental impacts of transportation modes, life-cycle environmental performance, including both the direct and indirect processes and services required to operate the vehicles, should be considered (Chester and Horvath, 2009). Only a few research papers have addressed the environmental characterization of EVCI. In Lucas et al. (2012), a mix of home, normal and fast chargers for electric cars was analyzed to estimate their relative contribution to the overall life-cycle GHG emissions and energy use of vehicles. In Traut et al. (2012), the optimal design and allocation of EVs and dedicated charging facilities, including home and workplace chargers, needed to minimize life-cycle costs and GHG emissions was analyzed. In Cooney et al. (2013), the authors analyzed the scale of the additional battery production and charging infrastructure impacts on the entire life cycle of electric buses. In all cases, the results demonstrate a reduced relative contribution of the EVCI to the environmental performance of the use phase and life-cycle of EVs. Nevertheless, the life-cycle inventories (LCIs) related to charging facilities provide limited information on the charger designs and installation and maintenance requirements, thus scarce information about the mobilized resources between life cycle stages. Additionally, the characterization of the relative environmental significance of the charging facilities is based on the definition of service ratios (lifetime energy outputs) assuming a stable fleet penetration of EVs in cities. However, this consideration does not reflect the present performance of the EVCI implemented worldwide which is underused due to the reduced EV penetration rates and lack of standardization of charging facilities (IEA, 2013).

The incorporation of life cycle environmental criteria in the planning, design, and management of supporting infrastructure for sustainable modes of transportation can contribute to reduce its contribution to the environmental burden imposed by the built environment, thereby increasing the environmental value of greening urban mobility (Oliver-Solà et al. 2009a; Oliver-Solà et al., 2011; Mendoza et al., 2012a, 2012b). In this early stage of electric mobility deployment, it is fundamental to start characterizing the life-cycle environmental performance of EVCIs in order to increase the understanding of the global environmental pressures related to electric mobility deployment and overlooking a range of complementary opportunities for sustainability-based decision-making.

7.1.2. Case scenario

In a first stage, and together with innovative mobility services, captive fleets such as public transport fleets can trigger the implementation of the adequate infrastructure and initiate the transition towards a mass deployment of EVs (ERTRAC and EPoSS, 2009). Fleets, including taxis (Amsterdam), buses (Los Angeles, Shanghai), freight (Berlin), and two-wheelers (Barcelona), are helping propel the city's ability to electrify the rest of the passenger vehicle stock (Stockholm) (IEA, 2012). In this sense, the EV City Casebook (IEA, 2012) describes a number of pioneering cities around the world that are committed to making electric mobility a reality. One of the cities leading by example is Barcelona (Spain), which is a center of electric mobility innovation and demonstration projects. In a city with 1,615,448 inhabitants, there are a total of 976,345 registered vehicles, of which 60.6% are cars, 30.2% are motorized two-wheelers, 6% are vans and trucks, and 3.2% are other vehicles (Departament d'Estadística, 2012). The City Council has committed itself, through the project LIVE (2009) to support and promote the deployment of electric mobility. The promotion of electric scooters and motorcycles (electric two-wheelers) is the city's main priority due to their ease of implementation and management, their economical attractiveness and their suitability for the city (LIVE, 2009). Barcelona is second only to Rome in the use of motorized two-wheelers for personal mobility in Europe (IEA, 2012).

The environmental gains related to electrification of large urban motorized two-wheeler vehicle fleets have been demonstrated by the outcomes of several research studies (Weinert et al., 2008; Sung, 2010; Amjad et al., 2011). However, none has considered the life-cycle environmental burden of the urban charging network for electric two-wheelers (E2Ws), even though they constitute the most successful electric-drive market in the world (Weinert et al., 2008). In fact, China alone has almost 180 million fully E2Ws, which far surpasses any other EV fleet worldwide (IEA, 2013).

A fleet of 21,000 on-road E2Ws is expected to be operating in Barcelona by 2014 (RACC, 2012). There are currently 248 slow charging points and 1 fast charging station located throughout the city (City Council of Barcelona, 2013 - http://w41.bcn.cat/). A total of 4,400 slow charging points and 20 fast charging stations are expected to be installed in the public space by 2014 (IEA, 2012). Currently, around two-thirds of the slow charging points are dedicated to E2W use. Of these, 30% (48 points) are located in underground parking lots and 70% (118 points) are located in public urban spaces.

This paper describes a comprehensive life-cycle environmental impact characterization of two standard designs of public charging facilities for E2Ws to determine the most suitable solution to supplying electricity at minimal environmental cost. Although the article focuses on a particular case scenario, the research is intended to provide complementary criteria for the on-going research on the life cycle management of electric mobility systems. In this way, the discussion section focuses on the consideration of a series of factors that can influence the potential environmental significance of EVCI at the macro scale.

7.2. Methodology

The LCA methodological framework (ISO 14040, 2006) was applied in this study. In a first stage, a detailed LCI of the charging facilities is presented, their life-cycle environmental performance is compared, and criteria for environmental improvement of charging facilities are provided. In a second stage, the relative environmental significance of the charging facilities to the environmental performance of the use phase of E2Ws is analyzed. Several scenarios (service ratios) for the use of charging facilities and the effect of upgrading the electricity mix are considered. Subsequently, criteria for the environmental management of EVs urban charging networks are provided.

7.2.1. Description of the charging facilities and system boundaries

The charging facilities assessed include an outdoor recharge post with two sockets available (ORP2) and an outdoor recharge station with six sockets available (ORS6). There are a total of 44 ORP2 facilities operating in the public space in Barcelona, providing 88 charging points, and 5 ORS6 facilities, providing 30 charging points. The charging facilities supply a power output of 3.7 kW (230 V AC/16 A) per available socket. An illustration of each charging facility is shown in Fig. 7.2 and Fig. 7.3. A description of the different components (a-d) and construction work requirements of charging facilities for public installation is presented in section B.1 in appendix III.

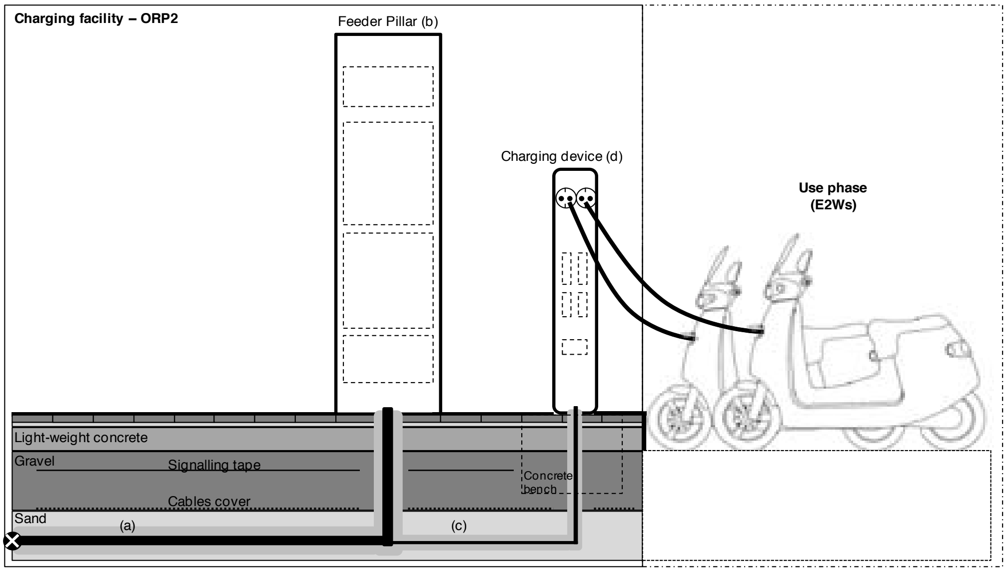

Fig. 7.2 Illustration of an outdoor recharging post with two sockets available (ORP2). Notes: (a) electrical connection to a municipal low-voltage line, (b) feeder pillar, (c) electrical connection from feeder pillar to the charging device, (d) charging device. Charging equipment = b + d; Charging facility = a + b + c + d.

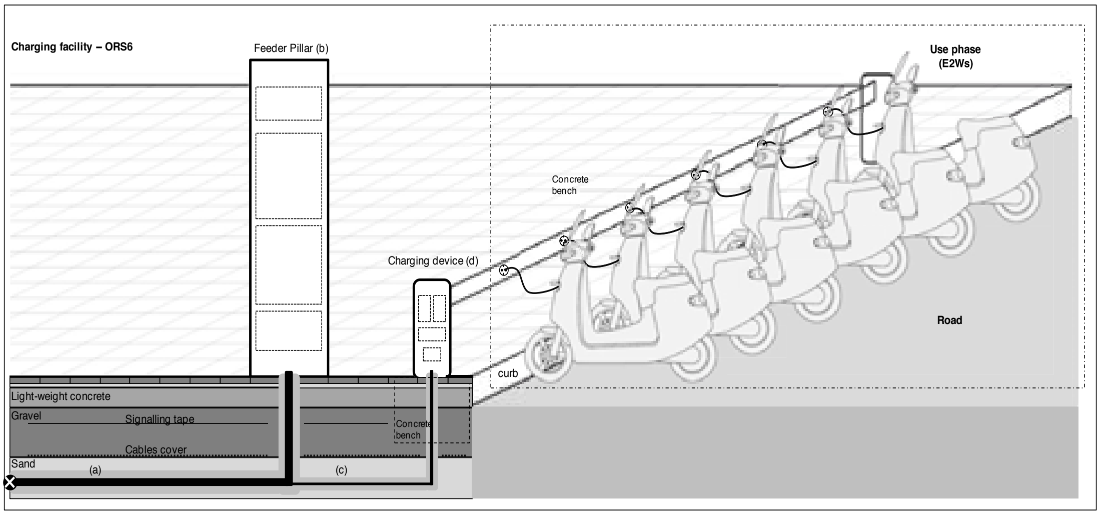

Fig. 7.3 Illustration of an outdoor recharging station with six sockets available (ORS6). Notes: (a) electrical connection to a municipal low-voltage line, (b) feeder pillar, (c) electrical connection from feeder pillar to the charging device, (d) charging device. Charging equipment = b + d; Charging facility = a + b + c + d.

The functional unit is defined as the relative environmental impact of the charging facility per kWh of electricity supplied for charging E2Ws over a time frame of 10 years. The maximum lifetime electricity supply of the charging facilities is used as the reference for making the environmental comparison of the product systems functionally equivalent. The basic assumption made is that all of the sockets available in the charging facilities are used by E2Ws and that all the sockets are used at an equal intensity over time. According to this assumption, three outdoor recharge posts (3xORP2) are required to supply the same amount of electricity as one outdoor recharge station (1xORS6).

7.2.2. Use of charging facilities

Various scenarios are defined to analyze the relative environmental significance of charging facilities to the environmental performance of the use phase (electricity consumption) of E2Ws. The scenarios reflect the combination of two factors. The first factor is defined as the service ratio of a charging facility and is the number of daily hours that supplies electricity to E2Ws. The second factor is defined as the use conditions and pertains to the circumstances affecting the expected performance of the charging facility to which the service ratios apply.

7.2.3. Definition of the service ratios of charging facilities

The service ratio of the charging facilities depends on a variety of factors, such as the evolution of the level of E2Ws penetration within cities, the type (model) of E2Ws most commonly used, and the availability of complementary charging alternatives (Fig. 7.1). Given that electric mobility is at an early stage of deployment, it is difficult to determine how the performance of the public urban charging network will evolve. The City Council of Barcelona is currently running pilot tests to identify the technical, economic and regulatory barriers to adapt the deployment of the charging infrastructure to conditions of the city. Thus there is not yet useful field data available to define accurately the service ratio of the public E2W urban charging network. For that reason, five service ratios for charging facilities were defined after consultation to EVCI managers (e.g. Mobec Point). These service ratios represent present realities and project future scenarios that could exist in cities, depending on the evolution of the E2W fleet.

The maximum service ratio of the charging facilities by E2Ws is established as 12 h per day per available socket. This number is associated with a scenario of high E2W penetration (three full battery charging cycles of 4 h each for conventional E2Ws). The minimum service ratio of the charging facilities is defined a 2 h per day and available socket. In this case, E2Ws are consuming electricity during 10% of the daytime hours. This scenario applies to a period of slow transition in the shift to electric mobility, in which the available public charging infrastructure is underused (present situation). This scenario also coincides with the amount of time defined as emergency charging in the guidelines established by the AEB (2011), representing what could happen if the public charging infrastructure were used only sporadically for topping up the E2Ws' batteries. The data and further details related to each scenario are provided in section B.2 in appendix III.

7.2.4. Use conditions affecting the performance of charging facilities

Normal Conditions (NC) refer to the scenario in which a charging facility begins being used by E2Ws immediately after its installation in the public urban space, at service ratios that vary according to the scenarios defined in section B.2 in appendix III. However, two special use conditions are defined for the purpose of sensitivity analysis to more accurately describe the variability in the relative environmental significance of charging facilities. One special condition is defined as a delay in the start of use (DU) of a charging facility, which is a period of time during which the charging facility is not used by E2Ws after its installation. The second special condition is defined as a quick renovation (QR) of a charging device before it reaches the end of its lifetime (10 years).

Many cities are in transition toward significant restructuring of urban mobility systems. This restructuring may take several years to generate the conditions needed to gain social involvement in the purchase and use of EVs. In Barcelona, installation of the public charging facilities began in 2009. The cumulative electricity supplied by the entire public charging infrastructure to date amounts to an average of 3-4 kWh supplied per charging point (pers. comm. City Council of Barcelona, 2013). Given that the charging infrastructure has hardly been used since its installation began, a scenario involving 4 years of delay before the charging facilities start to be used by E2Ws is defined.

With respect to the renovation of the charging devices, it should be noted that some electronic components and equipment are improved 3 to 5 years after their introduction to the market, due to technological development (pers. comm. CIRCONTROL, 2012). In fact, there are currently new designs for charging devices that are replacing older devices. Under this premise, we assume that the charging devices are replaced after 4 years of use by E2Ws. After the fourth year, a new charging device is installed, and the corresponding additional environmental burden of the new equipment should be taken into consideration.

7.2.5. Environmental burden of low-voltage electricity supply

The environmental burden of the electricity supply to E2Ws depends on the electricity mix. The Spanish (ES) electricity mix for 2011 (REE, 2011) and the projected ES electricity mix for 2020 (Sáenz de Miera, 2011) are used to determine the effect of upgrading the electricity mix with renewable energy sources. The ES electricity mix for 2020 is adjusted to the achievement of environmental national targets needed to fulfill the 20-20-20 European targets (European Commission, 2010a). To achieve this goal, the Spanish Plan for Renewable Energy 2011–2020 (IDEA, 2011) requires a 41% share of renewable energy sources in gross electricity generation. The electricity production for 2020 would therefore be 23% less carbon intensive and 11% less energy intensive than the electricity production for 2011. A description of the electricity mixes and the corresponding global warming potential (GWP) and primary energy demand (PED) indicators per kWh of low-voltage electricity consumption is provided in section B.3 in appendix III. The GWP and PED reference values are presented in Figures 7.5 and 7.6.

7.2.6. Environmental impact assessment method

The GWP, expressed as greenhouse gas (GHG) emissions measured in tons of carbon dioxide equivalent (kg CO_2-eq [100 years]), and the PED, expressed in equivalent gigajoules (MJ-eq from renewable and non-renewable resources [net cal. value]), indicators are used to characterize the environmental performance of the product systems. The environmental indicators are quantified by applying the CML baseline 2001 method (Guinée et al., 2001). The software GaBi (PE International, 2010) and the ecoinvent v2.2 database (SCLCI, 2010) are used as supporting analytical tools. The life cycle inventory (LCI) data related to the ORP2 and ORS6 facilities is presented in section C in appendix III.

7.3.Results

7.3.1.Life-cycle environmental performance of E2W charging facilities

Table 7.1 shows the life-cycle GWP and PED of the ORP2 and ORS6 facilities. A service ratio of 12 h of electricity supply (50% daytime hours) under normal conditions for 10 years is assumed. The GWP and PED values associated with the operation of charging facilities relate to low-voltage electricity consumption, considering the electricity mix for 2011.

The results show that the public charging network for E2Ws may contribute to a significant environmental burden on the built environment. Nevertheless, the environmental impact of the E2W charging network can be significantly reduced if environmental criteria are applied during planning and design. The ORS6 facility contributes half as much to GWP and consumes half as much primary energy as the ORP2 facility. The ORS6 facility makes better use of public space, has lower construction requirements (materials and construction efforts), optimizes the management of the electronic equipment per available outlet, consumes less energy in operation and requires less maintenance over time.

An examination of the environmental impact by life-cycle stages shows that the charging equipment makes the highest contribution to the overall environmental impact of the charging facilities. The operation stage makes the second highest contribution. Despite the considerable amounts of construction materials required to install the charging equipment (see section C in appendix III), the relative contribution of the construction phase to the GWP and PED is only approximately 10% of the total environmental impact of the charging facilities. Fig. 7.4 shows the environmental impact of the charging equipments disaggregated by the different constitutive elements to determine the major contributors to GWP and PED.

Table 7.1 Life-cycle GWP and PED of charging facilities.

Charging facility	Impact	Charging Equipment	Construction	Transportation	Installation	Operation	Maintenance	Removal	TOTAL
ORP2	GWP (kg CO_2 eq.)	3,688	907	213	216	812	486	20	**6,342**
	PED (MJ eq.)	64,729	13,572	3,393	3,093	19,373	8,260	131	**112,552**
ORS6	GWP (kg CO_2 eq.)	1,631	328	74	72	701	234	8	**3,047**
	PED (MJ eq.)	28,730	4,657	1.188	1,032	16,727	3,965	50	**56,349**

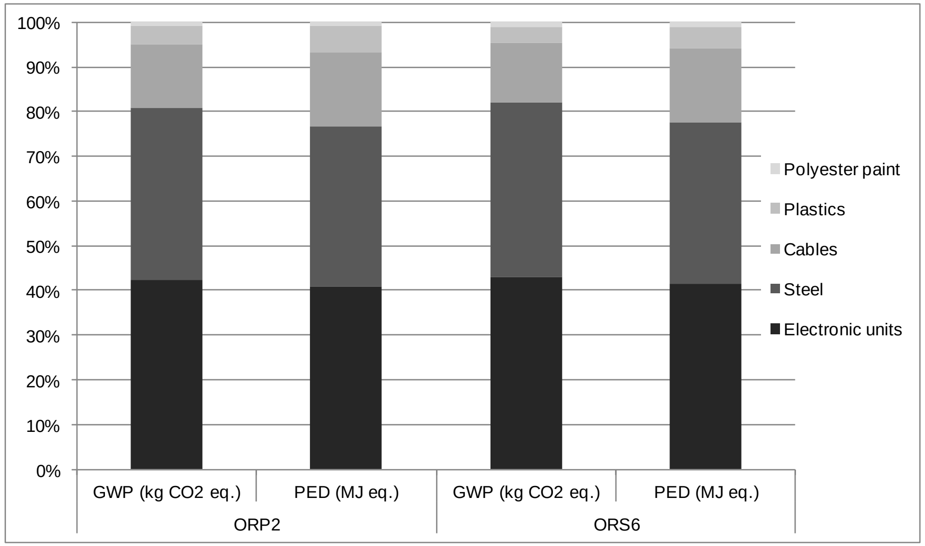

Fig. 7.4 Relative contributions to GWP and PED by the constitutive elements of the charging equipments assessed.

The electronic components and steel are the major contributors to the environmental impact of both the ORP2 and ORS6 charging equipments, accounting for 42% and 37%, respectively, of the GWP and PED. The electronic units alone contribute approximately 30% of the total GWP and PED over the life cycle of charging facilities, and the steel contributes approximately 21%. Although cables (Fig. 7.4) and construction materials (Table 7.1) do not contribute substantially to the overall environmental impact of the charging facilities, their environmental burden is not negligible, and they offer a way to easily improve the environmental performance of the product systems. If the construction requirements for installing the charging equipments are reduced, the amounts of cables and construction materials and the related transportation requirements will be reduced proportionally.

In view of the study's results, two main strategies could be promoted to minimize the environmental impact of public urban charging network for E2Ws. One strategy consists of promoting the application of eco-design principles. Important environmental gains could be achieve if the design of the charging facilities were optimized by reducing the amounts of materials used per available socket and/or by using more environmentally friendly materials, such as recycled elements or primary materials with improved environmental profiles. The second strategy consists of properly planning and managing the public charging network to ensure that charging facilities are actively used to charge E2Ws, making the contribution of these facilities to the environmental impact of the built environment more acceptable, as discussed in the following section.

7.3.2. Environmental significance of charging facilities for the use phase of E2Ws

Depending on the type and design of the E2W public charging network, an absolute environmental burden will be imposed by the built environment of cities. This environmental burden will have greater or reduced significance to the environmental performance of the use phase of EVs according to the system´s lifetime energy output. The relative environmental significance of the charging facilities per kWh supplied to E2Ws is presented in this section. The ORP2 design is chosen as reference, given that the usage assumptions are identical for both charging facilities. The ORS6 facility is considered to have approximately half of the environmental impact of the ORP2 design. Table 7.2 shows the relationship between the life-cycle environmental impact of the charging facility and the cumulative electricity consumption by E2Ws for different service ratios under normal conditions.

Table 7.2 Relationship between the life-cycle GWP and PED of the charging facility and the electricity consumption by E2Ws (use phase) for different service ratios and upgrading of the electricity mix over 10 years.

GWP	**Service ratio**	**10%**	**20%**	**30%**	**40%**	**50%**
Electricity for 2011	ORP2 (tn CO_2-eq.)	5.7	5.8	5.9	6.2	6.3
	E2Ws (tn CO_2-eq.)	82.1	164.2	246.3	328.4	410.5
Electricity for 2020	ORP2 (tn CO_2-eq.)	5.6	5.7	5.7	6.1	6.2
	E2Ws (tn CO_2-eq.)	63.1	126.2	189.3	252.4	315.5
PED	**Service ratio**	**10%**	**20%**	**30%**	**40%**	**50%**
Electricity for 2011	ORP2 (GJ-eq.)	98.8	101.1	103.3	110.3	112.6
	E2Ws (GJ-eq.)	1,957.8	3,915.7	5,873.5	7,831.4	9,789.2
Electricity for 2020	ORP2 (GJ-eq.)	97.6	99.7	101.7	108.3	110.4
	E2Ws (GJ-eq.)	1,737.9	3,475.8	5,213.7	6,951.6	8,689.5

The total life-cycle GWP and PED contributions of the charging facility increase slightly from one scenario to the next, depending on the corresponding increases in the energy and maintenance requirements (see section B.2 in appendix III). As the total electricity supply to E2Ws increases linearly by 194,472 kWh, there is a corresponding linear increase of 82 tn CO_2-eq and 1,958 GJ-eq, if the environmental impact correspond to the electricity grid mix for 2011. The cleaner electricity grid mix projected for 2020 corresponds to linear increases of 63 tn CO_2-eq and 1,738 GJ-eq for GWP and PED, respectively. However, the total life-cycle environmental impact of the charging facility is greatly exceeded by the environmental impact of the cumulative electricity consumption by E2Ws, after a few months of operation of the system. The higher the electricity demand by E2Ws is over time, the lower the relative environmental impact of the charging system becomes.

According to the results presented in Table 7.2, the relative environmental significance of the charging facility for the use phase of E2Ws can be considered negligible. One cut-off criterion established by ISO 14040 (2006) is a criterion for environmental significance that expresses the fact that elements contributing less than a certain percentage to the total environmental impact of a system of interest can be excluded during the process of inventory analysis and impact assessment. A maximum of 5% of the total environmental impact of the system of interest usually established for this percentage to ensure that the representativeness of the environmental outcomes is not compromised (European Commission, 2010d). The 5% cut-off rule is used as a reference to indicate the conditions under which the relative contribution of the charging facility to the environmental impact of the use phase of E2Ws can be considered negligible. Fig. 7.5 and Fig. 7.6 show the variation in the GWP and PED per kWh supplied to E2Ws as determined by internalizing the relative environmental impact of the charging facility (ORP2) for the different service ratios. The effect of a delay (DU) in starting to use the charging facility and the effect of quick replacement (QR) of the charging device before it reaches the end of its lifetime (sensitivity analysis) are included in the figures, along with data on the use of the charging facility under normal conditions (NC).

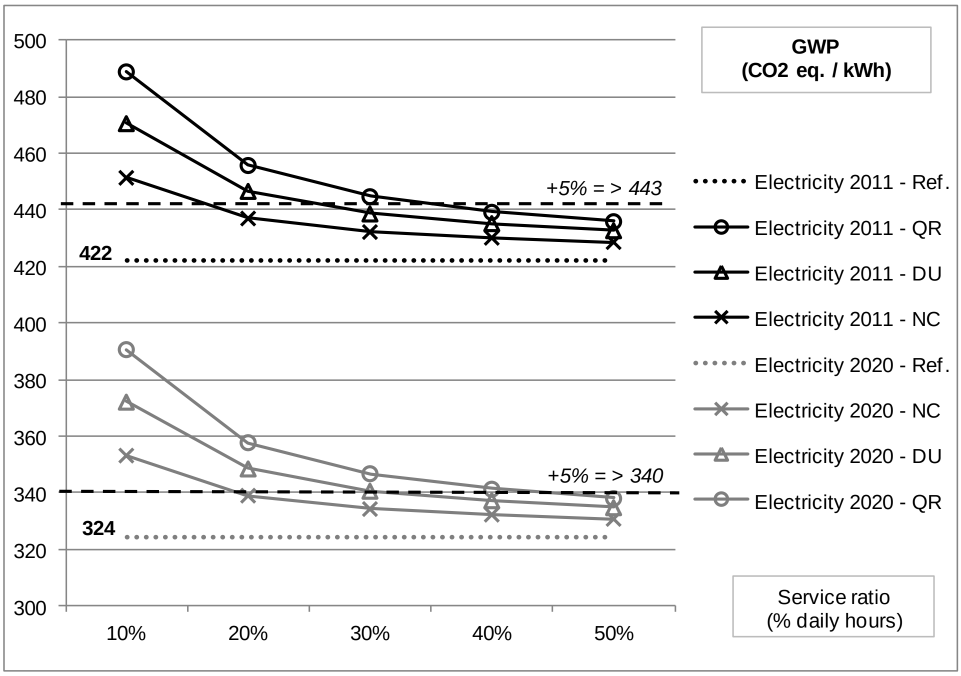

Fig. 7.5 GWP per kWh consumed by E2Ws by internalizing the relative environmental impact of the charging facility (ORP2) for the different scenarios considered.

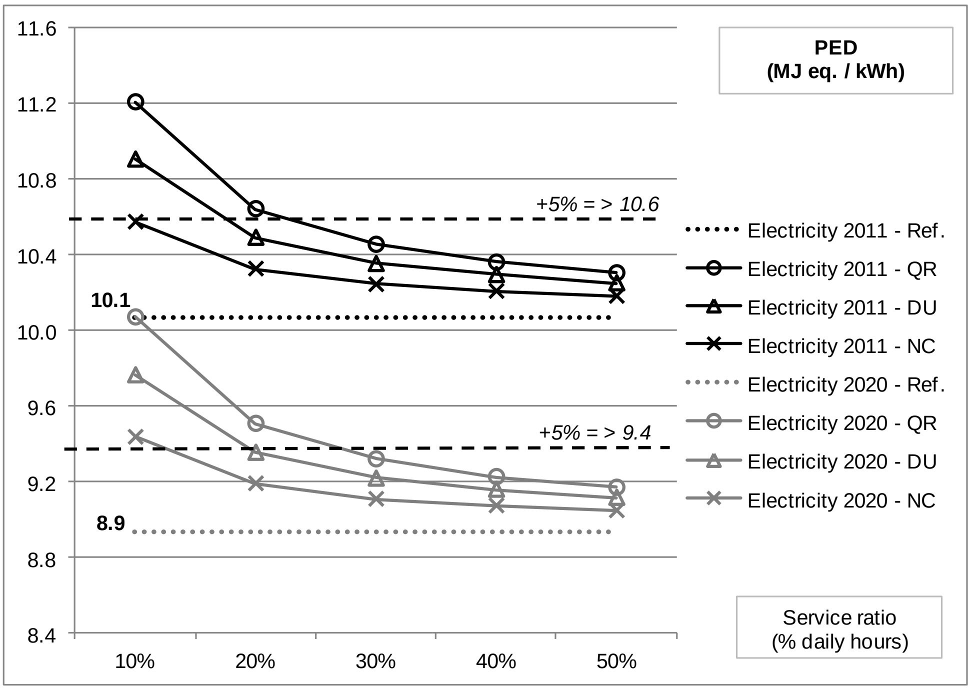

Fig. 7.6 PED per kWh consumed by E2Ws by internalizing the relative environmental impact of the charging facility (ORP2) for the different scenarios considered.

The reference GWP and PED values associated with the electricity produced with the ES 2011 and 2020 electricity mixes (see section B.3 from appendix III) are indicated in the figures to reflect the variability on the environmental impact. The red dotted lines indicate the GWP and PED values that represent over 5% increase in the environmental impact per kWh supplied to E2Ws.

The environmental outcomes related to the scenarios involving lower and higher service ratios of the charging facility by E2Ws show the maximum range of variation in its relative environmental significance. With respect to the effects on the environmental impact of electricity produced with the ES 2011 electricity mix, when the charging facility is used by E2Ws during 10% of daytime hours, the GWP per kWh supplied increases by 7% (+29 g CO_2-eq.), 11% (+48 g CO_2-eq.), and 16% (+67 g CO_2-eq) for the NC, DU, and QR use conditions, respectively. In terms of PED, the internalization of the relative embodied energy from the charging facility per kWh results in increases of 5% (NC), 8% (DU), and 11% (QR), corresponding to 0.5 MJ-eq, 0.8 MJ-eq, and 1.1 MJ-eq of additional embodied energy, respectively. When the charging facility is used during 50% of daytime hours, the increases in the GWP per kWh are only 1.5% (NC), 2.5% (DU) and 3.3% (QR), which correspond to 7 g, 11 g, and 14 g of additional CO_2-eq emissions. In terms of PED, the impact per kWh consumed by E2Ws increases by 0.12 MJ (+ 1.1%), 0.19 MJ (+ 1.8%), and 0.24 MJ-eq (+ 2.4%), respectively.

Considering the effects on the environmental impact of electricity produced with the ES 2020 electricity mix, the internalization of the relative environmental burden from the charging facility results in larger increases of GWP and PED per kWh consumed by E2Ws. In the scenario involving electricity supply to E2Ws during 10% of daytime hours, the GWP per kWh increases by 9% (NC), 15% (DU), and 20% (QR). The PED increases by 6%, 9% and 13%, respectively, for the same use conditions. In the scenario involving electricity supply to E2Ws during 50% of daytime hours, the increases in the GWP per kWh are 2.0%, 3.2% and 4.2%, respectively, whereas the increases in the PED are 1.3%, 2.0% and 2.6%, respectively. Translating these percentages into CO_2-eq and MJ-eq yields values similar to those indicated above.

If the 5% cut-off criterion is applied, the charging facility should be used by E2Ws at intensities of more than 30% of daytime hours (over 7 h of electricity consumption per day per available socket) to make the relative environmental significance of the charging system negligible for the use phase of E2Ws. In terms of PED, use intensities greater than 20% of daytime hours (greater than 5 h of electricity consumption by E2Ws per day per available socket) make the relative input of the charging facility no significant.

7.4.Discussion

The environmental performance of a particular case scenario related to the design and use of E2W public charging facilities has been analyzed. The results provided therefore do not aim to reflect the potential environmental significance of the global E2W (and EV) charging network. Nevertheless, findings are intended at providing criteria for further research in life cycle management of electric mobility systems. This section is focused on providing considerations related to a series of factors that can influence on the absolute and relative environmental significance the E2W and the entire EV public charging networks at the macro scale.

Environmental performance of EV urban charging infrastructure

The same type of EV (i.e. a particular E2W) operating in a concrete urban context and consuming a specific electricity grid mix, can contribute to different CO_2 emissions per kWh consumed, hence km travelled, depending on the design and service ratio of the charging alternative or the mix of charging alternatives (public charging network) chosen for daily charging of the batteries.

The results from this case study have demonstrated that if an ORP2 facility is used by only one e-scooter during 2h per day (partial battery recharging), the GWP per kWh (ES electricity grid mix 2011 - 2020) consumed by the e-scooter would be 5-7% (NC) to 12-16% (QR) higher than the GWP per kWh consumed by the same vehicle if the ORP2 facility was used during 12h per day (3 fully charged e-scooters). Instead, every kWh consumed by the e-scooter using the ORS6 facility, would account for only 2-3% (NC) to 6-8% (QR) higher GWP under equivalent circumstances. The use of other E2W charging alternatives or mix of charging facilities may have a greater or reduced relative environmental significance to the environmental performance of the operation stage of E2Ws. It will depend on the type (mode of battery charging), design (electronic and construction works requirements) and average lifetime energy output (electricity supply) of each charging alternative used. The relative life-cycle environmental significance of the entire urban EVCI to the use phase of EVs will be inversely proportional to the average lifetime energy supplied by the system.

Present reality shows that the publicly-accessibly EVCI currently implemented in cities is poorly used due to the variable number and diversity of charging alternatives and the still reduced on-road EV fleet (IEA, 2013). In the city of Barcelona (Spain), the cumulative electricity supplied up to date per every slow charging point implemented in the public urban space amounts to an average of only 3-4 kWh (pers. comm. City Council of Barcelona, 2013). Under this consideration, every kWh supplied by the ORP2 facility would account today for about 250 kg of CO_2 eq. According to ERTRACT (2012), the present of fast charging facilities implemented in the public space of some cities contribute to increment the use (km travelled) of EVs because it actively contributes to alleviate "range anxiety". Nevertheless, fast charging points are not used in the same proportion than EVs. Meanwhile, the IEA (2013) states that early attempts to cover cities with a widespread deployment of EVCI in anticipation of large-scale EV uptake resulted in some instances of EVCI experiencing little or no customer utilisation, whereas in other instances it did not lead to the expected jumpstart of EV sales. The design of EVCI, the scale of implementation and their urban location requires therefore a smarter approach to avoid over-investment that may result in unused assets. Instead of maximising the implementation of EVCI, it is better to optimise public infrastructure design, provision and management in relevant locations of the urban environment. This practice is particularly relevant given that underused assets could provide an important environmental burden to the electric mobility system.

Standardization of the charging infrastructure for EVs

Unlike the supporting infrastructure required for refueling conventional ICVs (petrol stations), the charging infrastructure necessary for operating EVs is not standardized. A petrol station can be used by any type of ICV. Options for recharging EVs´ batteries are numerous and diverse (Fig. 7.1). Slow and fast charging are the most common EV charging alternatives implemented in urban spaces worldwide. However, only a few types of EVs with adapted battery packs are able to take fast charging. Complementary charging alternatives include battery swapping stations, inductive and contact charging, and decentralized solar and wind-powered charging systems. Nevertheless, battery swapping, inductive and contact charging systems require a way to ensure full EV technology compatibility.

The future standardization of urban charging network and infrastructure is crucial to the widespread adoption of EVs (Eurelectric, 2009; ACEA, 2011). The EVCI has to assure that all type of EVs can be charged at any type of charging facility or that one single charging alternative can supply electricity efficiently to the entire urban EV fleet. Thus, EV drivers should be sure they can drive between different cities and countries without encountering incompatible EV charging networks. EVCI standardization will depend on proper planning parallel to the joint technological evolution in both charging equipments (power supply speed) and EVs´ design (battery pack size) and performance (driving range) (Nemry et al., 2010; Morrow et al., 2008). The estimated use of the EVs will finally determine the kind of charging alternatives and infrastructure more appropriate to optimize the system´s performance (ERTRAC, 2012).

Today, countries are approaching EVCI deployment in very different ways. For instance, Japan efforts on EVCI deployment concentrates on the provision of fast charging facilities, which is the highest amount for any country worldwide. In the US, the emphasis concentrates on slow charging due to more reliance on home parking. Finally, in the Netherlands a mix of slow and fast chargers is being deployed, resulting in the most EVCI per capita worldwide (IEA, 2013). Thus, there is no one unique correct path to approach EVCI design and deployment, rather different EVCI networks based on local needs (IEA, 2013).

Planning for EV charging network should include therefore the specificities of the urban design of cities- which influence travel patterns and determine the availability of mobility logistics- and the delivery capacity of and access to the available urban power grid, according to the type and volume of the (expected) on-road EV fleet in cities (ERTRACT and EPoSS, 2009; Eurelectric, 2010; Eurelectric, 2011).

Accounting the environmental significance of EVCI in the EV environmental labeling

Presently, fuel economy labels of vehicles report only energy consumption and the tailpipe emissions per km travelled (GFEI, 2014). For EVs, the GHG emissions from electricity consumption are reflected as zero. According to MacPherson et al. (2012), using only the fuel economy metric to convey the relative GHG intensity of a vehicle is insufficient for EVs. The authors suggest that the fuel economy labels should emphasize that a significant (life-cycle based) GHG emissions reporting for EVs are not captured and provide ranges for GHG emissions from EV charging in local and regional electricity grids in order to better report customers about the emissions profile of EVs. This recommendation for EV environmental labelling could be complemented with the integration of a range of additional charging infrastructure-related environmental burden according to the environmental performance of the urban charging network where EVs are used. The electricity grid mix and the configuration of the EV urban charging networks are both geographically-dependent. In this way, manufactures can clearly inform costumers about the local and regional urban scenarios and usage considerations that provide the best and the worst environmental performance of EV models compared to equivalent ICVs. This consideration may be especially relevant during the period of global standardization of the EVCI, where many different possibilities and usage scenarios exist. Cities and regions with a well-planned, designed and life-cycle managed charging infrastructure for EVs would contribute to minimize the relative environmental significance of charging infrastructures to the environmental performance of EVs´ operation. Based on the findings provided by our case scenario, the GWP and PED per kWh consumed by E2Ws can increase from 1% to 20% and from 1% to 13%, respectively, depending on the urban context, charging facility and usage conditions considered for daily charging of E2Ws.

EV urban ecosystem

EV ecosystem is a concept that defines the total infrastructure system required to support the mass operation of EVs in cities (Electrification Coalition, 2009; Ernst and Young, 2011; Urban Foresight Limited, 2013). It encompasses "hard infrastructure" such as recharging technologies, energy grids, buildings, and transport logistics, along with "soft infrastructure" such as regulation, information and communication technologies, commercial services, and community engagement programs. The key challenge consist on shaping a global vision of the entire urban infrastructure, innovative products and business models required to support mass adoption of EVs in the context of smart cities (IEA, 2013).

The EVCI is one key element of a complex mix of technology and infrastructure requirements to support electric mobility. The intelligent integration of the EVCI into the urban environment is essential for a sustainable transition towards mass electric mobility. A well-designed EV urban charging system could only need a few multi-point charging stations (i.e. ORS6) instead of blanketing a wide area with poorly used charging facilities (i.e. ORP2). Also, in some cities there could be no need to create a large dedicated EVCI but reinforce the existing electricity network to ensure security of supply (ERTRAC, 2012). In this sense, many urban synergies could be found in cities to charging EVs by means of the adaptation of the already available urban furniture, such as public telephone booths that are no longer in use or demand, electrical equipment for municipal lighting with considerable slack in power delivery or block heaters (this latter in Nordic European Countries). For instance, existing light fixtures and power poles could eliminate the need to trench through concrete or pavement and reducing the amount of renovation required to extend electrical conduits.

The early application of eco-design principles is essential to minimize environmental impacts of EV public charging networks. As a best practice, the implementation of multipoint EV urban charging networks with integrated renewable energy production systems (i.e. solar roof) adapted to charging different types of EVs (i.e. e-bikes, e-scooters and e-cars) using the same emplacement can provide important environmental benefits to the built environment of cities that could translate into important reductions on the contribution to the relative environmental impact to the use phase of EVs.

7.5.Conclusions

The environmental characterization of two conventional slow-charging facilities for E2Ws was conducted with the goals of identifying the more environmentally suitable solution and providing criteria for environmental improvement. The results showed that the public urban charging network for E2Ws in the Barcelona may contribute to a relevant environmental burden if no life-cycle environmental criteria are applied during planning, design and management phases. In this process, a comprehensive modeling on the service ratio (lifetime energy output) of charging facilities is critical. And this consideration may be extrapolated to the global urban charging network for EVs.

The electrification of the global vehicle fleet is a long-term ambition. The deployment of EVs in cities will require a continue provision of the supporting infrastructure and systems, and their integration in the full mobility system in a wide scale. Thus, it may take several decades until EV charging networks are globally standardized and optimally used according to the performance of the urban EV fleet on-road. Different designs and service ratios of EV urban charging networks may have different environmental significance for the use phase of EVs. It is essential therefore to start promoting the characterization of the life-cycle environmental performance of different charging alternatives and the local, regional and provincial configurations of EV charging networks in order to better understand the potential environmental significance of the EVCI at the macro scale. This type of environmental information would be useful to identify the most environmentally suitable urban EVCIs to promote a smart planning, design and management of electric mobility systems in a given local or regional area, especially during the period of transition towards a widespread adoption of electric mobility. In this process, the identification of urban synergies with the application of ecodesign principles based on the notion of promoting the development of sustainable urban EV ecosystems can provide significant long-term environmental savings to the urban environment. As starting point, the specifications and guidelines provided by regional governments and local authorities for the implementation of charging facilities in public and private urban locations should encourage the integration of environmental criteria among technical and socio-economical aspects.

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Supplementary Material (Appendix III)

Further data and descriptions related to the case study are available in the in the appendix III (electronic supplementary material related to the article under review in an international scientific journal).

Part V. Ecodesign of urban furniture

Chapter VIII. Eco-innovation of urban furniture for supporting smart (pedestrian and e-bike) mobility in cities.

8- Chapter 8. Eco-innovation of urban furniture for supporting smart (pedestrian and e-bike) mobility in cities.

This chapter is based in the following manuscript that will be submitted shortly to a peer-review international scientific journal:

Mendoza, J.M., Sanyé-Mengual, E., Angrill, S., García-Lozano, R., Feijoo, G., Josa, A., Gabarrell, X., Rieradevall, J., 2014. Eco-innovation of urban furniture for supporting smart (pedestrian and e-bike) mobility in cities.

Abstract

The provision of adecuate planned, designed and managed urban infrastructures are essential to support cleaner modes of mobility within cities. However, these infrastructures can contribute an important environmental burden to the urban space of cities. The application of life cycle environmental criteria is crucial to minimize long-term environmental burdens imposed to the urban public space.

This section shows the environmental outcomes from the application of an ecodesign approach in the re-conceptualization of a conventional pergola (CP) towards an eco-product. The resulted eco-product consists of a solar pergola (SP). The SP generates surplus photovoltaic electricity (spE) that provides a multifunctional character to the product system. According to the end-use of the spE produced, passive (spE is poured into the electricity grid) and active (spE is used as green energy input for clean e-bike charging) contributions to sustainability are distinguished. Findings are encouraged to denote the importance of promoting a smart approach in sustainability-based decision-making.

LCA is applied to characterize the environmental performance of the pergolas designs in terms of global warming potential (GWP – kg of CO_2 eq.) and primary energy demand (PED – MJ eq.). A total of nine scenarios related to the variability of hours of solar radiation and carbon content of the electricity mix are considered for calculations.

The implementation of the SP design in substitution of the CP design can contribute to save from 2,080 kg to over 47,185 kg of CO_2 eq. and from 350,390 MJ to over 692,760 MJ eq. in a timeframe of 10 years, depending on the case scenario considered. These savings would be equivalent to fully charging 2 to 9 e-bikes by day using clean energy inputs (SP_e-bike concept). An integral public service based on the provision of comfort for

pedestrian mobility and green energy for e-bike mobility can be supplied completely free of environmental burden.

Keywords. Ecodesign, Pergola, Pedestrian mobility, Electric bikes.

8.1.Introduction

Mobility of people and goods requires energy, regardless of the transport mode. However, the energy consumption between transport modes varies substantially. As the consumption of fossil energy affects the environment, it is an aim of sustainable development to fulfil the demand for mobility with clean low energy consuming transportation systems (EUROSTAT, 2011).

In Europe, half of all road transportation fuel is combusted in cities (European Commission, 2007a), where traffic is responsible for at least 40% of GHG emissions and more than two-thirds of local noxious emissions arising from this mode of transport (European Commission, 2007b). The Europe 2020 Strategy for smart, inclusive, and sustainable growth (European Commission, 2010a) stresses the importance to address the urban dimension of mobility in order to encourage a modernised and sustainable transport system.

Consistent with this vision, the European White Paper (European Commission, 2011a) highlights the need to make cities and their transport systems more as greener and smarter in order to achieve an essentially carbon-free multimodal mobility logistics. In this sense, the European Union (EU) call for rethinking urban mobility by undertaking the necessary action to facilitate walking and cycling, improve the quality and efficiency of collective transport services and promoting the substitution of conventionally-fuelled cars by the use of greener vehicles. In this latter case, the electrification of the urban vehicle fleet is given first priority in cities worldwideas a promising strategy to significantly reduce oil consumption and carbon emissions by motorized road mobility (IEA, 2011; ERTRAC, EPoSS and SMARTGRIDS, 2012; IEA, 2012; IEA, 2013).

Infrastructure shapes mobility thus no major changes in transport sustainability will be achieve without the provision of an adequate network of supporting urban infrastructure and an intelligent use of it (European Commission, 2011a). Supporting infrastructures for urban mobility include from the basic network of pavements that form the shell or framework in which everything else is embedded and must operate (Kenworthy, 2006) to a set of diversified and extensive urban (street) furniture. Each of these elements contributes to the absolute environmental burden of the built environment of cities and provides a relative environmental burden to each mode of urban mobility (Chester et al., 2010; Dave, 2010). In order to effectively mitigate environmental impacts from transportation, decisions should not be made based on partial considerations acting as indicators for whole system performance. Life-cycle environmental performance of urban infrastructures and elements required to support mobility should be considered (Chester and Horvath, 2009). In this way, the global environmental footprint of different transport modes can be comprehensibly quantified, whereas complementary hot-spots and valuable opportunities to reduce environmental impacts can be identified. Some authors have started to highlight the relevance of incorporating environmental criteria in the planning, design and management of supporting infrastructure for sustainable mobility to reduce its contribution to the environmental burden of the built environment, therefore increasing the environmental value of greening urban transportation (Mendoza et al., 2012b; Oliver-Solà et al., 2011).

Today there is a growing need to make mobility infrastructures more resilient, including to climate change, to keep pace with the growing mobility needs but in a resource efficient and smart manner. This requires the application of a range of innovative solutions, including the promotion of low-carbon and energy-harvesting infrastructure designs (European Commission, 2013f). In this process, ecodesign takes a central role. Ecodesign involves the consideration of the environmental implications of a product system during the early stage of conceptualization (Harper and Graedel, 2004). In this way, comprehensive environmental criteria is placed at the same level and given the same weighting and status as the more traditional technical, social and economical aspects considered right in the early stage of product design (such as functionality, safety, ergonomics, endurance, image, quality, aesthetics and costs). The early incorporation of environmental criteria is the best strategy for environmental impact prevention because over 80% of total environmental burdens of products are directly conditioned by their design stage (Kurk and Eagan, 2008; European Commission, 2012).

The application of ecocesign principles in the planning, deployment and management of infrastructures required to support sustainable mobility can represent a key element for the development of future smart cities (European Commission, 2013a). Ecodesign is applied in this article to re-conceptualize an urban pergola. Pergolas are a kind of urban furniture implemented in the public space of cities to provide comfort for pedestrian mobility by means of nocturnal lighting and diurnal shadow. This urban furniture has also additional functions, such as shelter from the rain, snow and wind. In this way, pergolas are implemented in dedicated urban hot-spots of cities where they represent a component of urban sustainable mobility networks. This applies an ecodesign methodological framework to re-conceptualize the design of a conventional pergola (CP) towards an eco-product. The eco-product consists of a solar pergola (SP). As a result of the eco-product design, the SP generates surplus photovoltaic electricity (spE) that provides a multifunctional character to the product system. According to the end-use of the amount of spE produced, passive (spE is considered to be poured into the electricity grid) and active (spE is considered to be used as energy input for e-bike charging) contributions to sustainability are distinguished to denote the importance of promoting a smart approach in sustainability-based decision-making. Being aware that the net environmental balance of SP design is geographical-dependent, a total of nine scenarios related to the variability on the hours of solar radiation and carbon intensity of the electricity grid mix are used for sensitivity analysis.

8.2. Materials and methods.

The Fig. 8.1 shows the ecodesign methodological framework applied to re-conceptualize the design of the CP towards an eco-product (SP). The ecodesign procedure is based on the approaches proposed by González-García et al. (2012a, 2012b) for the eco-innovation of urban furniture and Sanyé-Mengual et al. (2014) for the development of eco-products.

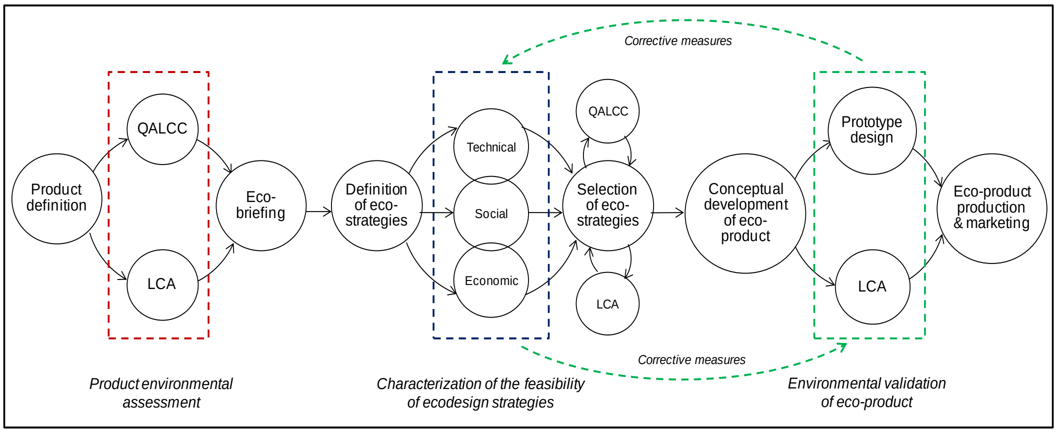


Fig. 8.1 Ecodesign methodological framework. Acronyms: QALCC - Qualitative Assessment of Life Cycle Criteria; LCA - Life Cycle Assessment.

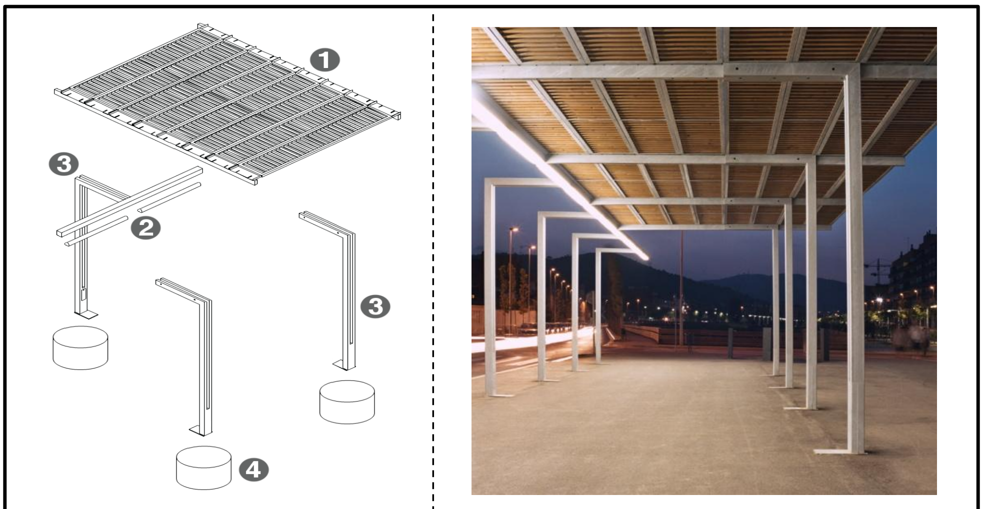
The ecodesign framework is divided into a series of successive iterative steps. Product definition is a basic stage to approach the goals of the ecodesign thinking process. A multidisciplinary team should be created in order to cover all the fields of knowledge implied in ecodesign. The multidisciplinary team should include industrial designers and engineers, environmental scientists, marketing managers, and other relevant agents involved in the product´s supply, production and delivery chain. This team will be responsible of taking thoughtful choices for the design and development of an environmentally-friendly product. Once the team is created, the attributes of the conventional product to be eco-designed should be clearly defined and its life-cycle characterized by means of the application of qualitative and quantitative environmental tools. While the Qualitative Assessment of Life Cycle Criteria (QALCC) (CPRAC, 2012) highlights the global perceptions of the multidisciplinary team regarding the incorporation of environmental criteria in product design, the Life Cycle Assessment (LCA) (ISO 14044, 2006) provides a comprehensive evaluation of the product´s contribution to environmental impacts. The results obtained though QALCC and LCA are the bases to build an eco-briefing (Smith and Wyatt, 2006) that shows, through a valuation matrix of product´s environmental performance, the most environmentally relevant hotspots for product´s environmental improvement. As a result from the eco-briefing, a series of eco-design strategies are proposed and a feasibility assessment is performed in order to detect their technical, economic and social constrains. In this process, those feasible ecodesign strategies are classified according to their priority of implementation. These ecodesign strategies are subsequently characterized by means of a new round of QALCC and LCA. According to the results obtained, the most suitable solutions for achieving significant improvement in the product´s life-cycle environmental performance are chosen for the conceptual development of the eco-product. This process must insure that the marketed eco-product will excel in environmental performance and all other aspects that lead to customer satisfaction and product profitability (Rose, 2000). In this way, previous to the eco-product production and marketing, two interactive steps are addressed. First, a prototype of the design of eco-product is developed for testing purposes. Second, the life-cycle environmental performance of the eco-product´s prototype is validated through LCA. In this later stage, ecodesign problems may be found but re-design solutions can be proposed in order to avoid or minimizing costly and time consuming industrial and marketing interventions.

Further descriptions of the ecodesign methodological framework with the corresponding results generated in each step can be found in the Appendix IV (sections A.1-A.5). Following, the basic information for understanding the case scenarios and the environmental results are presented.

8.2.1. Description of the conventional and the eco-designed product systems

A Spanish company, located in Barcelona (Catalonia), has participated in the research. The company is one of the most important Spanish producers of urban furniture. Thus the product system analyzed is a very representative model of CP widely implemented in urban public spaces throughout the geography of Spain. The cities of Barcelona, Bilbao, Madrid and Murcia represent the largest market volumes for the company.

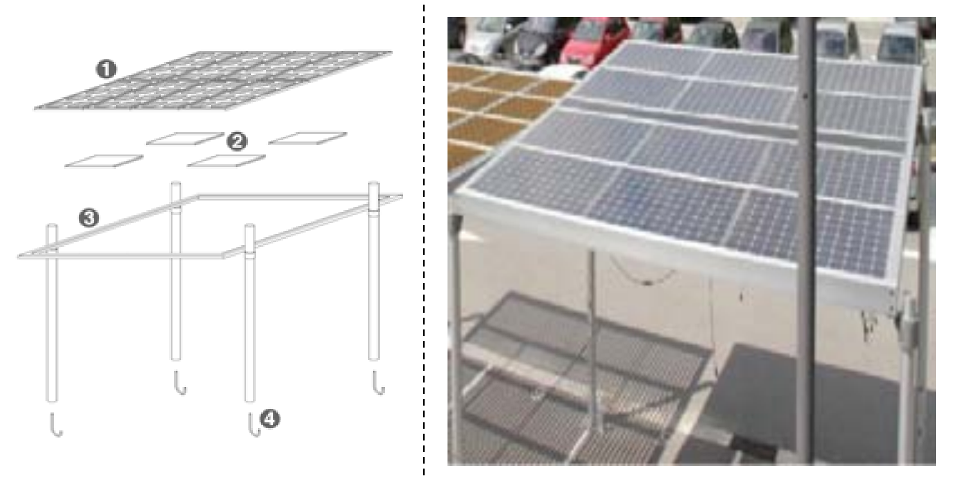
The CP consists of a simple design based on the repetition of a basic module with an 18 m^2 cover made up of eight wooden (red pine) slatted that is supported by a fluorescent lamp-post and two steel columns. The Fig. 8.2 shows an exploded illustration and briefly description of the main components of the CP design.



1- Wooden cover (176 kg); 2- Lighting equipment (fluorecent 2x 58 W and luminary 2x 65W); 3- Steel structure (352 kg); 4- Concrete foundation (2,990 kg)

Fig. 8.2 Exploded illustration and briefly description of the CP product system.

The resulted eco-designed product (SP), consists of a repetition of a 23 m^2 module with a cover made up of twelve high energy efficient (mc-Si) photovoltaic panels that supply energy to a LED lighting equipment. The equipment integrates mobility sensors that contribute to 50% reduction in energy consumption through light attenuation. The photovoltaic cover is supported by an extruded mixed aluminium frame and four columns. The Fig. 8.3 shows an exploded illustration and briefly description of the main components of the SP design.



1- Photovoltaic cover (12 panels – 305 W of nomical power per panel – 10 inclination);
2- Lighting equipment (LED 4x 41 W); 3- Aluminium structure (331 kg); 4- Steel anchors (4 units)

Fig. 8.3 Exploded illustration and basic description of the SP product system.

The ecodesign efforts related to the SP product system were focus on the product concept, material use and lifetime energy consumption in order to solve the most critical environmental aspects related to the CP design (see section 8.3.1). A detailed description of the technical aspects of CP and SP product systems can be found in appendix IV (section A.1 and A.3).

8.2.2. Life cycle environmental impact assessment

The functional unit (FU) used to characterize and compare the life-cycle environmental performance of the product systems has been defined as the prospect of supplying diurnal shadow (45,000 h) and nocturnal light (42,600 h) per module of pergola implemented in the public in the city of Barcelona (Spain) as a service of comfort for pedestrian mobility during a timeframe of 10 years.

According to the characteristics of the lighting equipment of each product system (Fig. 8.2 and Fig. 8.3), the energy consumption of the CP design would correspond to 10,480 kWh whereas it would account for 3,468 kWh for the SP design. Nevertheless, the photovoltaic electricity production of the SP design would account for 33,600 kWh (see section A.4 from appendix IV). Just 10% of this amount of energy would be required as input for nocturnal lighting. The surplus photovoltaic electricity (spE) generation by the SP design is significant (30,132 kWh). The environmental performance of the SP design would be highly dependent therefore on the management of its multifunctional character (section 8.2.3).

The life cycle inventory (LCI) data required to characterize the environmental performance of each product system has been collected and calculated by relying on information directly provided by the technical staff from the designer company involved in the research. All the relevant unit processes from cradle to end-of-lifetime have been considered. Appendix IV (sections A.2 and A.4) presents a diagram of the system boundaries related to the CP and SP designs and provides their complete LCI dataset.

Being aware of the socio-political relevance of promoting low-carbon energy-efficient urban mobility systems to achieve the environmental targets defined in the context of Europe 2020 (European Commission, 2010a), the global warming potential (GWP), measured in kg of CO_2 eq. emissions [100 years] according to the IPCC (2007) guidelines and the primary energy demand (PED) measure in MJ eq. from renewable and non-renewable resources [net cal. value] according to the Hischier et al. (2010) method, are used as reference to characterize the life-cycle environmental performance of the product systems. Nevertheless, a complete list of CML midpoint environmental indicators (Guinée et al., 2001) can be found in appendix IV (section A.2 and A.4). The software Simapro (PRé Consultants, 2013) and the ecoinvent v2.2 database (SCLCI, 2010) were used as supporting analytical tools.

8.2.3. Definition of scenarios for environmental comparison

Environmental comparisons between product systems shall be made on the basis of the same function(s), quantified by the same functional unit(s) in the form of their reference flows. In this way, product systems associated with the delivery of additional functions should be characterized in a way that makes its comparison equivalent with regard to a mono-functional product system. The differentiation between main functions/services and co-functions/co-services takes therefore a central position in LCA and DfE studies since it directly affects the reliability of the environmental results. The ISO 14044 (2006) specifies a hierarchy of different approaches to characterize the environmental performance of multifunctional product systems. When multifunctionality cannot be directly subdivided into mono-functional single operation unit processes to determine the environmental impact of each specific function separately, allocation (partitioning the environmental impacts between the main functions and co-functions) should be avoided by applying a system expansion approach. In practice there are two optional ways for applying system expansion in LCA (European commission, 2010d). The first option consists of subtracting from the multifunctional product system the environmental burden of the conventional function(s) that are superseded or replaced by the alternative co-function(s) provided. A second option consists of adding to the mono-functional product system the not-provided (missing) co-function(s) that the multifunctional product system provides in order to make both product systems comparable. Both system expansion alternatives are mathematically equivalent, while not necessarily in their meaning and interpretation.

In this case study, both system expansion approaches are applied (section 8.3.2 and section 8.3.3) to compare the environmental performance between CP and SP product systems. The system expansion approach applied in each case depends on the management of the spE generation by SP design. According to the end-use(r) promoted, passive and active contributions to sustainability are distinguished (Fig. 8.4). In this way, a complete overview of the potential for environmental improvement related to the SP product system is provided to contribute for a robust sustainability-based smart decision-making process.

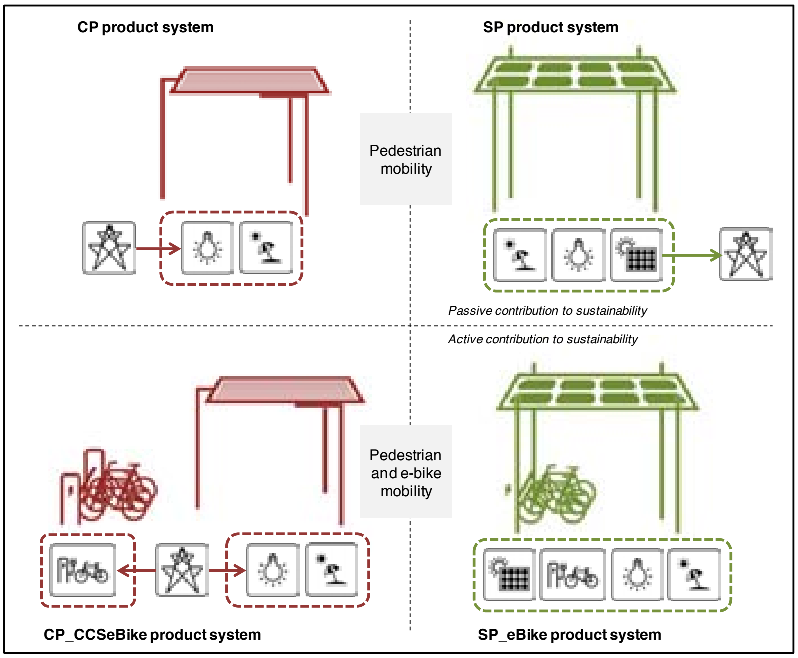


Fig. 8.4 Conceptual diagram of the functional equivalence of CP and SP designs according to the approaches of passive and active contribution to sustainability.

8.2.3.1. Passive contribution to sustainability

Passive contribution to sustainability is defined as the promotion of the implementation of the SP design with no encouragement of a defined end-use(r) of the spE. It is directly poured into the electricity grid with the assumption to substitute the production of an equivalent amount of conventional electricity grid mix. The environmental burden of the avoided amount of conventional electricity grid mix is subtracted from the total life-cycle environmental impact of the SP design.

8.2.3.2. Active contribution to sustainability

Active contribution to sustainability is defined as the promotion of the implementation of the SP design with encouragement of a specific end-use(r) of the spE generation. In this case, spE is considered to be used as energy input for supporting a public service of "clean" electric bike (e-bike) charging.

E-bikes are gaining in popularity in many countries worldwide as environmentally desirable vehicles for urban environments. In some countries, such as China (the biggest e-bike market of the world), e-bikes are even replacing fossil fuel-powered mopeds and small motorcycles (The New York Times, 2010). Pioneering Spanish cities in promoting sustainable mobility initiatives are also heavily encouraging the use of e-bikes (Fundación ECA - Bureau Veritas, 2012). The City Council of Barcelona, for instance, is currently running pilot tests for the electrification of a share of the "bicing" network (a public servive of bike sharing) to encourage multimodal sustainable urban mobility (Plataforma LIVE, 2013).

Nowadays, there are a variety of types of e-bikes available worldwide, from e-bikes that have a small motor to assist the rider's pedal-power (i.e. pedelecs) to more powerful e-bikes which tend closer to moped-style functionality (ETRA 2013). Table 8.1 presents the key technical aspects considered to calculate the number of conventional e-bikes that could be daily charged using as reference energy input the annual net amount of spE "free" of environmental burden produced by the SP design (see section 8.3.3).

Table 8.1 Basic technical data of conventional e-bikes used in environmental calculations.

Technical aspects of conventional e-bikes	Average values
Engine size	0.25 kWh – 0.35 kW
Battery capacity	24V – 36V / 9Ah –10Ah
Charging time	4h – 6h
Charging energy (full charging cycle)	0.9 kWh – 2.2 kWh

E-bikes can travel an average range of 30 – 40 km (on a single charge) at the speed of 25 to 45 km/h. The electricity consumption in operation accounts for 1 to 1.5 kWh/100km (Weinert et al., 2008). These vehicles offer therefore high performance to cover daily urban commuting at a minimum energy cost. The small size of the battery pack makes e-bikes very good candidates for receiving the benefits of charging via solar power input or other renewable energy resources. Thus, many companies are capitalizing "solar parking lots" in which e-bike riders can charge their e-bikes while parked under photovoltaic panels (i.e. Sanyo's solar lots, located in Tokyo's Setagaya ward, INHABITAT, 2010). One of the most controversial environmental aspects of electric vehicles, which consist of the carbon intensity of the electricity grid mix used for daily battery charging (Doucette and McCulloch, 2011), could be easily solved for e-bikes charged by taking advantage of the implementation of local photovoltaic production systems.

According to Fig. 8.4, the boundaries of the CP product system should be expanded in order to integrate a service of public e-bike charging using as reference the net spE generation from the SP design. The environmental burden of a functionally equivalent conventional charging station (CCS) for e-bikes (charging infrastructure plus electricity supply) is added to the life cycle environmental burden of the CP design. The LCI data and related environmental burden from the CCS was adapted from the results provided by Mendoza et al. (2014) who characterized the life-cycle environmental performance of conventional public charging facilities for electric two-wheelers. The description of the procedure applied to determine the functionally equivalent environmental burden of the CCS is presented in appendix IV (section A.5). However, values are integrated in Fig. 8.7. In this case scenario, the CP product system is re-named as CP_CCSeBike, whereas the SP product system is redefined as SP_eBike.

8.2.3.3. Sensitivity analysis

A total of nine scenarios resulted from the combination of a variability on photovoltaic electricity production and carbon intensity of the electricity grid mix are considered to provide a comprehensive overview of the potential environmental performance of product systems.

The Spanish (ES) electricity grid mix defined according to Red Eléctrica Española (REE, 2011) and the photovoltaic electricity generation by the SP design considering its emplacement in the city of Barcelona (Spain) conform the baseline case scenario.

A maximum and a minimum amount of photovoltaic electricity production has been calculated by considering the local urban specificities of the Spanish cities (Barcelona, Bilbao, Madrid, and Murcia) which represent the largest market volumes for the designer company involved in the research. These cities provide a useful representation of the variability on the solar radiation moving from Mediterranean to Atlantic Spanish latitudes. The resulted values may be also representative of the performance of the SP design when it is implemented in other countries affected by similar bioclimatic conditions. The energy consumption during operation of the CP and SP product system is adjusted according to the annual average requirements for nocturnal lighting during the timeframe considered. Information provided by the Spanish National Statistical Institute (INE, 2014) regarding the annual hours (1997-2012) of sun insulation by provinces has been used in calculations. The PV Potential Estimation Utility developed by the Join Research Centre of the European Commission (http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php) was applied to calculate the total photovoltaic electricity generation by the SP product system.

The Greek (GR) and the French (FR) electricity grid mixes defined according to ecoinvent 2.2 dataset (SCLCI, 2010) have been chosen as reference to determine the effect of the substitution of the consumption of high carbon and low carbon intensity electricity grid by using photovoltaic electricity production.

Table 8.2 summarizes the basic data related to each case scenario considered for environmental calculations. Further descriptions and data about the composition of the ES, GR and FR electricity mixes, the adjustment of the energy demand of the operation of CP and SP product systems implemented in different Spanish geographical latitudes with the corresponding calculation of the photovoltaic electricity production by the SP design, can be found in appendix IV (section A.5).

Table 8.2 Data considered for the sensitivity analysis of the environmental performance of the CP and SP product systems.

Case scenarios	Lighting (h/10 years)	Energy demand (kWh)		Photovoltaic production (kWh)			Electricity grid mix	PED (MJ eq.)/kWh	GWP (kg CO_2 eq.)/kWh
		CP	SP	CP	SP	SP_spE			
Baseline latitude (Barcelona)	42,600	10,480	3,468	-	33,600	30,132	Baseline (ES)	10.067	0.422
Atlantic latitude (Bilbao)	58,350	14,354	4,750	-	29,600	24,850	Low-carbonized (FR)	13.497	0.107
Mediterranean latitude (Murcia)	35,850	8,819	2,918	-	37,200	34,282	High-carbonized (GR)	17.101	1.144

8.1.Results and Discussion

8.1.1.Life cycle environmental performance of CP and SP designs

Table 8.3 presents the life cycle GWP and PED of the CP and SP designs. The environmental savings related to the end-use of the lifetime spE generated by the SP product system are cut-off. This issue is comprehensibly addressed in the subsequent sections.

Table 8.3 Life cycle environmental performance of CP and SP product systems. Note: the environmental benefits related to the end-use of the spE generation by the SP design (operation stage) are cut-off.

Environmental impacts	Pergolas´ designs	Life cycle stages				Total
		Materials	Transportation	Installation	Operation	
GWP (kg CO_2 eq.)	**CP**	1,249	1,309	133	4,424	**7,116**
	SP	3,438	1,275	107	0	**4,820**
PED (MJ eq.)	**CP**	18,614	18,721	1,941	105,503	**144,779**
	SP	63,634	18,375	1,562	0	**83,571**

The SP contributes 32% less to GWP (- 2,295 kg CO_2 eq.) and 42% less to PED (- 61,208 MJ eq.) than the CP. While the operation of the SP does not contribute to environmental impact, the operation stage of the CP is the most relevant environmental hot-spot. Electricity consumption by CP accounts for 62% of the total GWP and 73% of the total PED. In the SP, the materials contribute 71% to GWP and 76% to PED. The materials embedded in the SP design represent 2.8 times higher contribution to GWP and 3.4 times higher contribution to PED than materials used for the CP design. Fig. 8.5 shows the relative contribution to GWP and PED by the type of materials employed for each design of pergola.

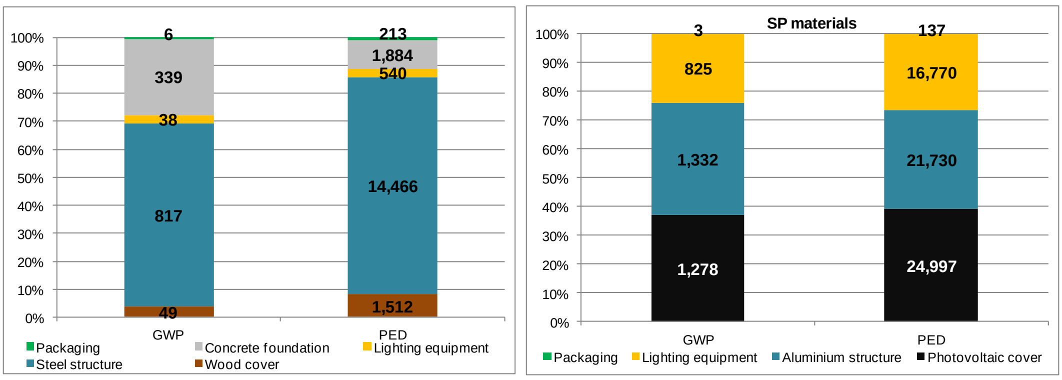


Fig. 8.5 Relative contribution to GWP and PED by type of materials used for the design of the CP and SP.

The amount of steel used in the structure of the CP accounts for 65% of the total GWP by the materials, whereas the concrete required for the installation of the pergola at the public urban space represent 27% of the total GWP. The contribution to GWP by these materials is determined basically by the energy requirements during their industrial processing. In terms of PED, therefore, the steel structure and concrete foundation are also the dominant contributors with 78% and 10%, respectively.

The photovoltaic cover of the SP design which contributes to a clean operation stage represents the element that provides the highest contribution to GWP and PED. Photovoltaic panels account for 37% of GWP and 39% of PED. The aluminium structure has also a high contribution to GWP (39%) and PED (34%). Although LED lamps are high energy efficient lighting products in comparison to the use of fluorescence lamps, LEDs determine 24% for GWP and 26% for PED of all the materials employed in the design of the SP product system. In this way, materials embedded in the SP design account for a higher environmental burden than the materials used in the CP design. However, their environmental strength lies on the performance given during the operation of the product system, which is the most critical stage of energy-related products (European Commission, 2009c).

8.1.2. Passive contribution to sustainability by SP implementation and management

Fig. 8.6 shows the life cycle GWP and PED of the CP and SP product systems for different geographical emplacements. The lifetime spE generated by the SP design is considered to be poured into the electricity grid in substitution of a baseline (ES), high-carbonized (GR) and low-carbonized (FR) electricity grid mix.

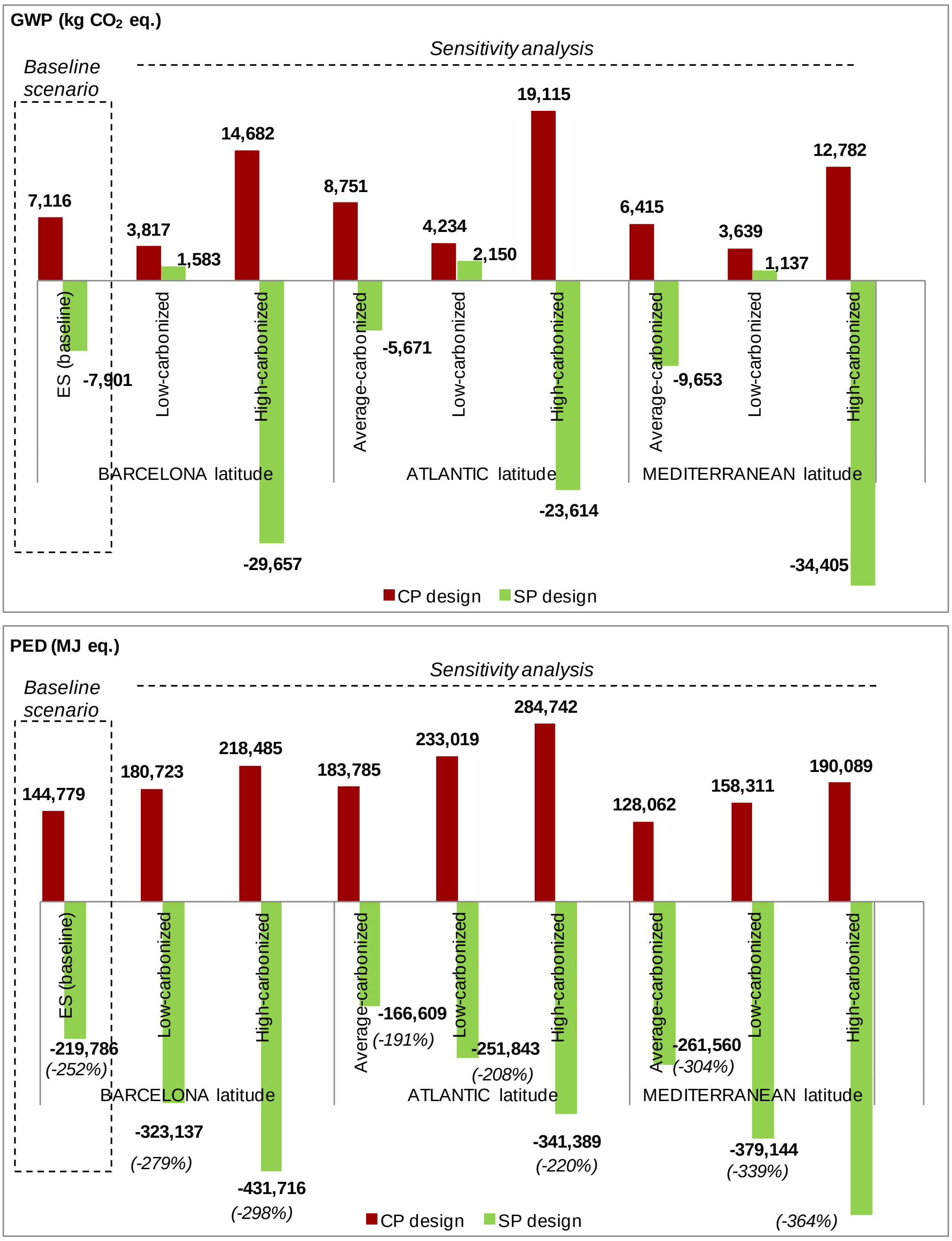


Fig. 8.6 Comparative life cycle environmental performance of CP and SP product systems for different geographical emplacements with variable carbon-intensity of electricity grid mixes.

The difference on the life-cycle environmental performance of CP and SP product systems relies directly on the variability of the environmental impact of the operation stage under the different case scenarios considered.

Focusing on the baseline case scenario, around 11,417 kWh of spE are required to compensate the entire life cycle GWP (4,820 kg CO_2 eq.) of the SP design, whereas 8,301kWh of spE are enough to compensate the life cycle PED (83,571 MJ eq.). It means that the complete life-cycle environmental burden of the SP product system would be compensated after 3 to 4 years of operation. After that moment in time, each kWh of spE poured into the electricity grid would contribute to net environmental savings. In this way, the overall potential for environmental improvement by the implementation of the SP design in substitution of the CP design would account for 211% in GWP (- 15,017 kg CO2 eq.) and 252% in PED (- 364,564 MJ eq.) in a timeframe of 10 years. Nevertheless, these values might be lower or even higher depending on the geographical emplacement of the product system. According to Fig. 8.6, the minimum potential for environmental improvement by the SP product system would account for 49% for GWP (- 2,080 kg CO_2 eq.) and 191% for PED (- 350, 394 MJ eq.), which by the way represent significant environmental savings. The maximum potential for environmental improvement could account for 369% in GWP (47,187 kg CO_2 eq.) and 364% for PED (692,764 MJ eq.)

Table 8.4 summaries the most relevant environmental data related to the life cycle performance of the SP product system under the different case scenarios (Table 8.2).

Table 8.4 Life cycle environmental performance indicators of the SP product system operating in different geographical emplacements with variable carbonized electricity grid mixes. (*) compared to the implementation of the CP product system

Environmental Indicator	Geographical emplacement	Electricity grid mix	Annual savings	Life-cycle payback (years)	"clean" lifetime spE (kWh)	Total lifetime savings (*)
GWP ($kg\ CO_2$ eq.)	Barcelona latitude	**ES (baseline)**	**1,272**	**3.8**	**18,715**	**15,017**
		Low-carbonized	324	14.9	-14,730	2,235
		High-carbonized	3,448	1.4	25,920	44,339
	Atlantic latitude	Average-carbonized	1,049	4.6	13,433	14,423
		Low-carbonized	267	18.1	-20,012	2,083
		High-carbonized	2,843	1.7	20,637	42,729
	Mediterranean latitude	Average-carbonized	1,447	3.3	22,864	16,068
		Low-carbonized	368	13.1	-10,580	2,502
		High-carbonized	3,923	1.2	30,069	47,187
PED (MJ eq.)	Barcelona latitude	**ES (baseline)**	**30,336**	**2.8**	**21,831**	**364,564**
		Low-carbonized	40,671	2.1	23,941	503,860
		High-carbonized	51,529	1.6	25,245	650,201
	Atlantic latitude	Average-carbonized	25,018	3.3	16,549	350,394
		Low-carbonized	33,541	2.5	18,659	484,862
		High-carbonized	42,496	2.0	19,963	626,131
	Mediterranean latitude	Average-carbonized	34,513	2.4	25,981	389,622
		Low-carbonized	46,272	1.8	28,090	537,454
		High-carbonized	58,625	1.4	29,395	692,764

The lower the spE generation and cleaner the electricity grid mix, the reduced the potential for environmental improvement of the SP product system becomes. In this sense, a lower potential for environmental improvement is observed when the SP product system is implemented in an Atlantic bioclimatic geography (low spE generation) with a low-carbonized electricity grid mix. In these case scenarios, the life-cycle GWP cannot be completely compensated but only reduced. The life cycle GWP payback-time would account for 15 to 18 years that would correspond to pouring an extra amount of 10,580 kWh to over 20,000 kWh of spE into the electricity grid. Findings demonstrate therefore that the SP product system has the higher potential for environmental improvement if it was implemented in geographies (regions) with high solar radiation and high-carbonized electricity grid mixes. In these places, the life-cycle GWP of the SP product system could be compensated after 1 to 4 years of operation thus a significant amount of "GWP free" spE is generated that could provide notably net environmental savings over time.

Taking as reference the total lifetime GWP savings of the SP product system for the baseline case scenario (15,017 kg CO_2 eq.), they can be reduced by 86% (SP implemented in an Atlantic geography with low-carbonized electricity grid mix) or they can be increased by 214% (SP implemented in a Mediterranean geography with high-carbonized electricity grid mix). Regarding the CED indicator, the environmental savings are notably for all the case scenarios considered. The life-cycle PED of the SP product system would be amortized after 1 to 3 years of operation. The CED related to the electricity grid mixes considered is high, even for the low-carbonized one (FR) used in calculations. In this case, the input of nuclear power provides the high relative contribution to CED (see section A.5 from the SI file).

Taking as reference the total lifetime PED savings of the SP product system for the baseline case scenario (364,564 MJ eq.), they can be reduced by only 4% (SP implemented in an Atlantic geography with average-carbonized electricity grid mix, ES) but they can be increased by 90% (SP implemented in a Mediterranean geography with high-carbonized electricity grid mix).

All the findings indicate that the implementation of a SP design in the public space of cities would contribute to provide comfort for pedestrian mobility (diurnal shadow and nocturnal lighting) with no environmental cost but only environmental savings. Nevertheless, overall environmental gains could be increased if a specific end-use(r) of the spE generation by the SP design is actively promoted.

8.1.3. Active contribution to sustainability by SP_eBike (concept) implementation and management

8.1.3.1. Clean e-bike charging

The spE generated by the SP design could be encouraged to be used for providing a sustainable service of public charging of e-bikes. The Table 8.5 presents the number of e-bikes that could be daily charged by using the amount of spE "free" of environmental burden according to the different case scenarios (Table 8.4). At this point, the SP product system is re-defined as the SP_eBike concept.

A minimum, average and maximum number of daily charged e-bikes are determined according to the combination of the specificities regarding battery capacity and charging time of conventional e-bikes (Table 8.1).

Table 8.5 Number of e-bikes fully charged by day (annual average) by using clean spE generation by the SP_eBike concept under different case scenarios. NOTE: Min. (e-bikes with a battery pack of 36V / 10 Ah that required 6h for a full charge), Max. (e-bikes with a battery pack of 24V / 9 Ah that takes 4h for a full charging cycle), average (e-bikes with battery packs of 36 V / 9 Ah, which require 5h for a full charge).

Geographical emplacement	**Electricity grid mix**	**Nº daily (100%) charged e-bikes**					
		GWP "free"			**PED "free"**		
		Min.	**Average**	**Max.**	**Min.**	**Average**	**Max.**
Barcelona latitude	**ES (baseline)**	**2.3**	**3.2**	**5.7**	**2.7**	**3.7**	**6.6**
	Low-carbonized	0.0	0.0	0.0	3.0	4.0	7.3
	High-carbonized	3.2	4.4	7.9	3.1	4.3	7.7
Atlantic latitude	Average-carbonized	1.7	2.3	4.1	2.1	2.8	5.0
	Low-carbonized	0.0	0.0	0.0	2.3	3.2	5.7

	High-carbonized	2.6	3.5	6.3	2.5	3.4	6.1
Mediterranean latitude	Average-carbonized	2.8	3.9	7.0	3.2	4.4	7.9
	Low-carbonized	0.0	0.0	0.0	3.5	4.8	8.6
	High-carbonized	3.7	5.1	9.2	3.7	5.0	8.9

Depending on the geographical emplacement, the electricity grid mix and the model of e-bikes, a minimum of 2 e-bikes to a maximum of 9 e-bikes could be daily charged per module (23 m^2) of the SP_eBike concept implemented in the public space of cities. Only in geographical emplacements with a very low-carbonized electricity grid mix there would be no potential for clean e-bike charging. In this cases, the life-cycle GWP and PED of the SP product system could not be amortized hence there is no available clean spE.

The additional infrastructure requirements for the SP_eBike concept are considered to be minimal. Each column (x4) of the product system can be used as e-bike plug-in (i.e. one plugged e-bike per column) instead a plug-holder bar can be installed (see Fig. 8.4) when the number of e-bikes to be daily charged is greater (i.e. over four). In this way, the same electrical connection of the pergola to the municipal low-voltage network, the structure of the product system and part of its electrical components and equipment can be directly used to supply power to e-bike charging. This fact provides also a multifunctional character to the material structure of the product system.

Taking as reference the implementation of an four-module of the SP_eBike concept, which would account for around 92 m^2 of "solar parking", the system would supply enough surplus green energy for a clean daily charging of 8 to 36 e-bikes. These e-bikes will not contribute to any environmental impact during their use by riders. These findings demonstrate the environmental viability of promoting the implementation of the SP_eBike concept to support a sustainable municipal service of public e-bike charging. Lot of the knowledge and expertise regarding to the management of conventional bicycle-sharing services already implemented in many cities worldwide (EPOMM, 2013) could be used for the conceptualization and management of "sustainable e-bike sharing systems" based on the implementation of the SP_eBike concept. Tourist areas can represent interesting urban hot-spots for the implementation of the SP_eBike concept to support sustainable tourism initiatives by providing e-bikes to visitors for clean sightseeing instead of using motorized conventional transportation systems. Tourists using e-bikes can move a range of 30 to 40 km (on a single charge) throughout the city with no contribution to environmental impact.

E-bikes can be also especially useful for people living in hilly urban areas where riding a conventional bike would prove too strenuous for many to consider taking up cycling as a daily means of transport. People, who can need some assistance, as it could be the case for elderly people, can also take advantage of the use of e-bikes to move throughout the city what could contribute to some health improvements due to softer exercise. By this way, steep urban areas with high density of elderly people could represent other interesting hot-spot for the implementation of the SP_eBike concept.

8.1.3.2. Environmental performance of CP_CCSeBike and SP_eBike product systems

The life cycle environmental performance of the SP_eBike concept related to the CP_CCSeBike product system (section 8.2.3.2) is compared in order to determine the additional potential for environmental improvement.

The Fig. 8.7 shows the life cycle GWP and PED of the CP_CCSeBike and SP_eBike product systems for different geographical emplacements with variable carbonized electricity grid mixes. The lifetime clean spE (Table 8.4) and the corresponding potential number of daily charged e-bikes (Table 8.5) were taken as reference to compare the environmental impacts between product systems under equivalent functional conditions.

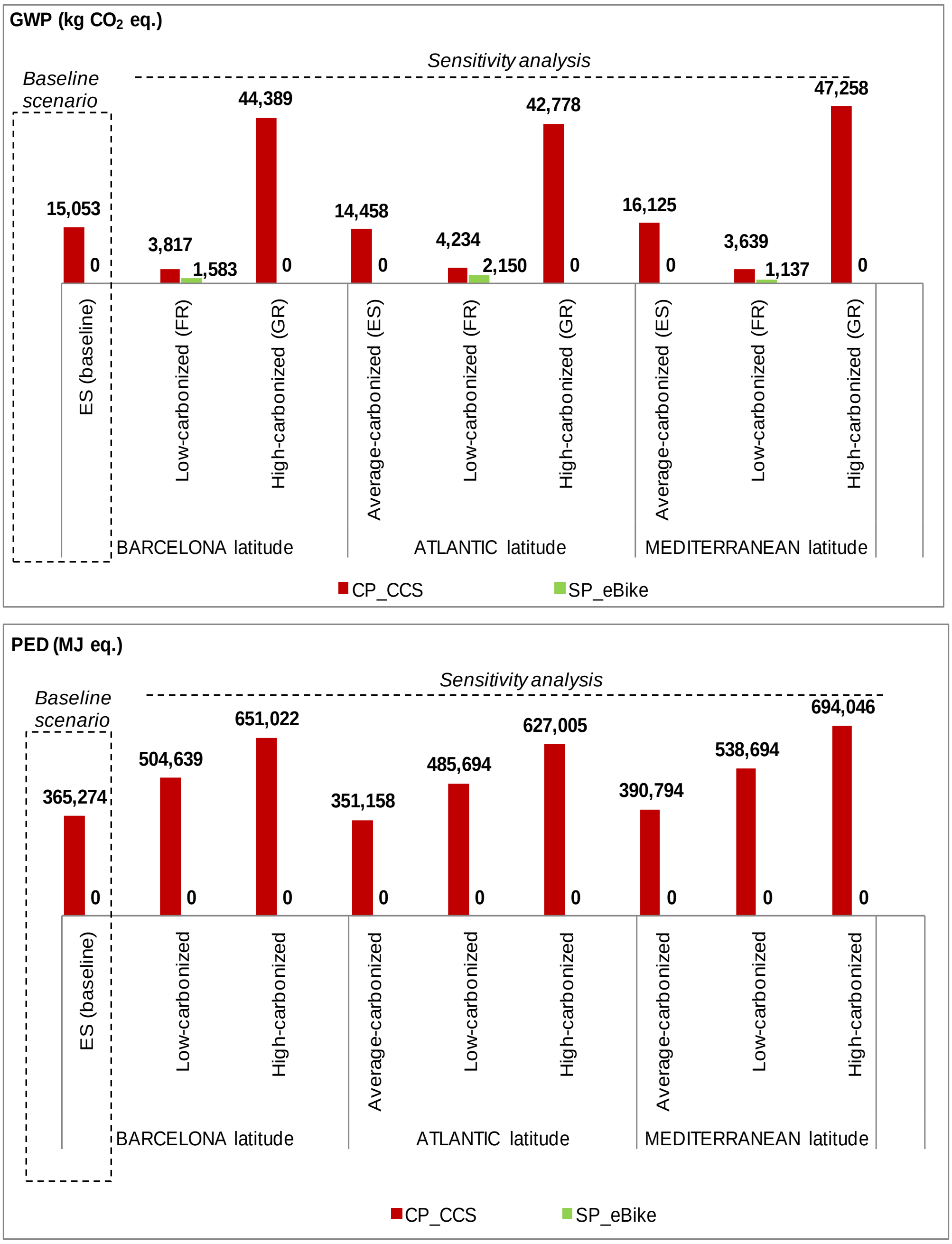


Fig. 8.7 Comparative life cycle environmental performance of CP_CCSeBike and SP_eBike product systems for different geographical emplacements with variable carbonized electricity grid mixes.

In this case scenario, the life-cycle GWP and PED related to the SP_eBike concept is always zero for the different geographical emplacements considered. The environmental burden of the product system is assumed to be compensated first by the avoided environmental burden resulted through the substitution of conventional electricity from the grid mix. Except when the electricity grid mix is very clean (i.e. FR).

The explanations provided in the case scenario of passive contribution to sustainability are also applicable for this analysis. The main difference on the life-cycle environmental impact of the CP_CCSeBike product system compared to the SP_eBike concept relies on the additional environmental burden related to the provision of a functionally equivalent service of e-bike charging. Findings indicate that a slightly (less than 1%) environmental improvement would be achieved. These environmental improvements account for an extra saving of 35 to 71 kg of CO_2 eq. and 710 to 1,281 MJ eq. Although, additional environmental gains are minimal, the SP_eBike concept represents a multifunctional product system that can play a key role in the design and support of multimodal sustainable mobility networks in cities. Indirectly, the implementation of these systems can contribute to induced cycling mobility in detrimental of the use of conventional high-pollutant transportation vehicles, which is a critical issue for transport sustainability. Additionally, the SP_eBike concept could take part in the planning and management of clean-energy-storage urban networks. The batteries of e-bikes could be used to as storage systems for solar energy in order to supply clean energy directly to the pergola´s lighting system or to the local lighting network to provide sustainable energy security. These circumstances could contribute therefore to generate additional environmental savings to be attributed to this urban furniture that can play an interesting role in the support of smart mobility for future smart cities.

8.2. Conclusions

Ecodesign has been demonstrated to be a valuable tool for promoting the eco-innovation of urban furniture in order to support smart green mobility in cities. Although a specific product system has been evaluated, findings are very significant. The implementation of urban solar pergolas with surplus photovoltaic generation (multifunctional product systems) can provide diurnal shadow, nocturnal lighting and green electricity for pedestrian and e-bike mobility with no environmental cost for the built environment of cities but only environmental savings. From 2,080 kg to over 47,185 kg of CO_2 eq. and from 350,390 MJ to over 692,760 MJ eq. can be saved in a timeframe of 10 years, according to the depending on the geographical region and electric system considered in calculations. Geographical regions with high solar radiation and a high-carbonized electricity grid mixes represent the most suitable hot-pots for the implementation of solar pergolas. Findings demonstrate that the promotion of innovative solutions based on the deployment of multifunctional urban infrastructures that support multimodal sustainable transportation modes can play a key role to contribute to an energy-efficient, clean and resilient urban environment.

Supplementary Material (Appendix IV)

Further descriptions and data related to the ecodesign methodological framework, case scenarios and environmental results are presented in the appendix IV.

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Part VI. General conclusions

Chapter IX. General conclusions.

Chapters 3 to 8 of the dissertation have presented the scientific results from the different case studies, including their specific discussion, conclusions and recommendations for future research. This chapter summarizes the most relevant findings according to the different areas of action of the dissertation.

9- Chapter 9. General conclusions

This dissertation has demonstrated that there is a high potential to improve the environmental performance of the public space of cities by promoting the implementation of life cycle environmental criteria in the design and management of urban pavements, materials, elements and furniture dedicated to the support of sustainable (pedestrian, cycling and electric) mobility.

9.1. Relevant Findings

Following, a series of relevant considerations and actions for the environmental optimization of these product systems are outlined.

Action on urban pavements (sidewalks)

- The GWP and PED per square meter of sidewalk can vary from 56 kg of CO_2 eq. to 500 kg of CO_2 eq. (+ 787%) and 612 MJ eq. to 6,967 MJ eq. (+ 1038%), respectively. This variability on GWP and PED depends on the design and service life of the construction solutions.
- Proper planning, construction and management of sidewalks to ensure long functional lifetimes can contribute to reduce 60% to 80% the environmental burden of each construction solutions due to lower maintenance and repair requirements over time.
- However, long-lived construction solutions do not ensure a lower environmental burden than those of others shorter-lived designs; total environmental savings between sidewalks depend on the environmental performance of the construction material chosen as top-layer (asphalt, concrete tiles or granite tiles). Findings have revealed that a short-life (15-years) asphalt sidewalk contributes 7% to 38% less GWP than a concrete and granite sidewalks, respectively, with a service life of 30 years. The industrial production of asphalt is cleaner compared to the production of concrete and granite tiles.
- Urban planners should integrate life-cycle environmental data and careful service-life planning consideration in order to identify the most environmentally friendly solutions according to the urban specificities in cities.

- The use of local construction materials is also recommended. The use of construction materials comming from regional or global markets, as it can be the case for granite, can contribute to increase 20% to 177% the life-cycle environmental impact of the sidewalk.
- Complementary actions such as optimizing the use of materials by avoinding oversizing the construction solutions or using alternative materials can contribute to reduce the overall impact of the sidewalks, while fulfilling their function.
- Considering the total urban area dedicated to sidewalks in cities and the increasing annual investment in the deployment of new pedestrian and cycling infrastructure, the implementation of environmentally-suitable construction solutions represents an interesting opportunity to mitigate environmental impacts.
- Nevertheless, decisions should not be based only on the implementation of product systems with best environmental performance at the current state of the art. In order to achieve major environmental savings at the urban scale, the environmental performance of those product systems with high environmental footprint should be also improved. This consideration drives to the following action.

Action on construction materials (granite)

- The natural properties of granite, which define its high technical quality as a construction material, are also the main reasons that determine the poor environmental performance of its industrial manufacture cycle. The hardness and abrasiveness of the stone requires the use of heavy equipment, which is high energy and water intensive and provides low resource efficiency.
- Granite block sawing into slabs is by far the most environmentally-relevant unit process of the entire production chain but it has a huge room for environmental improvement through the application of cleaner production techniques.
- The use of diamond multi-wire saw technology in substitution of conventional multi-blade gangsaw machines can contribute 30% of water savings (considering direct and indirect water flows), 40% of energy savings (electricity) and 80% of material savings (mainly steel) per square meter of finished tiles produced from cradle-to-gate. These resource savings would contribute to reduce by 53% (- 312 MJ eq./m^2) the PED and by 63% (-18.2 kg CO_2 eq./m^2) the GWP per finished square meter of granite tiles.

- The implementation of rainwater harvesting systems has been demonstrated to represent a suitable water management strategy to alleviate by half the use of groundwater and tap water inputs. The use of tools such as plugrisost can contribute to identify the feasibility and optimum design of rainwater harvesting systems.
- Granite sludge has suitable properties to be used as a by-product in a range of different industrial application. The material recovery of granite slugde can contribute to improve resource efficiency. However, further research should determine the economically and environmentally feasibility for the local and regional implementation of this by-product exchange.
- All these actions demonstrate that there is a great potential to improve the environmental performance of granite products and, as a consequence, to improve the environmental performance of those construction solutions where granite tiles are employed.
- It is highly encouraged the development of reference documents on best available techniques (BAT) related to the entire granite production chain in order to provide an overview of the overall potential for environmental improvement associated with this industry.

Action on urban elements (EV charging infrastructure)

- The life-cycle GWP and PED related to the implementation of conventional outdoor recharge posts (ORP2) for charging electric two-wheelers (E2Ws) can account for over 6,300 kg of CO_2 eq. and 112,500 MJ eq. for a timeframe of 10 years, respectively.
- Depending on the service ratio (lifetime energy output) and carbon intensity of the electricity grid mix supplied to E2Ws, the use of this type of charging facility can contribute to increase by 1% to 20% the environmental burden of the use phase (electricity consumption) of E2Ws.
- Under the same use conditions, the implementation of optimized designs of charging facilities for E2Ws, such as outdoor recharge stations (ORS6), can contribute to reduce these environmental burdens by half. The concentration of charging points in a single facility contributes to reduce construction requirements and optimize the use and management of the electronic equipment per available outlet.

- The design and service ratio of the charging facilities are key aspects to be considered for the sustainable deployment and management of public EV charging facilities. This consideration is especially relevant along the period of global standardization of urban EV charging networks, where many different possibilities and usage scenarios exist.
- The design of EV charging facilities, the scale of implementation and their urban location requires a smart approach to avoid over-investment that may result in unused assets that contribute to important long-term environmental impacts.
- The early application of eco-design principles is essential. In this process, the identification of synergies between urban elements can represent a suitable strategy to support electric mobility at a minimum environmental cost. This consideration drives to the next action.

Action on urban furniture (pergolas)

- Ecodesign is presented as a valuable tool for the identification of solutions that lead to the conceptualization of multifunctional urban furniture to support multimodal sustainable mobility.
- The implementation of solar pergolas with integrated charging points (SP_eBike concept) can provide diurnal shadow and nocturnal lighting for pedestrian comfort and green electricity for e-bikes with "zero" environmental cost.
- The implementation of the SP_eBike concept in substitution of functionally equivalent conventional pergolas and charging facilities for e-bikes can contribute to save from 2,080 kg of CO_2 eq. to over 47,100 kg of CO_2 and from 350,390 to over 692,760 MJ eq., depending on the geographic emplacement, for a timeframe of 10 years.
- Geographic areas with high solar radiation and a high-carbonized and primary-energy intensive electricity grid mixes represent the most suitable places to support a service of sustainable e-bike sharing. In these places, each module of the SP_eBike concept may be able to provide green energy to charge at least 9 conventional e-bikes by day. These e-bikes will not contribute to any environmental impact during their use by riders.
- Instead of maximizing infrastructure deployment to support different modes of sustainable mobility, the implementation of ecodesigned multifunctional urban

elements can play a relevant role to mitigate the environmental burden imposed to the urban public space, thereby increasing the environmental value of greening urban mobility.

9.2.Limitations of the research

The main complexity to address the research presented in dissertation was the data acquisition for the development of the LCIs of the different product systems. Data collection took an average of 3 to 6 months. This constraint was especially relevant for the environmental characterization of charging facilities for EVs (chapter 7). Many meetings and contacts with industrial designers and energy suppliers were performed but the level of involvement and collaboration was minimal. This situation limited the development of the research initially planned for this area of action. An interdisciplinary participation of experts in dissemination seminars can provide a global vision of the relevance of promoting the development of LCA studies related to the environmental characterization of urban EV charging urban networks. According to the results presented in the dissertation (chapters 7-8), the importance of this field of research should not be underestimated.

The involvement of industrial firms coordinated by the intermediation of the Spanish Cluster of Granite Producers has been essential to conduct a full environmental analysis of the granite production chain (chapters 5-6). However, the adquisition of specific LCI data disaggregated by granite pieces with different geometry (length and width) and thickness was very complex. The technical staff from the processing facilities that have participated in the research could not provide industrial data disaggregated by different products due to the lack of a protocol for product-specific measurement. Processing facilities usually conduct their industrial balances considering the production of 2 cm-thick granite pieces as reference, which is the most common thickness produced. From a life cycle approach, the allocation of the inputs and outputs per unit of finished product can change depending on the geometry of the piece produced. Coordination and support has already been given for industrial facilities start to measure product-specific LCI data for further LCIA of granite products.

9.3. Transfer of knowledge

Part of the research developed throughout the dissertation has been reported through different media to different groups of interest:

Academy

- *Scientific articles, conferences and seminars* The research presented in chapters 3 to 6 has been already published in scientific international peer-reviewed journals. Part of the research has also been presented through oral and poster participations in different international conferences and seminars.

Local government authorities

- *Forums* The research on pedestrian pavements (chapters 3-4) has been presented in a forum on urban pavements organized by the City Council of Barcelona and the Technical University of Catalonia within the framework of the Project Àgora with the aim to serve as a point of contact and collaboration between universities, companies and local governments to share knowledge for the life cycle management of the pavements in the city of Barcelona.

Industrial producers

- *Cluster of industrial producers* The research on pedestrian pavements (chapter 3-4) and granite production (chapters 5-6) has been presented in different workshops organized by the Spanish Cluster of Granite Producers (http://www.clustergranito.com/en/) in order to get knowledge about the environmental performance of their products and the potential for cleaner production and environmental management.

- *Panel of experts* The research presented in chapters 5-6 has been useful for the participation in a panel of experts for the definition of Product Category Rules for the development of Environmental Product Declaration of Natural Stone Products (http://www.csostenible.net/index.php/es/sistema_dapc). This initiative has been promoted by the Association of Surveyors, Architects and Building Engineers of Barcelona (http://www.apabcn.cat/ca_es/Pagines/inici.aspx).

Sistema DAPc®
Declaración Ambiental de Productos de Construcción

General public: academy, industry and local authorities

- *Public LCA databases* All the LCI data related to each of the case studies presented in chapters 3 to 8 have been introduced into the LCADB.sudoe tool (http://lcadb.sudoe.ecotech.cat/) developed by Sostenipra Research Group (www.sostenipra.cat), according to the information provided in chapter 2. The main aim is to share life cycle data with companies, administration, research institutions and in general LCA practitioners for improving the efficiency of the productive sectors. LCADB.sudoe tries to promote the inclusion of environmental information as a decisions factor in the design of products and process.

Chapter X. Future research.

Chapter 10 compiles a list of some of the most general future research lines that could be followed after this dissertation to complement and expand the results obtained in the four main areas of attention.

10- Chapter 10. Future research

Urban pavements (sidewalks)

- Development of LCA studies related to other standard designs of sidewalks and other paved surfaces dedicated to support walking and cycling activities in cities. Access to new information would contribute to overlook a range of different opportunities for significant environmental improvement at the city scale.
- Dump the environmental data related to urban pavements into a Geographical Information System (GIS) to map the environmental performance of different designs of pedestrian and cycling networks. It would contribute to urban planners carry out a dynamic historical-chart-record of the contribution to environmental impacts as a result of the urban actions carried out in cities due to urban refurbishment.

Construction materials (granite)

- Development of IE studies based on the identification and analysis of potential cleaner production alternatives at the level of all the different unit process of the granite production chain (quarrying, sawing, finishing and cutting).
- Identification and analysis of the environmental, economical and social feasibility of the local and regional implementation of inter-firm energy and material exchanges (industrial synergies and symbiosis) in order to improve resource efficiency.

Urban elements (EV charging facilities)

- Development of LCA focused on the characterization of different designs of charging facilities and different configurations of urban EV charging networks in order to provide a complete overview of the potential environmental burden of the deployment of the electric mobility in cities with the identification of areas for environmental improvement.

Urban furniture (pergolas)

- Extend the research to analyze the environmental viability of the implementation of an entire network of the SP_eBike concept to support sustainable multimodal (pedestrian and e-bike) mobility at the city scale. This research can be complemented with the analysis of critical issues for transport sustainability, such as diversion factors from the use of public and private conventional transport modes towards the use of e-bikes for daily commuting.
- Development of ecodesign research projects focused on the identification of urban synergies and eco-innovative alternatives that can contribute to conceptualize multifunctional urban elements to support sustainable multimodal mobility in the context of smart cities.

Part VII. Supplementary material

Chapter XI. Supplementary information related to the case studies (Appendices).

Chapter 11 presents further descriptions and data related to the different case studies addressed throughout the development of the dissertation.

This chapter is structured as follows:

- **Appendix I:** Supplementary material related to the life cycle inventory analysis of granite production from cradle-to-gate (chapter 5)

- **Appendix II:** Supplementary material related to the environmental management of granite slabs production from an industrial ecology standpoint (chapter 6)

- **Appendix III:** Supplementary material related to the assessment of the environmental significance of public charging facilities for electric two-wheelers (chapter 7)

- **Appendix IV:** Supplementary material related to the eco-innovation of urban furniture for promoting smart mobility in cities (chapter 8)

11- Chapter 11. Supplementary information related to the case studies (Appendices).

11.1. Appendix I. Supplementary material related to chapter 5.

This file contains further inventory data related to the case study, which is structured as follows:

- **Section A.** Production volumes (2010) of the quarries and processing facilities analyzed
- **Section B.** Detailed description of the production chain and technological coverage
- **Section C.** Quantification of the net production of granite products and wastes per each unit process of the granite processing stage
- **Section D.** LCI data per quarried granite block
- **Section E.** LCI data per processed granite block
- **Section F.** LCI data per sanded, flamed and bush-hammered granite block
- **Section G.** Disaggregated LCI data of the production chain from cradle to gate of one square meter of finished granite tiles with dimensions of 60 cm x 40 cm x 2 cm

Section A. Production volumes (2010) of the quarries and processing facilities analyzed. NOTE: (*) 8.67 m^3/unit.

Granite quarries	Quarry A	Quarry B	Quarry C	TOTAL
NACE	08.11	08.11	08.11	**08.11**
Operating area - Ha	4.14	15.41	16.76	**36.31**
Quarried granite - m^3	10,628	11,424	26,000	**48,052**
Equivalence in commercial blocks – units*	1,226	1,318	2,999	**5,542**
Processing facilities	**Facility A**	**Facility B**	**Facility C**	**TOTAL**
NACE	23.70	23.70	23.70	**23.70**
Processed granite – m^2 (total production)	318,813	281,096	281,497	**881,406**
Sawn granite - m^2 (slabs)	318,813	221,659	281,497	**821,969**
Finished granite - m^2 (slabs)	290,968	281,096	231,007	**803,071**
Polished granite - m^2 (slabs)	258,126	190,985	143,300	**592,411**
Sandblasted granite - m^2 (slabs)	19,492	63,022	0	**82,514**
Flamed granite - m^2 (slabs)	12,250	27,089	87,707	**127,046**
Bush-hammered granite - m^2 (slabs)	1,100	0	0	**1,100**
Cut granite - m^2 (tiles)	54,043	13,200	115,274	**182,517**

Table I.1. Production volumes (2010) of quarries and processing facilities.

The production volume of the processing facilities is divided into the net production volume from each of the unit processes of granite processing: granite sawing, granite finishing and granite cutting. The total production volume of processing facilities A and C corresponds to the total amount of granite slabs that leave the sawing process. For cases A and C a large part of the granite slabs receive a finishing application but only a share of them passes directly to the cutting tiles. Facility B has produced a higher amount of finished granite slabs than those leaving the sawing process. In this case, the facility has received sawn granite slabs from intermediate sawing facilities. The entire amount of granite slabs that left the sawing process received a finishing application and subsequently a few of them are cut into tiles.

Section B. Detailed description of the production chain and technological coverage

Granite quarrying A granite bench is removed from a deposit by a combination of drilling, blasting and cutting operations. The first operation consists of the drilling of two boreholes in the ground plane and one borehole in the vertical plane for the subsequent passage of the diamond wire to begin cutting the stone. The boreholes are created by using probe drives that are driven by air compressors powered by diesel. The preparation of the boreholes requires between 24 and 36 h. Subsequently, electric-powered diamond wire machines begin cutting the vertical planes of the bench. The cutting speeds of these machines range from 2 to 7 $m^2 h^{-1}$. A series of boreholes separated by 80 cm each are created along the perimeter of the ground plane. The boreholes are filled with gun powder and detonating cord (6–12 g m^{-1}) to create a pushing action on the stone. Detonators and safety fuses are used to initiate blasting. The process of lifting the granite bench requires from 48 to 72 h.

The subdivision of the granite bench into primary granite blocks is performed by the application of the following two techniques:

- Drilling and blasting. Pneumatic hammers driven by electrically powered air compressors or diesel-powered backhoes equipped with drills are employed. The drilling process can utilise the full height of the bench (10–14 m), or an average length of 6 m, with a spacing of approximately 30 cm. The separation of the primary granite block from the bench requires a small amount of gun powder and/or a detonating cord.
- Cutting. A diamond wire cutting machine is used to obtain thinner granite blocks (~ 6 m). These blocks are easier to cut into commercial blocks, which eliminates an intermediate cutting step. The use of diamond wire cutting machines achieves higher efficiencies.

The primary granite block is dumped on the ground of the quarry to subdivide them into commercial granite blocks (quarry marketable products) with suitable dimensions for transporting and handling in processing industries. A sand or clay bed is created to cushion the impact and prevent stone breakage. A diesel-powered loader is used to prepare the sand or clay bed and a backhoe equipped with a mechanical arm is used to dump the primary block on the ground. Boreholes with 15-cm spacings and approximate lengths of 1.4 m are drilled using hydraulic hammers to define cleavage planes. Pneumatic hammers driven by a compressed air circuit are used to introduce steel shims and wedges in the boreholes to break the stone. The granite blocks are squared using pneumatic hammers and/or diamond wire. The dimensions of the granite blocks are conditioned by the characteristics of the machinery that is employed to saw the blocks in the processing industries. The average dimensions of the commercial granite blocks that are quarried and processed are 1.7 m high, 3 m long and 1.7 m wide (8.67 m^3). A continuous stream of cooling water during the drilling and cutting operations is required to dissipate the heat generated by the process, as sufficiently elevated temperatures can cause significant machine and material damage. The final phase in granite quarrying consists of washing the commercial blocks and inspecting and classifying them prior to their storage in or transportation to processing facilities. Granite of insufficient quality or handling size is utilised in producing masonry products, sent to a crushing facility for the production of aggregate for construction applications, or stored on-site for future site reclamation. Commercial blocks are transferred to storage using diesel-powered loaders. Due to legal concerns, a truck can only transport a single commercial block per voyage.

Granite processing The operations related to granite processing can be divided into three major unit processes: sawing (primary cutting), finishing (surface treatment), and (secondary) cutting (and/or shaping). Prior to the sawing process, the granite blocks may need to be squared to remove lumps and their dimensions may require adjustments to optimise the yield of production. During the sawing process, the granite block is cut into slabs with dimensions defined by the dimensions of the granite block. Their thicknesses, however, are defined by customer demand, which determines the number of granite slabs produced per sawn block. The processing facilities use gang saw machines to saw the granite blocks. Gang saws are the most widely used technology for the mass production of granite slabs with thicknesses of 2–3 cm. In the gang saw machines, a granite block is eroded by the action of a steel blade mounted in a heavy frame, which is moved back and forth at high speeds by a transmission mechanism. The steel blades are typically 5 mm thick, 100 mm wide and 3,000–3,500 mm long. The length of the blades is dependent on the dimensions of the gang saw, which are typically 2,000–2,100 mm high, 3,500–5,500 mm wide and 3,000–3,500 mm long. Gang saws have an installed power that ranges from 95 kW to 165 kW. Sawing a granite block into slabs requires 48 h to 72 h. A water flow of 80 litres h^{-1} to 200 litres h^{-1} is required. In the process of granite sawing, the function of the water input is to refrigerate the steel blades used to erode the stone and remove the fines generated during the process. Water also contains a load of steel grit, which causes stone cutting as a result of the thrust force generated by the steel blades. The water also contains hydrated lime to raise the viscosity of the fluid and maintain the grit in suspension. The hydrated lime also minimises oxidation. To guarantee the efficiency of the process, the excess of granite fines and the worn grit in the water need to be removed periodically. The fluid is sent to a cyclone in which heavier particles are deposited on the bottom of the tank. This fraction is mixed with additions of the new abrasive mixture and returned to the gang saw. The finer mixture passes to a decanter where coagulants and flocculants are added to accelerate the process of decantation. Carbon dioxide is also added to reduce the alkalinity of the wastewater. The carbon dioxide reacts with the calcium hydroxide to produce calcite. Two fractions are generated upon separation: clarified water and granite sludge that contains the finely ground stone, worn grit, steel blade particles and calcite. Clarified water is sent back to the production line, whereas the granite sludge is sent to filter press devices where granite sludge is partially dried. As a result, granite sludge cakes catalogued as inert non-hazardous wastes are generated, collected and transported to an authorised landfill. The moisture content of granite sludge cakes are typically in the range of 35%–40% in weight.

After the sawing process, granite slabs can either pass directly to the finishing line to obtain a specific texture on the surface of the stone or bypass the finishing process and go directly to the cutting line once the granite product is determined to have a "natural" appearance and the texture generated by the sawing process fulfils the function required in construction. An array of finishing applications exists. The following finishing processes conducted by the processing facilities are considered in this study:

- *Polishing*. The treatment of the surface of the stone with progressively finer abrasive grains. A smooth and shiny finish surface is generated with almost zero porosity. Polishing is the most common finishing process applied to granite products. Polished granite slabs are used for indoor flooring and indoor and outdoor cladding. Polishing machines have an installed power of approximately 375 kW. Approximately 80 $m^2 h^{-1}$ can be polished. A continuous stream of 1,500 litres h^{-1} of cooling water is required.
- *Sandblasting.* A sandblasted finish is achieved by projecting silica sand or corundum on the surface of the stone through a nozzle at high speeds and variable air pressures. Depending on the pressure applied and the abrasive flow, the process provides a finer or thicker finished surface. Sandblasted granite tiles are typically used in indoor

and outdoor cladding. Sandblasting machines have an installed power of approximately 130 kW. Approximately 200 m^2 h^{-1} can be sandblasted. Cooling water is not required.

- *Flaming.* This process involves the application of a flame at approximately 2,800 ºC through a torch on the surface of the stone, which causes the detachment of small chips or splinters. The process is performed automatically in special chambers, whose main component is a mobile oxy-propane torch. It provides a rough, vitreous, undulating and irregular surface that is resistant to atmospheric chemical alteration. Flamed granite tiles are typically utilised in outdoor paving due to their anti-slipping properties. Flaming machines have an installed power of 4.5 kW and a process speed of 30 m^2 h^{-1}. A continuous stream of 100 to 450 litres h^{-1} of cooling water is required.
- *Bush-hammering.* A previously flattened surface is repeatedly hit with a hammer that contains one or more bushes with small pyramidal teeth. Although it can be performed manually, jackhammers are often used, which are moved either manually or automatically over the surface of the stone. As a result, a rough flat and slightly irregular surface with small craters is obtained. Bush-hammered granite tiles are mainly applied in outdoor paving projects due to their anti-slipping properties. The installed power is approximately 4.5 kW and approximately 20 m^2 h^{-1} can be bush-hammered. The process does not require water.

The last step in granite processing consists of cutting the granite slabs into granite tiles of desired dimensions, which is accomplished using electric-powered diamond disc saws. Diamond disc saws have an installed power of approximately 190 kW. The diameter of diamond discs can vary but their average thickness is 2.5 mm. A continuous stream of cooling water is also required in production. Granite tiles are packed using wooden pallets, boards and crates. Steel slings fasteners are also applied.

Section C. Quantification of the net production of granite products and wastes per each unit process of the granite processing stage

Calculation considerations	Sawing Process	Finishing Process	Cutting Process
Number of cuts on the stone	60 cuts per granite block	0 cuts per granite slab	8 cuts per granite slab

Number of pieces produced	60 granite slabs block^{-1}	1 granite slab slab^{-1}	16 granite tiles slab^{-1}
Dimension of each piece	1.7 m x 3 m x 0.02 m (slabs)	1.7 m x 3 m x 0.02 m (slab)	0.60 m x 0.40 m x 0.02 m (tiles)
Volume of granite pieces	6.12 m^3 block^{-1}	0.0995 m^3 slab^{-1}	0.0075 m^3 slab^{-1}
Volume lost by friction (sawdust)	2.14 m^3 block^{-1}	0.0026 m^3 slab^{-1}	0.0009 m^3 slab^{-1}
Volume lost as scrap	0.41 m^3 block^{-1}	0 m^3 slab^{-1}	0.024 m^3 slab^{-1}
Resource efficiency	70.6%	97.5%	75.3%
Net production	306 m^2 granite slabs block^{-1}	5.10 m^2 granite slabs slab^{-1}	3.84 m^2 granite tiles slab^{-1}

Table I.2 Net production of granite products and wastes per each unit process of the granite processing stage.

Table I.2 indicates the raw amount of granite entering each unit process and the net amount of granite product exiting each unit process in the granite processing stage. During the sawing process, it is assumed that 4 cm of each side of the granite block is not useful for production; these pieces become granite scrap. The remainder of the length of a granite block (1.62 m) is cut into granite slabs. The thickness of each cut generated by the steel blades is 7 mm; 5 mm correspond to the thickness of each blade, which increases by 2 mm due to the addition of steel grit required for stone cutting. A total of 60 units of 2 cm-thick granite slabs can therefore be produced per sawn granite block. In this process, approximately 25% of the net volume of the granite block is lost as granite sawdust, which is generated by the friction of the steel blades over the stone. It is assumed that 0.5 mm of the surface of each granite slab is eroded during the finishing processes by the action of the tools and the elements used to provide texture and aesthetics to the material. Therefore, the thickness of the granite slabs is slightly reduced in this process. The amount of raw granite lost in the process is equivalent to the amount of sawdust produced. As there are no cuts required in finishing, no granite scrap is produced in this stage. Considering the dimensions of each granite slab, a total of 8 units of granite tiles with dimensions of 60 cm x 40 cm x 2 cm can be produced per slab. The dimensions of the tiles to be produced determine the amount of granite scrap to be generated; in this case, this amount accounts for almost 24% of the volume of each granite slab. Potential breakage of the stone due to natural cleavage is not considered in calculations.

To calculate the inputs and outputs of the granite production chain on a granite block and square meter basis, the weight of each industrial facility in total production volume was considered. A density of 2,700 kg m^{-3} for granite was used in the calculations.

Section D. LCI data per quarried granite block

Industrial flows	Inputs	QUARRYING	StDv 95%
Energy	Low voltage electricity (kWh)	2.91E+02	70.3
	Diesel (MJ)	5.05E+03	423.8
Water	Groundwater (kg)	2.07E+03	1,897
	Surface water (kg)	4.46E+03	5,642
	Public supply (kg)	0.00E+00	0.00
Ancillary materials	ANFO (kg) - Explosives	4.70E+00	3.72
	PETN (kg) - Detonating cord	3.39E-01	0.15
	PVC (kg) - Detonating cord	3.89E-01	0.17
	High carbon steel (kg) - Drill rods and bits	1.01E+01	8.46
	Stainless steel (kg) - Diamond wire	3.10E-01	0.01
	Rubber (kg) - Diamond wire	3.44E-02	0.00
	Oil (kg) - Machinery	2.96E+00	0.98
	Lead acid (kg) - Detonators	2.08E-06	0.00
	PETN (kg) - Detonators	5.19E-06	0.00
	Gunpowder (kg) - Wick	4.52E-04	0.00
	PVC (kg) – Wick	7.54E-03	0.00
	Cotton (kg) - Wick	7.54E-03	0.00
Granite in ground	Granite (kg) - gross	3.90E+04	0.00
Industrial flows	**Outputs**	**QUARRYING**	**StDv 95%**
Product	Commercial granite block (kg) - net	2.34E+04	0.00
Granite wastes	Granite sawdust (kg)	7.78E+02	0.00
	Granite scrap (kg)	1.48E+04	0.00
Wastewater	Wastewater to ground (kg)	6.53E+03	7,538
Solid and semi-solid wastes	steel scrap (kg)	1.05E+01	8.47
	Residual oil (kg)	1.82E+00	0.17

Table I.3 LCI data per quarried granite block.

Section E. LCI data per processed granite block

Industrial flows	Inputs	SAWING	StDv 95%	POLISHING	StDv 95%	CUTTING	StDv 95%	TOTAL	StDv 95%
Energy	Low voltage electricity (kWh)	3.54E+03	843.0	3.99E+02	18.5	2.28E+03	471.1	6.22E+03	1,332.6
	Diesel (MJ)	1.02E+02	50.1	9.49E+01	50.1	9.46E+01	37.7	2.91E+02	138
	Propane (MJ)	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00
Water	Groundwater (kg)	3.29E+03	4,894	2.56E+03	327	4.18E+02	815	6.27E+03	6,036
	Surface water (kg)	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00
	Public supply (kg)	4.94E+03	7,279	3.92E+03	501	2.07E+03	1,807	1.09E+04	9,588
Ancillary materials	Carbon steel (kg) – Gang saw blades	3.92E+02	85.1	0.00E+00	0.00	0.00E+00	0.00	3.92E+02	85.1
	Steel grit (kg) - Abrasive mixture	5.40E+02	165	0.00E+00	0.00	0.00E+00	0.00	5.40E+02	165
	Carbon steel (kg) - Disc saw blades	0.00E+00	0.00	0.00E+00	0.00	3.16E+01	0.00	3.16E+01	0.00
	Lime (kg) - Abrasive mixture	2.78E+02	2.26	0.00E+00	0.00	0.00E+00	0.00	2.78E+02	2.26
	Abrasives (kg)	0.00E+00	0.00	1.98E+01	26.9	0.00E+00	0.00	1.98E+01	26.9
	Sand (kg)	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00
	Resigns (l)	0.00E+00	0.00	2.08E+00	0.00	0.00E+00	0.00	2.08E+00	0.00
	Timber (kg) - Material manipulation and Packaging	0.00E+00	0.00	1.63E+02	19.4	1.28E+02	16.7	2.91E+02	36.2
	Coagulants (kg) - Wastewater treatment	2.31E+00	1.58	1.60E+00	0.83	0.00E+00	0.00	3.91E+00	2.41
	Flocculants (kg) - Wastewater	5.56E-01	0.17	3.65E-01	0.10	0.00E+00	0.00	9.21E-01	0.26

	treatment								
	Oil (kg) - Machinery	2.71E+00	1.24	3.72E-01	0.28	1.92E+00	1.30	5.00E+00	2.82
	Grease (kg) - Machinery	8.09E-01	0.15	1.08E-01	0.03	4.73E-01	0.41	1.39E+00	0.59
	CO2 (kg) - Wastewater treatment	2.49E+01	2.04	0.00E+00	0.00	0.00E+00	0.00	2.49E+01	2.04
	O2 (kg) - Oxidizer for combustion in flaming	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00
	Industrial steel (kg) - Packaging	0.00E+00	0.00	0.00E+00	0.00	1.23E+00	0.00	1.23E+00	0.00
Granite – raw material	Granite (kg) - gross	2.34E+04	0.00	1.65E+04	0.00	1.61E+04	0.00	2.34E+04	0.00
Industrial flows	**Outputs**	**SAWING**	**StDv 95%**	**POLISHING**	**StDv 95%**	**CUTTING**	**StDv 95%**	**TOTAL**	**StDv 95%**
Product	Granite (kg): slabs --> slabs --> tiles - net	1.65E+04	0.00	1.61E+04	0.00	1.21E+04	0.00	1.21E+04	0.00
	Granite sawdust (kg)	2.89E+02	0.00	2.07E+01	0.00	7.42E+00	0.00	3.17E+02	0.00
	Granite scrap (kg)	1.10E+03	0.00	0.00E+00	0.00	3.83E+03	0.00	4.93E+03	0.00
Wastewater	Wastewater (kg) - evaporated	4.47E+03	6,622	6.24E+03	797	2.39E+03	2,517	1.31E+04	9,936
Solid and semi-solid wastes	Granite sludge (kg) - mix of elements	1.02E+04	5,753	6.56E+02	57.9	2.41E+02	105	1.11E+04	5,917
	Steel scrap (kg)	2.48E+02	53.8	0.00E+00	0.00	3.16E+01	0.00	2.79E+02	53.8
	Residual oil (kg)	1.99E+00	0.82	2.72E-01	0.17	1.36E+00	1.47	3.62E+00	2.46
	Waste wood (kg)	0.00E+00	0.00	1.63E+02	19.4	1.28E+02	16.7	2.91E+02	36.2
	Industrial steel (kg) - Packaging	0.00E+00	0.00	0.00E+00	0.00	1.23E+00	0.00	1.23E+00	0.00

Table I. 4 LCI data per processed granite block

Section F. LCI data per sanded, flamed and bush-hammered granite block

Industrial flows	Inputs	SANDBLASTING	StDv 95%	FLAMING	StDv 95%	BUSHHAMMERING	StDv 95%
Energy	Low voltage electricity (kWh)	1.45E+02	41.9	8.62E+00	2.9	7.65E+00	0.0
	Diesel (MJ)	9.49E+01	50.1	9.49E+01	50.1	9.49E+01	50.1
	Propane (MJ)	0.00E+00	0.00	3.58E+03	1,139	0.00E+00	0.00
Water	Groundwater (kg)	0.00E+00	0.00	1.38E+03	813.8	0.00E+00	0.00
	Surface water (kg)	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00
	Public supply (kg)	0.00E+00	0.00	2.11E+03	1,247	0.00E+00	0.00
	Sand (kg)	2.33E+02	164.8	0.00E+00	0.00	0.00E+00	0.00
	Timber (kg) - Material manipulation and Packaging	1.63E+02	19.4	1.63E+02	19.4	1.63E+02	19.4
	Oil (kg) - Machinery	3.72E-01	0.28	3.72E-01	0.28	3.72E-01	0.28
	Grease (kg) - Machinery	1.08E-01	0.03	1.08E-01	0.03	1.08E-01	0.03
	O2 (kg) - Oxidizer for combustion in flaming	0.00E+00	0.00	3.03E+02	169.2	0.00E+00	0.00
Granite – raw material	Granite (kg) - gross	1.65E+04	0.00	1.65E+04	0.00	1.65E+04	0.00

Industrial flows	Outputs	SANDBLASTING	StDv 95%	FLAMING	StDv 95%	BUSHHAMMERING	StDv 95%
Product	Granite (kg): slabs --> slabs --> tiles - net	1.61E+04	0.00	1.61E+04	0.00	1.61E+04	0.00
	Granite sawdust (kg)	4.13E+02	0.00	2.07E+01	0.00	4.13E+02	0.00
	Granite scrap (kg)	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00
Wastewater	Wastewater (kg) - evaporated	0.00E+00	0.00	3.36E+03	1,985	0.00E+00	0.00
Solid and semi-solid wastes	Granite sludge (kg) - mix of elements	0.00E+00	0.00	5.21E+02	76	0.00E+00	0.00
	Residual oil (kg)	2.72E-01	0.17	2.72E-01	0.17	2.72E-01	0.17
	Residual sand (kg)	2.33E+02	165	0.00E+00	0.00	0.00E+00	0.00
	Waste wood (kg)	1.63E+02	19.4	1.63E+02	19.4	1.63E+02	19.4

Table I.5 LCI data per sanded, flamed and bush-hammered granite block

General comment for sections B, C and D The mean values have been calculated by considering the weight of the different quarries and processing facilities in the total production volumes considered in the calculations (section A). Note that for some inputs and outputs the standard deviation of the data is very high. Only three quarries and three processing facilities have been analyzed as part of the research. Although the quarries and processing facilities analyzed represent an important share of the regional and national production volumes of granite, the sample is small. This results in a high standard deviation.

Section G. Disaggregated LCI data of the production chain from cradle to gate of one square meter of finished granite tiles with dimensions of 60 cm x 40 cm x 2 cm

Industrial flows	INPUTS	QUARRYING*	PROCESSING						TOTAL (*)
			Sawing*	FINISHING				Cutting*	
				Polishing*	Sandblasting	Flaming	Bush-hammering		
Energy	Low voltage electricity (kWh)	1.26E+00	1.54E+01	1.73E+00	6.29E-01	3.74E-02	3.32E-02	9.90E+00	**2.83E+01**
	Diesel (MJ)	2.19E+01	4.42E-01	4.12E-01	4.12E-01	4.12E-01	4.12E-01	4.11E-01	**2.32E+01**
	Propane (MJ)	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.55E+01	0.00E+00	0.00E+00	**0.00E+00**
Water	Groundwater (kg)	8.99E+00	1.43E+01	1.11E+01	0.00E+00	5.97E+00	0.00E+00	1.81E+00	**3.62E+01**
	Surface water (kg)	1.94E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	**1.94E+01**
	Public supply (kg)	0.00E+00	2.14E+01	1.70E+01	0.00E+00	9.15E+00	0.00E+00	9.00E+00	**4.75E+01**
Ancillary materials	ANFO (kg) - Explosives	2.04E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	**2.04E-02**
	PETN (kg) - Detonating cord	1.47E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	**1.47E-03**
	PVC (kg) - Detonating cord	1.69E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	**1.69E-03**
	High carbon steel (kg) - Drill rods and bits	4.40E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	**4.40E-02**
	Lead acid (kg) - Detonators	9.01E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	**9.01E-09**
	PETN (kg) - Detonators	2.25E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	**2.25E-08**

	Gunpowder (kg) - Wick	1.96E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	**1.96E-06**
	PVC (kg) - Wick	3.27E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	**3.27E-05**
	Cotton (kg) - Wick	3.27E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	**3.27E-05**
	Stainless steel (kg) - Diamond wire	1.34E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	**1.34E-03**
	Rubber (kg) - Diamond wire	1.49E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	**1.49E-04**
	Carbon steel (kg) - Gang saw blades	0.00E+00	1.70E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	**1.70E+00**
	Steel grit (kg) - Abrasive mixture	0.00E+00	2.34E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	**2.34E+00**
	Stainless steel (kg) - Disc saw blades	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.37E-01	**1.37E-01**
	Lime (kg) - Abrasive mixture	0.00E+00	1.21E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	**1.21E+00**
	Abrasives (kg)	0.00E+00	0.00E+00	8.58E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	**8.58E-02**
	Silica sand (kg)	0.00E+00	0.00E+00	0.00E+00	1.01E+00	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**
	Resigns (l)	0.00E+00	0.00E+00	9.04E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	**9.04E-03**
	Timber (kg) – Transportation and packaging	0.00E+00	0.00E+00	7.08E-01	7.08E-01	7.08E-01	7.08E-01	5.56E-01	**1.26E+00**
	Coagulants (kg) - Wastewater treatment	0.00E+00	1.00E-02	6.96E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	**1.70E-02**
	Flocculants (kg) - Wastewater	0.00E+00	2.41E-03	1.58E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	**4.00E-03**

	treatment								
	Oil (kg) - Machinery	1.28E-02	1.18E-02	1.62E-03	1.62E-03	1.62E-03	1.62E-03	8.31E-03	**3.45E-02**
	Grease (kg) - Machinery	0.00E+00	3.51E-03	4.68E-04	4.68E-04	4.68E-04	4.68E-04	2.05E-03	**6.03E-03**
	CO_2 (kg) - Wastewater treatment	0.00E+00	1.08E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	**1.08E-01**
	O_2 (kg) - Oxidizer for combustion in flaming	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.32E+00	0.00E+00	0.00E+00	**0.00E+00**
	Industrial steel (kg) - Packaging	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.34E-03	**5.34E-03**
Granite – raw material	Granite (kg) - gross	**1.69E+02**	1.02E+02	7.17E+01	7.17E+01	7.17E+01	7.17E+01	6.99E+01	**1.69E+02**
Industrial flows	**OUTPUTS**	**QUARRYING***	**Sawing***	**Polishing***	**Sandblasting**	**Flaming**	**Bush-hammering**	**Cutting***	**TOTAL (*)**
Granite product	Granite (kg) - net	1.02E+02	7.17E+01	6.99E+01	6.99E+01	6.99E+01	6.99E+01	**5.27E+01**	**1 m²**
Granite wastes	Granite sawdust (kg)	3.37E+00	1.26E+00	8.96E-02	1.79E+00	8.96E-02	1.79E+00	3.22E-02	**4.75E+00**
	Granite scrap (kg)	6.44E+01	4.78E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.66E+01	**8.58E+01**
Wastewater	Wastewater (kg) - evaporated	2.83E+01	1.94E+01	2.71E+01	0.00E+00	1.46E+01	0.00E+00	1.04E+01	**8.52E+01**
Solid wastes	Granite sludge (kg) - mix of elements	0.00E+00	4.44E+01	2.85E+00	0.00E+00	2.26E+00	0.00E+00	1.05E+00	**4.83E+01**
	Steel scrap (kg)	4.54E-02	1.08E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.37E-01	**1.26E+00**
	Residual oil (kg)	7.91E-03	8.64E-03	1.18E-03	1.18E-03	1.18E-03	1.18E-03	5.91E-03	**2.36E-02**

	Residual sand (kg)	0.00E+00	0.00E+00	0.00E+00	1.01E+00	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**
	Waste wood (kg)	0.00E+00	0.00E+00	7.08E-01	7.08E-01	7.08E-01	7.08E-01	5.56E-01	**1.26E+00**
	Industrial steel (kg) - Packaging	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.34E-03	**5.34E-03**

Table I.6 Disaggregated LCI data of the production chain from cradle to gate of one square meter of finished granite tiles with dimensions of 60 cm x 40 cm x 2 cm.

11.2. Appendix II. Supplementary material related to chapter 6.

This file contains further data and descriptions related to the case study analysed, especially focused on the determination of the potential of RWH for use in granite sawing. The information presented in this file is structured as follows:

Section A. Life cycle inventory analysis and environmental impact assessment

- **Section A.1** Basic technical specifications of the sawing technologies under assessment
- **Section A.2** Data collection and quality
- **Section A.3** Data calculation procedure
- **Section A.4** Complete LCI dataset per sawn block by MBGS and DMWS technologies.
- **Section A.5** Environmental performance of granite production
  - **Section A.5.1** Considerations for life cycle environmental impact assessment
  - **Section A.5.2** List of ecoinvent processes selected to determine the environmental impact of granite production
  - **Section A.5.3** Environmental impacts per square meter of granite slab production for each sawing technology
  - **Section A.5.4** Environmental performance of the production chain from cradle to gate of one square meter of finished granite tiles with dimensions of 60 cm x 40 cm x 2 cm when using a gangsaw technology mix or the MBGS 180, DMWS 35 and DMWS 100 technologies for granite sawing.

Section B. Calculation of the potential for rainwater harvesting for use in granite sawing

- **Section B.1** General characterization of the Atlantic and Mediterranean rainfall series considered to determine the variability in the RWH potential according to the bioclimatic geography where granite sawing is being addressed.
- **Section B.2** Potential daily rainwater availability for industrial use according to the industrial surface dedicated for rainwater catchment. NOTE: Daily water requirements of sawing technologies, considering 24h of use, are indicated in the graphics to visualize the potential for fully coverage with rainwater supply.

- **Section B.2.1** Potential daily rainwater availability for industrial use by using the sawmill roof (2,000 m^2) as rainwater catchment surface.
- **Section B.2.2** Potential daily rainwater availability for industrial use by using the industrial plot (28,500 m^2) as rainwater catchment surface.
- **Section B.2.3** Potential daily rainwater availability for industrial use by using the industrial area (574,100 m^2) as rainwater catchment surface.

- **Section B.3** Potential coverage of daily water consumption by sawing technologies if all available rainwater is fully harvested and stored (ideal scenario).
  - **Section B.3.1** Potential coverage of daily water consumption by sawing technologies if all available rainwater by using the sawmill roof as catchment surface is harvested and stored.
  - **Section B.3.2** Potential coverage of daily water consumption by sawing technologies if all available rainwater by using the industrial plot as catchment surface is harvested and stored.
  - **Section B.3.3** Potential coverage of daily water consumption by sawing technologies if all available rainwater by using the industrial area as catchment surface is harvested and stored.
- **Section B.4** Complete overview of the variability in the potential for RWH in Atlantic and Mediterranean climate geographies according to variability in rainwater tank sizing depending on the industrial surface dedicated to rainwater catchment and the water demand to be satisfied. Analytical software applied: Plugrisost® (Morales-Pinzón et al. 2012a).
  - **Section B.4.1** Sample of the variability in the potential for RWH in an Atlantic climate geography according to variability in rainwater tank sizing depending on the rainwater catchment surface and sawing technology considered.
  - **Section B.4.2** Sample of the variability in the potential for RWH in a Mediterranean climate geography according to variability in rainwater tank sizing depending on the rainwater catchment surface and sawing technology considered.

Section A. Life cycle inventory analysis and environmental impact assessment

Section A.1 Basic technical specifications of the sawing technologies under assessment

Technical Characteristic	MBGS 180	DMWS 35	DMWS 100
Cutting dimensions (width x length x height)	5300 mm x 3500 mm x 2100 mm	1000 mm x 3500 mm x 2200 mm	2800 mm x 3700 mm x 2200 mm
Number and dimension of cutting tools (width x length x height)	180 steel blades 5 mm x 4440 mm x 100 mm	35 diamond wires Ø 7.2 mm x 27650 mm	100 diamond wires Ø 7.2 mm x 28500 mm
Abrasive mixture	Steel grit/lime/granite fines	Not required	Not required
Kerf width	7 mm	7.2 mm	7.2 mm
Lowering speed	32 mm h^{-1}	250 mm h^{-1}	250 mm h^{-1}
Total installed power	163 kW	142 kW	300 kW
Working power	85%	85%	85%
Cooling water flow	800 l h^{-1} (+ 130 l h^{-1} for the addition of abrasive mixture)	14000 l h^{-1}	40000 l h^{-1}

Table II.1 Technical specifications of the sawing technologies under assessment. Acronyms: MBGS 180 - multi-blade gangsaw with 180 steel blades; DMWS 35 - diamond multi-wire saw with 35 wires; DMWS 100 - diamond multi-wire saw with 100 wires.

Section A.2 Data collection and quality

The industrial activity of two granite processing facilities in the O Porriño area in Pontevedra (Galicia), which is Spain's major granite-producing region, are analyzed as part of this study. One processing facility bases granite slab production on the use of multi-blade gangsaw technology, whereas the second is based fully on employing diamond multi-wire saws.

The technical specifications required to determine the inputs (energy, water and materials) and outputs (wastes) according to the net productivity (granite slabs) of each sawing technology were acquired though the distribution of data collection surveys to processing facilities in the study area. Along with technical data, the processors provided complementary information regarding the inputs and outputs according to the annual production volume of each sawing technology, which corresponds to over 112,760 m^2 by the MBGS 180 and 100,000 sawn m^2 by the DMWS 35 and DMWS 100 each. The collected data refer to the industrial activity for 2010, which coincides with the last updated outcomes from energy audit reports and complete industrial and economical balances conducted by the processing facilities. The type of granite processed is the so-called "Rosa Porriño," which is one of the predominant types of internationally traded granite (CBI, 2010) and has a density of approximately 2,700 kg m^{-3}. The data provided by granite processors serve as a basis for checking, completing and validating the LCI results. The LCI dataset can therefore be used to characterize the environmental performance of granite sawing technologies and products in a representative manner.

Section A.3 Data calculation procedure

The cutting dimensions of each sawing technology (section A.1) define its loading capacity. In this way, it is very important to achieve an optimum loading coefficient to ensure maximum productivity per downward motion (defined in particular by the cutting width). It has been considered that sawing machines are loaded with granite blocks of optimal width, whereas their length and height remain fixed. The granite blocks produced in quarries from the geographical area under study are typically 3 m long x 1.7 m high. The MBGS 180 is therefore loaded with a cargo equivalent to three 1.7-m-wide granite blocks, which corresponds to a total volume of 26 m^3 (8.67 m^3 $block^{-1}$). The DMWS 35 and DMWS 100 are loaded with only one granite block each that measures 2 m and 2.8

m wide, corresponding to a cargo of 10.2 m^3 and 14.3 m^3, respectively. In this way, only one downward motion is required by the MBGS 180 and DMWS 100, whereas the DMWS 35 requires two downward motions to fully process its cargo. Sawing granite blocks into slabs requires 53.1 hours using the MBGS 180, 13.6 hours using the DMWS 35 and 6.8 hours using the DMWS 100. The significantly different lowering speeds between sawing technologies are essentially determined by the performance of the cutting tools applied. In DMWS technologies the stone-cutting action is carried out directly through the friction generated by the synthetic diamond present in the wire beads, offering significantly faster lowering speeds compared to the steel blades in gangsaw technology. Steel blades are considered to last for 3 sawing stages, which corresponds to a service life (or productivity) of 3-4 m^2 per line meter, while diamond wires have a service life of 9-10 m^2 m^{-1}. The width of the kerfs generated by the cutting tools determines resource efficiency. In the case of the MBGS 180, the width of the kerfs generated by steel blades increases by 2 mm due to the effect of the steel grit required for production. The net production volume of granite slabs is calculated by considering that 4-5 cm of the granite blocks' longitudinal faces are not useful in production due to the presence of lumps, formed by the squaring process used on such blocks in quarries. These pieces become granite scrap. The granite slabs produced by each sawing technology, although variable in number (pieces), have the same dimensions (1.7 m wide x 3 m long x 0.02 m thick), making the results directly comparable on a square meter basis.

Section A.4 Complete LCI dataset per sawn block by MBGS and DMWS technologies.

INPUT		MBGS 180	DMWS 35	DMWS 100
Energy	Electricity – *low voltage* (kWh)	2.45E+03	1.64E+03	1.73E+03
	Diesel (MJ)	1.02E+02	1.19E+02	1.65E+02
Water	Water (kg)	4.43E+03	2.86E+04	4.08E+04
Materials	Steel (kg)	3.92E+02	1.21E+01	1.71E+01
	Steel grit (kg)	5.40E+02	0.00E+00	0.00E+00
	Hydrated lime (kg)	2.78E+02	0.00E+00	0.00E+00
	Coagulants & Flocculants (kg)	2.86E+00	1.21E+00	1.74E+00
	Oil & Grease (kg)	3.52E+00	5.94E+00	8.50E+00
	CO_2 (kg)	2.49E+01	0.00E+00	0.00E+00
Granite	Granite gross (kg)	2.34E+04	2.75E+04	3.86E+04

OUTPUT		MBGS 180	DMWS 35	DMWS 100
Granite	**Granite slabs (total kg/total m^2)**	1.65E+04	1.92E+04	2.75E+04
	Granite scrap (kg): *by-product*	2.89E+02	3.46E+02	4.96E+02
	Granite sawdust (kg) – *emitted to air*	1.10E+03	1.38E+03	1.10E+03
	Granite sludge (kg) – *granite waste*	1.02E+04	1.09E+04	1.55E+04
Water	Water to air (kg) – *evaporated*	6.64E+02	2.43E+04	3.47E+04
Other wastes	Steel scrap (kg)	2.48E+02	1.21E+01	1.71E+01
	Residual oil (kg)	1.99E+00	3.56E+00	5.10E+00

Table II.2 LCI dataset per sawn block by MBGS and DMWS technologies.

Section A.5 Environmental performance of granite production

Section A.5.1 Considerations for life cycle environmental impact assessment

LCI results and considerations provided by Mendoza et al. (2014a) are used as reference to characterize the environmental impacts of the entire granite production chain. LCI data is disaggregated into the unit processes of granite quarrying, granite sawing (based on a conventional gangsaw technology mix), granite finishing (polishing) and granite cutting. Inputs and outputs are allocated to each unit process according to the net production volume of finished granite tiles per quarried and processed granite block.

LCI results related to granite slabs production by MBGS 180, DMWS 35 and DMWS 100 technologies (Table 6.1 from chapter 6) are use to determine the potential for environmental improvement to the sawing unit process, and consequently at the processing stage level and over the entire granite production chain, by promoting the optimization of the sawing technology (Fig. II.1).

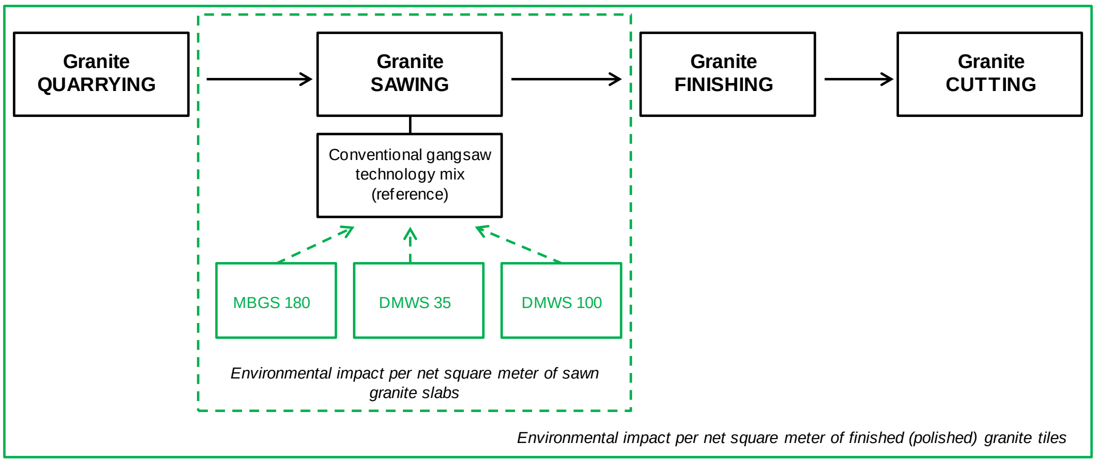


Fig. II.1 Diagram of the life cycle environmental impact assessment of granite production.

The environmental footprint indicators defined by the European Recommendation (European Commission, 2013e) to measure and communicate the life cycle environmental performance of products and organizations are used as reference. The list of environmental indicators is completed with the integration of two LCI indicators: primary energy demand (embodied energy) and total freshwater consumption (embodied water). The software GaBi 6 (PE International, 2013) and the ecoinvent v2.2 database (SCLCI, 2010) are used as supporting analytical tools.

The environmental impact assessment excludes waste management. Only the transportation of wastes to recycling facilities and/or final disposal to landfill is considered in calculations. Granite sludge is the only waste which is disposed to landfill. Steel scrap, waste wood and residual oil are sent to recycling facilities to be used as inputs for the production of new products. In this way, the expenditure for the recycling of wastes is considered to be allocated to the new product systems. Regarding the environmental impact of granite sludge disposal to landfill, ecoinvent 2.2 database do not integrates any process related to granite sludge management. We based on scientific literature review to assume that granite sludge does not constitute a significant hazard to the environment due to its inert nature. Chapter 6 integrates a specific section (section 6.3.3) where this issue is briefly discussed.

Regarding transportation operations related to granite production, a local market perspective has been applied according to the information provided by industrial producers. Table II.3 describes transportation distances and type of truck for each of the inputs and outputs of the granite production chain.

Elements	Distances	Truck
Material inputs	50 km (from industry to quarry/processing facility)	lorry >28t
diesel inputs	15 km (to quarry)	lorry >28t
	10 km (to processing facility)	lorry >28t
Granite block	20 km (from quarry to processing facility)	lorry >28t
Wastes	20 km (from quarry/processing facility to recycling facilities/final disposal to landfill)	lorry >28t

Table II.3 Description of transportation operations related to the granite production chain

Section A.5.2 List of ecoinvent processes selected to determine the environmental impact of granite production

Section A.5.2.1 ecoinvent processes selected to determine the environmental impacts of the different unit processes related to granite production from cradle-to-gate

Unit process	Input flows	ecoinvent processes
Granite quarrying	Energy	Low-voltage electricity (ES 2013)
		GLO: diesel, burned in building machine
	Water	RER: tap water, at user (adapted according to surface and groundwater inputs)
	Materials	CH: explosives, tovex, at plant
		RER: penta-erythritol, at plant
		RER: polyvinylchloride, at regional storage
		RER: steel, converter, chromium steel 18/8, at plant
		RER: steel, converter, unalloyed, at plant
		RER: synthetic rubber, at plant
		RER: lubricating oil, at plant
Granite sawing	Energy	Low-voltage electricity (ES 2013)
		GLO: diesel, burned in building machine
	Water	RER: tap water, at user (adapted according to groundwater and tap water inputs)
	Materials	RER: steel, converter, unalloyed, at plant

		RER: steel, converter, chromium steel 18/8, at plant
		RER: milling, steel, small parts
		CH: iron (III) chloride, 40% in H2O, at plant
		RER: aluminium sulphate, powder, at plant
		RER: iron sulphate, at plant
		RER: sodium hydroxide, 50% in H2O, production mix, at plant
		RER: carbon dioxide liquid, at plant
		RER: lubricating oil, at plant
Granite finishing (polishing)	Energy	Low-voltage electricity (ES 2013)
		GLO: diesel, burned in building machine
	Water	RER: tap water, at user (adapted according to groundwater and tap water inputs)
	Materials	RER: silicon carbide, at plant
		RER: polyester resin, unsaturated, at plant
		CH: iron (III) chloride, 40% in H2O, at plant
		RER: aluminium sulphate, powder, at plant
		RER: iron sulphate, at plant
		RER: sodium hydroxide, 50% in H2O, production mix, at plant
		RER: sawn timber, hardwood, raw, air dried, u=20%, at plant
		RER: lubricating oil, at plant
Granite cutting	Energy	Low-voltage electricity (ES 2013)
		GLO: diesel, burned in building machine
	Water	RER: tap water, at user (adapted according to groundwater and tap water inputs)
	Materials	RER: steel, converter, chromium steel 18/8, at plant
		RER: steel, converter, low-alloyed, at plant
		RER: sawn timber, softwood, raw, air dried, u=20%, at plant
		RER: lubricating oil, at plant
Transport operations		RER: transport, lorry 16-32t, EURO4

Table II.4 List of ecoinvent processes selected for environmental impact calculations

Section A.5.2.2. Electricity mix considered for the characterization of the environmental impact related to low-voltage electricity consumption

The environmental burden of the electricity consumption depends on the national electricity mix. The more fossil fuel-intensive the electricity mix is, the higher the environmental impact of electricity consumption will be. The Spanish electricity mix for 2013 (REE, 2013) has been used as reference in environmental impact calculations.

ecoinvent processes	Amount
Electricity, hard coal, at power plant/ES U	0.459 MJ
Electricity, lignite, at power plant/ES U	0.025 MJ
Electricity, oil, at power plant/ES U	0.033 MJ
Electricity, natural gas, at combined cycle plant, best technology/RER U	0.311 MJ
Electricity, industrial gas, at power plant/ES U	0.022 MJ
Electricity, hydropower, at power plant/ES U	0.503 MJ
Electricity, hydropower, at pumped storage power plant/ES U	0.101 MJ
Electricity, nuclear, at power plant/UCTE U	0.788 MJ
Electricity, production mix photovoltaic, at plant/ES U	0.188 MJ
Electricity, at wind power plant/RER U	0.715 MJ
Electricity, at cogen ORC 1400kWth, wood, allocation exergy/CH U	0.055 MJ
Electricity, at cogen with biogas engine, allocation exergy/CH U	0.014 MJ
Electricity, at cogen 500kWe lean burn, allocation exergy/CH U	0.366 MJ
Electricity from waste, at municipal waste incineration plant/CH U	0.020 MJ

Table II.5 Electricity mix and related ecoinvent processes considered to determine the environmental impact of low-voltage electricity consumption for granite production

Section A.5.3 Environmental impacts per square meter of granite slab production for each sawing technology.

Section A.5.3.1 Environmental impacts per square meter of granite slab production for a conventional gangsaw technology mix (the reference sawing technology).

Env. Ind.	**Gangsaw technology mix**										**Transportation operations**						**TOTAL IMPACT**
	Electricity	Diesel	Cooling water	Steel blades	Steel grit	Hydrated lime	Coag. & Flocc.	Liquid CO_2	Lubricating oil	**TOTAL**	Material inputs	Diesel inputs	Granite scrap	Granite sludge	Other wastes	TOTAL	
A	3.51E-02	3.26E-04	4.02E-05	8.88E-03	3.74E-02	7.50E-04	4.72E-05	1.93E-04	1.25E-04	*8.28E-02*	1.74E-04	6.56E-08	3.09E-05	5.74E-04	1.40E-05	*7.93E-04*	**8.36E-02**
EAFW	2.82E+01	2.31E-02	5.64E-02	1.35E+01	1.72E+02	1.06E-01	8.71E-02	3.21E-01	5.78E-02	*2.15E+02*	1.16E-01	4.38E-05	2.06E-02	3.83E-01	9.36E-03	*5.30E-01*	**2.15E+02**
FWE	1.70E-03	1.50E-06	4.64E-06	1.25E-03	5.34E-03	8.81E-06	6.20E-06	2.46E-05	4.42E-06	*8.34E-03*	3.02E-06	1.14E-09	5.36E-07	9.95E-06	2.43E-07	*1.38E-05*	**8.36E-03**
HTc	3.19E-07	9.08E-10	1.12E-09	5.57E-07	3.25E-06	1.85E-09	1.01E-09	2.78E-09	7.30E-10	*4.13E-06*	1.88E-09	7.06E-13	3.33E-10	6.18E-09	1.51E-10	*8.54E-09*	**4.14E-06**
HTn-c	1.50E-06	1.58E-09	3.10E-09	5.02E-07	5.05E-06	7.31E-09	7.03E-09	1.54E-08	3.35E-09	*7.09E-06*	1.36E-08	5.12E-12	2.41E-09	4.48E-08	1.09E-09	*6.20E-08*	**7.15E-06**
IR	2.56E+03	5.77E-01	2.96E+00	1.07E+02	1.92E+03	2.01E+01	2.58E+00	1.05E+01	1.91E+00	*4.63E+03*	2.07E+00	7.79E-04	3.67E-01	6.82E+00	1.66E-01	*9.42E+00*	**4.63E+03**
GW	4.09E+00	3.05E-02	7.15E-03	2.06E+00	8.13E+00	6.84E-01	6.02E-03	6.63E-02	1.21E-02	*1.51E+01*	3.35E-02	1.26E-05	5.95E-03	1.11E-01	2.70E-03	*1.53E-01*	**1.52E+01**
ME	8.04E-04	1.45E-05	1.65E-06	3.82E-04	3.77E-03	2.07E-05	2.04E-06	1.17E-05	2.44E-06	*5.01E-03*	7.45E-06	2.81E-09	1.32E-06	2.46E-05	6.00E-07	*3.40E-05*	**5.04E-03**
OD	3.11E-07	3.80E-09	4.00E-10	4.42E-08	4.63E-07	4.77E-08	6.69E-09	4.36E-09	7.46E-09	*8.89E-07*	5.31E-09	2.00E-12	9.42E-10	1.75E-08	4.27E-10	*2.42E-08*	**9.13E-07**
RI	3.33E-03	4.19E-05	4.97E-06	5.71E-01	8.71E-03	1.07E-04	4.99E-06	1.98E-05	9.39E-06	*5.83E-01*	1.38E-05	5.19E-09	2.45E-06	4.54E-05	1.11E-06	*6.28E-05*	**5.84E-01**
POF	1.46E-02	4.21E-04	2.10E-05	6.89E-03	2.13E-02	8.74E-04	1.69E-05	9.31E-05	1.78E-04	*4.44E-02*	2.10E-04	7.93E-08	3.74E-05	6.94E-04	1.69E-05	*9.59E-04*	**4.54E-02**
RD	2.05E-04	1.52E-07	1.03E-07	6.16E-05	4.75E-04	4.17E-07	2.80E-07	8.47E-07	3.14E-07	*7.43E-04*	9.45E-07	3.56E-10	1.68E-07	3.12E-06	7.60E-08	*4.30E-06*	**7.48E-04**
TE	5.09E-02	1.53E-03	6.94E-05	1.94E-02	7.32E-02	1.96E-03	5.82E-05	2.91E-04	1.44E-04	*1.48E-01*	7.36E-04	2.77E-07	1.31E-04	2.43E-03	5.92E-05	*3.35E-03*	**1.51E-01**
WD	3.22E+00	1.66E-03	2.95E+00	4.00E-01	1.41E+01	8.09E-02	4.87E-03	1.64E-02	4.21E-03	*2.08E+01*	4.01E-03	1.51E-06	7.11E-04	1.32E-02	3.22E-04	*1.82E-02*	**2.08E+01**
PED	1.13E+02	4.33E-01	1.39E-01	2.86E+01	1.29E+02	3.81E+00	1.17E-01	8.35E-01	8.66E-01	*2.78E+02*	5.29E-01	1.99E-04	9.39E-02	1.74E+00	4.26E-02	*2.41E+00*	**2.80E+02**
TFWC	3.32E+01	1.71E-02	3.04E+01	4.13E+00	1.46E+02	8.34E-01	5.02E-02	1.69E-01	4.34E-02	*2.15E+02*	4.13E-02	1.55E-05	7.33E-03	1.36E-01	3.32E-03	*1.88E-01*	**2.15E+02**

Table II.6 Relative contribution to environmental impacts by the energy, water and material inputs, including transportation operations, per square meter of granite slabs produced by a conventional gangsaw technology mix.

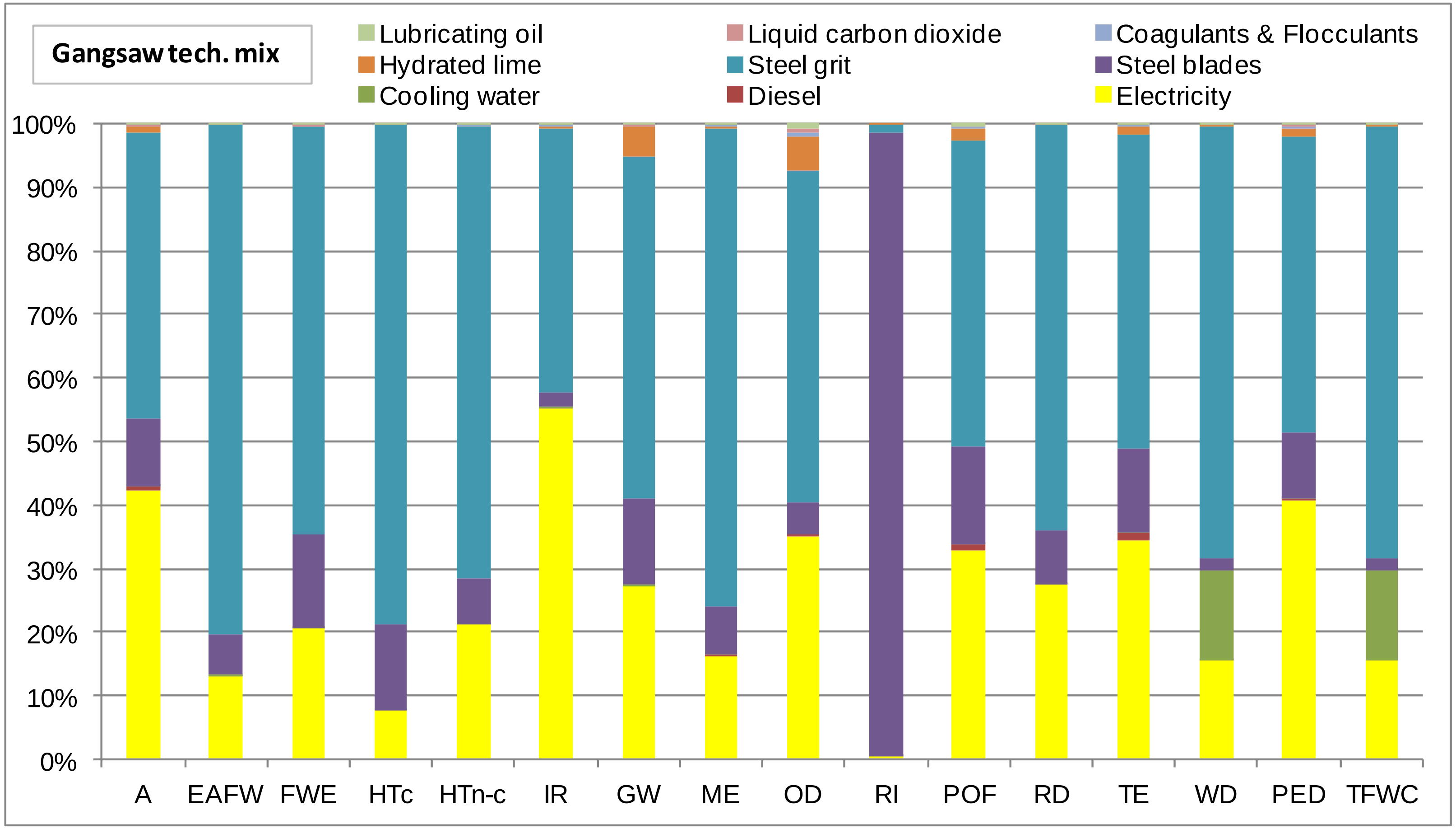


Fig. II.2 Relative contribution to environmental impacts by the energy, water and material inputs per square meter of granite slabs produced by a conventional gangsaw technology mix.

Section A.5.3.2 Environmental impacts per square meter of granite slab production for MBGS 180.

Env. Ind.	MBGS 180										Transportation operations						TOTAL IMPACT
	Electricity	Diesel	Cooling water	Steel blades	Steel grit	Hydrated lime	Coag. & Flocc.	Liquid CO_2	Lubricating oil	**TOTAL**	Material inputs	Diesel inputs	Granite scrap	Granite sludge	Other wastes	TOTAL	
A	2.43E-02	3.26E-04	2.16E-05	8.88E-03	3.74E-02	7.50E-04	4.72E-05	1.93E-04	1.22E-04	*7.20E-02*	1.74E-04	6.56E-08	3.09E-05	5.75E-04	1.40E-05	*7.94E-04*	**7.28E-02**
EAFW	1.96E+01	2.31E-02	3.03E-02	1.35E+01	1.72E+02	1.06E-01	8.71E-02	3.21E-01	5.67E-02	*2.06E+02*	1.16E-01	4.38E-05	2.06E-02	3.84E-01	9.36E-03	*5.30E-01*	**2.07E+02**
FWE	1.18E-03	1.50E-06	2.50E-06	1.25E-03	5.34E-03	8.81E-06	6.20E-06	2.46E-05	4.33E-06	*7.82E-03*	3.02E-06	1.14E-09	5.36E-07	9.97E-06	2.43E-07	*1.38E-05*	**7.83E-03**
HTc	2.21E-07	9.08E-10	6.04E-10	5.57E-07	3.25E-06	1.85E-09	1.01E-09	2.78E-09	7.16E-10	*4.03E-06*	1.88E-09	7.06E-13	3.33E-10	6.19E-09	1.51E-10	*8.55E-09*	**4.04E-06**
HTn-c	1.04E-06	1.58E-09	1.67E-09	5.02E-07	5.05E-06	7.31E-09	7.03E-09	1.54E-08	3.29E-09	*6.63E-06*	1.36E-08	5.12E-12	2.41E-09	4.49E-08	1.09E-09	*6.20E-08*	**6.69E-06**
IR	1.77E+03	5.77E-01	1.60E+00	1.07E+02	1.92E+03	2.01E+01	2.58E+00	1.05E+01	1.88E+00	*3.84E+03*	2.07E+00	7.79E-04	3.67E-01	6.83E+00	1.66E-01	*9.43E+00*	**3.85E+03**
GW	2.83E+00	3.05E-02	3.85E-03	2.06E+00	8.13E+00	6.84E-01	6.02E-03	6.63E-02	1.18E-02	*1.38E+01*	3.35E-02	1.26E-05	5.95E-03	1.11E-01	2.70E-03	*1.53E-01*	**1.40E+01**
ME	5.57E-04	1.45E-05	8.87E-07	3.82E-04	3.77E-03	2.07E-05	2.04E-06	1.17E-05	2.39E-06	*4.76E-03*	7.45E-06	2.81E-09	1.32E-06	2.46E-05	6.00E-07	*3.40E-05*	**4.79E-03**
OD	2.16E-07	3.80E-09	2.15E-10	4.42E-08	4.63E-07	4.77E-08	6.69E-09	4.36E-09	7.31E-09	*7.93E-07*	5.31E-09	2.00E-12	9.42E-10	1.75E-08	4.27E-10	*2.42E-08*	**8.17E-07**
RI	2.31E-03	4.19E-05	2.68E-06	5.71E-01	8.71E-03	1.07E-04	4.99E-06	1.98E-05	9.21E-06	*5.82E-01*	1.38E-05	5.19E-09	2.45E-06	4.55E-05	1.11E-06	*6.28E-05*	**5.83E-01**
POF	1.01E-02	4.21E-04	1.13E-05	6.89E-03	2.13E-02	8.74E-04	1.69E-05	9.31E-05	1.74E-04	*3.99E-02*	2.10E-04	7.93E-08	3.74E-05	6.95E-04	1.69E-05	*9.60E-04*	**4.09E-02**
RD	1.42E-04	1.52E-07	5.55E-08	6.16E-05	4.75E-04	4.17E-07	2.80E-07	8.47E-07	3.07E-07	*6.81E-04*	9.45E-07	3.56E-10	1.68E-07	3.12E-06	7.60E-08	*4.31E-06*	**6.85E-04**
TE	3.53E-02	1.53E-03	3.74E-05	1.94E-02	7.32E-02	1.96E-03	5.82E-05	2.91E-04	1.41E-04	*1.32E-01*	7.36E-04	2.77E-07	1.31E-04	2.43E-03	5.92E-05	*3.36E-03*	**1.35E-01**
WD	2.23E+00	1.66E-03	1.59E+00	4.00E-01	1.41E+01	8.09E-02	4.87E-03	1.64E-02	4.12E-03	*1.85E+01*	4.01E-03	1.51E-06	7.11E-04	1.32E-02	3.22E-04	*1.83E-02*	**1.85E+01**
PED	7.86E+01	4.33E-01	7.48E-02	2.86E+01	1.29E+02	3.81E+00	1.17E-01	8.35E-01	8.49E-01	*2.43E+02*	5.29E-01	1.99E-04	9.39E-02	1.75E+00	4.26E-02	*2.41E+00*	**2.45E+02**
TFWC	2.30E+01	1.71E-02	1.64E+01	4.13E+00	1.46E+02	8.34E-01	5.02E-02	1.69E-01	4.25E-02	*1.90E+02*	4.13E-02	1.55E-05	7.33E-03	1.36E-01	3.32E-03	*1.88E-01*	**1.90E+02**

Table II.7 Relative contribution to environmental impacts by the energy, water and material inputs, including transportation operations, per square meter of granite slabs produced by MBGS 180.

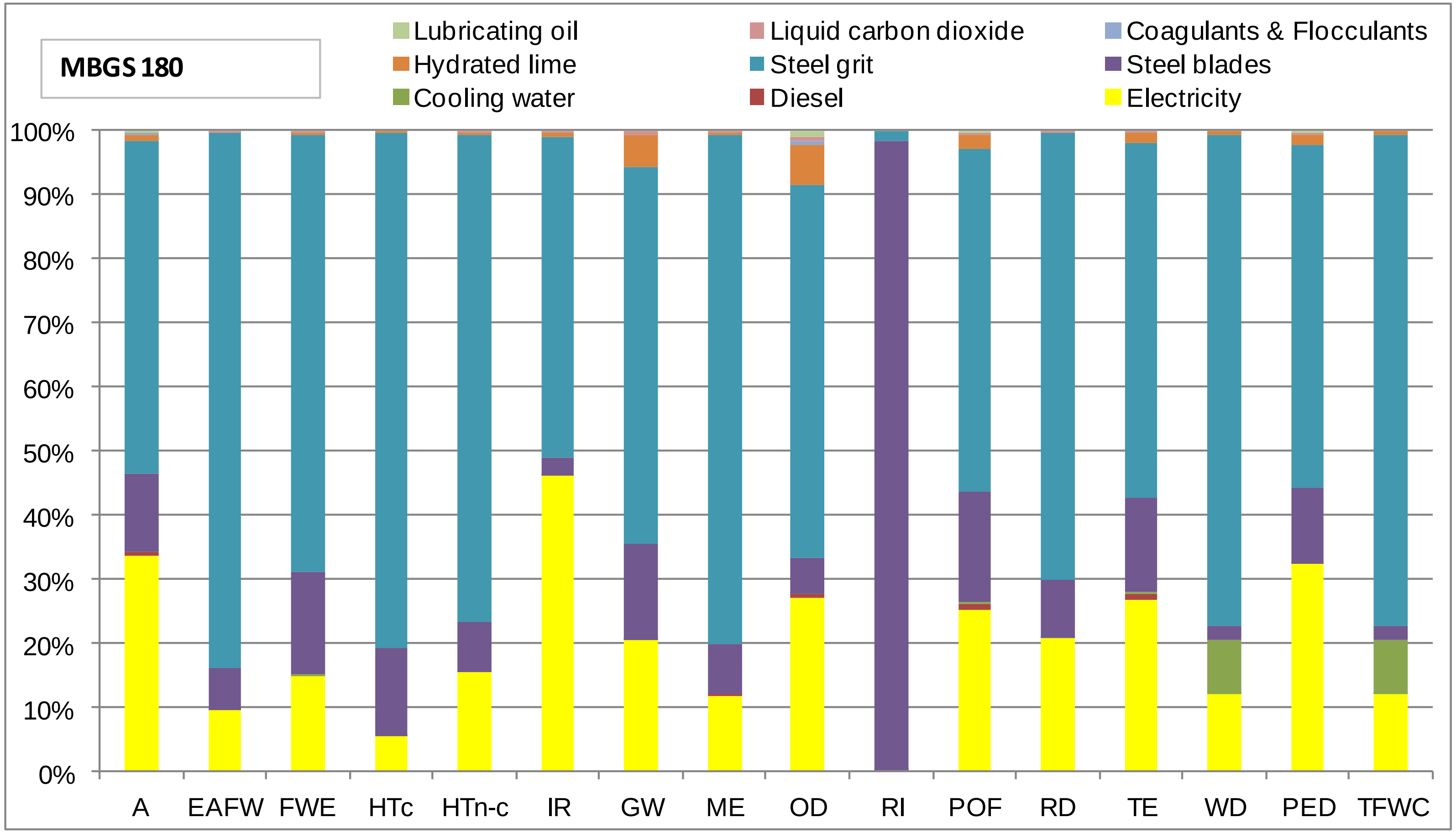


Fig. II.3 Relative contribution to environmental impacts by the energy, water and material inputs per square meter of granite slabs produced by MBGS 180.

Section A.5.3.3 Environmental impacts per square meter of granite slab production for DMWS 35.

Env. Ind.	**DMWS 35**							**Transportation operations**						**TOTAL IMPACT**
	Electricity	Diesel	Cooling water	Steel wires	Flocc.	Lubricating oil	TOTAL	Material inputs	Diesel inputs	Granite scrap	Granite sludge	Other wastes	TOTAL	
A	1.40E-02	3.27E-04	1.20E-04	9.47E-04	4.02E-06	1.80E-04	*1.56E-02*	2.32E-06	6.59E-08	3.32E-05	5.24E-04	7.54E-07	*5.60E-04*	**1.61E-02**
EAFW	1.12E+01	2.32E-02	1.68E-01	2.66E+00	1.11E-02	8.37E-02	*1.42E+01*	1.55E-03	4.40E-05	2.22E-02	3.50E-01	5.04E-04	*3.74E-01*	**1.46E+01**
FWE	6.78E-04	1.50E-06	1.38E-05	7.36E-05	7.50E-07	6.39E-06	*7.74E-04*	4.02E-08	1.14E-09	5.75E-07	9.08E-06	1.31E-08	*9.70E-06*	**7.84E-04**
HTc	1.27E-07	9.12E-10	3.35E-09	3.48E-08	8.70E-11	1.06E-09	*1.67E-07*	2.50E-11	7.09E-13	3.57E-10	5.64E-09	8.12E-12	*6.03E-09*	**1.73E-07**
HTn-c	5.97E-07	1.59E-09	9.26E-09	8.56E-08	5.87E-10	4.85E-09	*6.99E-07*	1.81E-10	5.14E-12	2.59E-09	4.09E-08	5.89E-11	*4.37E-08*	**7.42E-07**
IR	1.02E+03	5.80E-01	8.84E+00	1.81E+01	2.96E-01	2.77E+00	*1.05E+03*	2.75E-02	7.82E-04	3.94E-01	6.22E+00	8.96E-03	*6.65E+00*	**1.06E+03**
GW	1.63E+00	3.06E-02	2.13E-02	1.51E-01	6.61E-04	1.75E-02	*1.85E+00*	4.46E-04	1.27E-05	6.39E-03	1.01E-01	1.45E-04	*1.08E-01*	**1.96E+00**
ME	3.20E-04	1.45E-05	4.92E-06	3.10E-05	1.98E-07	3.52E-06	*3.74E-04*	9.92E-08	2.82E-09	1.42E-06	2.24E-05	3.23E-08	*2.40E-05*	**3.98E-04**
OD	1.24E-07	3.81E-09	1.19E-09	7.07E-09	3.68E-11	1.08E-08	*1.47E-07*	7.06E-11	2.01E-12	1.01E-09	1.60E-08	2.30E-11	*1.71E-08*	**1.64E-07**
RI	1.33E-03	4.21E-05	1.48E-05	5.84E-01	4.78E-07	1.36E-05	*5.85E-01*	1.83E-07	5.21E-09	2.63E-06	4.14E-05	5.97E-08	*4.43E-05*	**5.85E-01**
POF	5.81E-03	4.23E-04	6.27E-05	5.09E-04	1.63E-06	2.57E-04	*7.06E-03*	2.80E-06	7.96E-08	4.01E-05	6.33E-04	9.12E-07	*6.77E-04*	**7.74E-03**
RD	8.14E-05	1.53E-07	3.07E-07	7.97E-05	3.33E-08	4.54E-07	*1.62E-04*	1.26E-08	3.57E-10	1.80E-07	2.84E-06	4.09E-09	*3.04E-06*	**1.65E-04**
TE	2.03E-02	1.54E-03	2.07E-04	1.69E-03	5.71E-06	2.09E-04	*2.39E-02*	9.79E-06	2.78E-07	1.40E-04	2.21E-03	3.19E-06	*2.37E-03*	**2.63E-02**
WD	1.28E+00	1.67E-03	8.79E+00	4.94E-02	4.67E-04	6.09E-03	*1.01E+01*	5.33E-05	1.52E-06	7.63E-04	1.20E-02	1.73E-05	*1.29E-02*	**1.01E+01**
PED	4.52E+01	4.35E-01	4.14E-01	2.38E+00	1.31E-02	1.25E+00	*4.97E+01*	7.04E-03	2.00E-04	1.01E-01	1.59E+00	2.29E-03	*1.70E+00*	**5.14E+01**
TFWC	1.32E+01	1.72E-02	9.07E+01	5.09E-01	4.81E-03	6.28E-02	*1.04E+02*	5.50E-04	1.56E-05	7.87E-03	1.24E-01	1.79E-04	*1.33E-01*	**1.05E+02**

Table II.8 Relative contribution to environmental impacts by the energy, water and material inputs, including transportation operations, per square meter of granite slabs produced by DMWS 35.

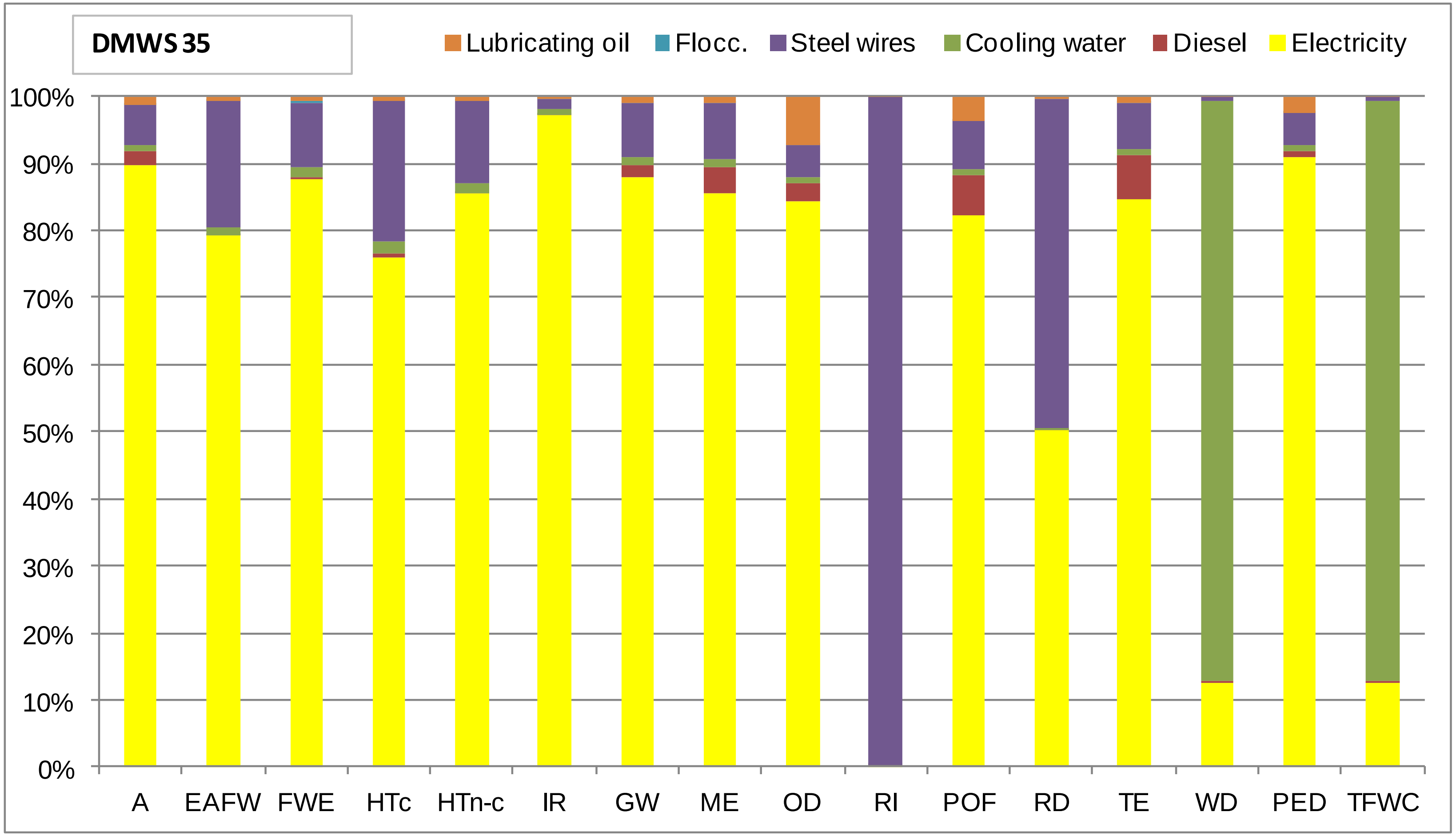


Fig. II.4 Relative contribution to environmental impacts by the energy, water and material inputs per square meter of granite slabs produced by DMWS 35.

Section A.5.3.4 Environmental impacts per square meter of granite slab production for DMWS 100.

Env. Ind.	DMWS 100							Transportation operations						TOTAL IMPACT
	Electricity	Diesel	Cooling water	Steel wires	Flocc.	Lubricating oil	TOTAL	Material inputs	Diesel inputs	Granite scrap	Granite sludge	Other wastes	TOTAL	
A	1.03E-02	3.18E-04	1.20E-04	9.45E-04	4.01E-06	1.80E-04	*1.19E-02*	2.30E-06	6.39E-08	1.85E-05	5.23E-04	7.48E-07	*5.45E-04*	**1.24E-02**
EAFW	8.30E+00	2.25E-02	1.68E-01	2.66E+00	1.11E-02	8.35E-02	*1.12E+01*	1.54E-03	4.27E-05	1.24E-02	3.49E-01	5.00E-04	*3.64E-01*	**1.16E+01**
FWE	5.01E-04	1.46E-06	1.38E-05	7.34E-05	7.48E-07	6.38E-06	*5.96E-04*	3.99E-08	1.11E-09	3.21E-07	9.07E-06	1.30E-08	*9.44E-06*	**6.06E-04**
HTc	9.38E-08	8.85E-10	3.34E-09	3.48E-08	8.68E-11	1.05E-09	*1.34E-07*	2.48E-11	6.88E-13	2.00E-10	5.63E-09	8.05E-12	*5.87E-09*	**1.40E-07**
HTn-c	4.40E-07	1.54E-09	9.24E-09	8.54E-08	5.86E-10	4.84E-09	*5.42E-07*	1.80E-10	4.99E-12	1.45E-09	4.09E-08	5.84E-11	*4.25E-08*	**5.85E-07**
IR	7.51E+02	5.63E-01	8.83E+00	1.80E+01	2.95E-01	2.76E+00	*7.82E+02*	2.73E-02	7.59E-04	2.20E-01	6.21E+00	8.88E-03	*6.47E+00*	**7.88E+02**
GW	1.20E+00	2.97E-02	2.13E-02	1.50E-01	6.59E-04	1.75E-02	*1.42E+00*	4.43E-04	1.23E-05	3.57E-03	1.01E-01	1.44E-04	*1.05E-01*	**1.53E+00**
ME	2.36E-04	1.41E-05	4.90E-06	3.09E-05	1.97E-07	3.52E-06	*2.90E-04*	9.86E-08	2.74E-09	7.94E-07	2.24E-05	3.20E-08	*2.33E-05*	**3.13E-04**
OD	9.14E-08	3.70E-09	1.19E-09	7.06E-09	3.67E-11	1.08E-08	*1.14E-07*	7.02E-11	1.95E-12	5.65E-10	1.59E-08	2.28E-11	*1.66E-08*	**1.31E-07**
RI	9.79E-04	4.09E-05	1.48E-05	5.84E-01	4.77E-07	1.36E-05	*5.85E-01*	1.82E-07	5.06E-09	1.47E-06	4.14E-05	5.92E-08	*4.31E-05*	**5.85E-01**
POF	4.28E-03	4.11E-04	6.25E-05	5.08E-04	1.62E-06	2.56E-04	*5.52E-03*	2.78E-06	7.73E-08	2.24E-05	6.32E-04	9.04E-07	*6.59E-04*	**6.18E-03**
RD	6.01E-05	1.49E-07	3.07E-07	7.96E-05	3.32E-08	4.53E-07	*1.41E-04*	1.25E-08	3.47E-10	1.01E-07	2.84E-06	4.06E-09	*2.96E-06*	**1.44E-04**
TE	1.50E-02	1.50E-03	2.07E-04	1.68E-03	5.70E-06	2.08E-04	*1.86E-02*	9.73E-06	2.70E-07	7.84E-05	2.21E-03	3.16E-06	*2.30E-03*	**2.09E-02**
WD	9.47E-01	1.62E-03	8.78E+00	4.93E-02	4.66E-04	6.08E-03	*9.78E+00*	5.30E-05	1.47E-06	4.27E-04	1.20E-02	1.72E-05	*1.25E-02*	**9.79E+00**
PED	3.33E+01	4.23E-01	4.14E-01	2.38E+00	1.30E-02	1.25E+00	*3.78E+01*	7.00E-03	1.94E-04	5.63E-02	1.59E+00	2.27E-03	*1.66E+00*	**3.95E+01**
TFWC	9.77E+00	1.67E-02	9.05E+01	5.08E-01	4.80E-03	6.26E-02	*1.01E+02*	5.46E-04	1.52E-05	4.40E-03	1.24E-01	1.77E-04	*1.29E-01*	**1.01E+02**

Table II.9 Relative contribution to environmental impacts by the energy, water and material inputs, including transportation operations, per square meter of granite slabs produced by DMWS 100.

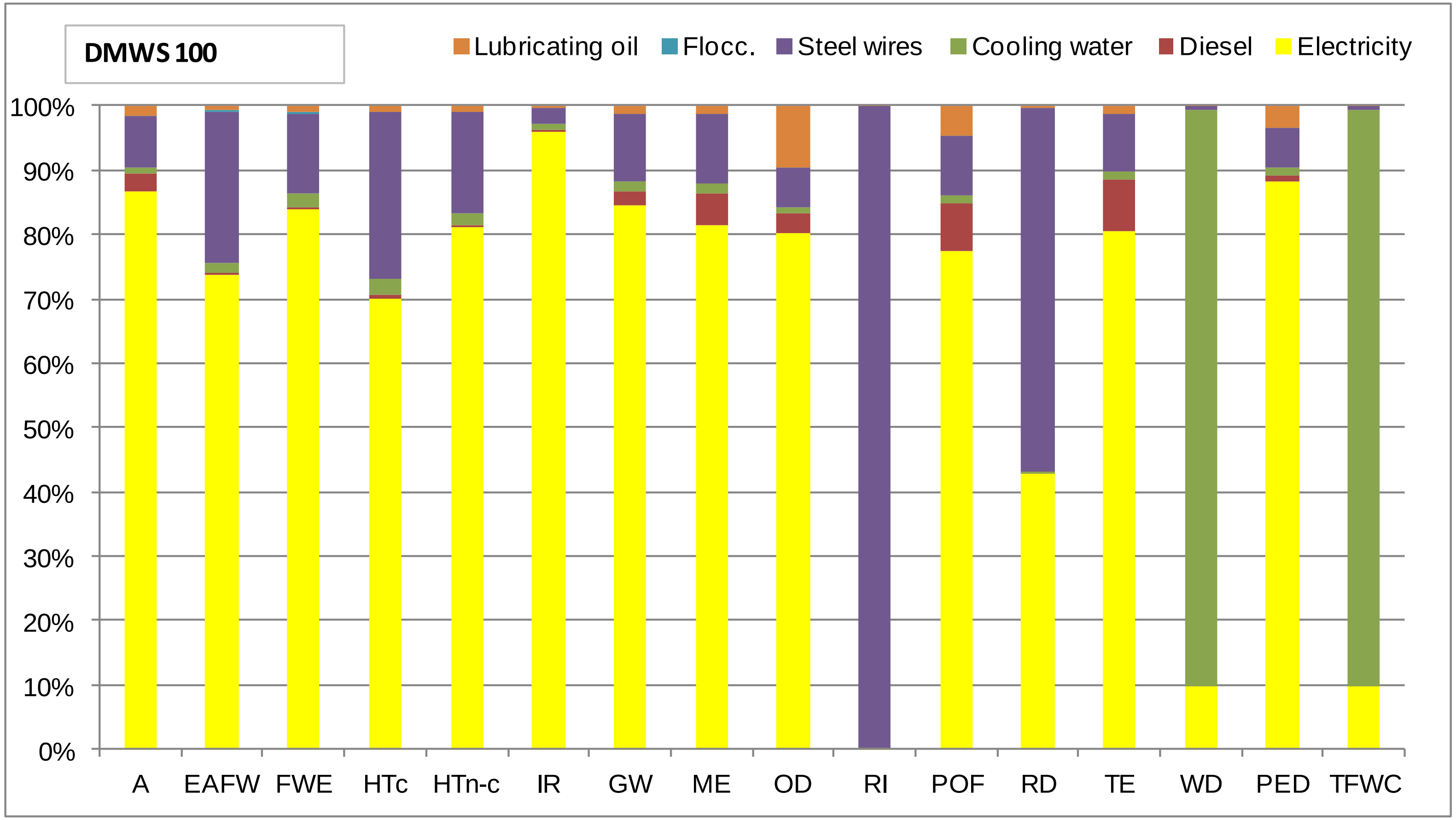


Fig. II.5 Relative contribution to environmental impacts by the energy, water and material inputs per square meter of granite slabs produced by DMWS 100.

Section A.5.4 Environmental performance of the production chain from cradle to gate of one square meter of finished granite tiles with dimensions of 60 cm x 40 cm x 2 cm when using a gangsaw technology mix or the MBGS 180, DMWS 35 and DMWS 100 technologies for granite sawing.

Section A.5.4.1 Environmental impacts related to the production from cradle-to-gate of one square meter of finished granite tiles with dimensions of 60 cm x 40 cm x 2 cm.

Environmental indicators	QUARRYING*	SAWING				POLISHING*	CUTTING*	TOTAL(*)
		GANGSAW TECH. MIX*	Technological alternatives					
			MBGS 180	DMWS 35	DMWS 100			
A	2.84E-02	1.11E-01	9.67E-02	2.14E-02	1.65E-02	1.03E-02	3.48E-02	**1.85E-01**
EAFW	7.08E+00	2.86E+02	2.74E+02	1.93E+01	1.54E+01	7.66E+00	3.95E+01	**3.40E+02**
FWE	3.91E-04	1.11E-02	1.04E-02	1.04E-03	8.05E-04	7.11E-04	1.74E-03	**1.39E-02**
HTc	1.47E-07	5.50E-06	5.37E-06	2.30E-07	1.86E-07	9.65E-08	8.14E-07	**6.56E-06**
HTn-c	4.89E-07	9.50E-06	8.88E-06	9.84E-07	7.76E-07	4.00E-07	1.97E-06	**1.24E-05**
IR	3.59E+02	6.16E+03	5.11E+03	1.40E+03	1.05E+03	6.20E+02	2.29E+03	**9.42E+03**
GW	3.05E+00	2.02E+01	1.86E+01	2.59E+00	2.03E+00	1.43E+00	4.18E+00	**2.89E+01**
ME	1.18E-03	6.69E-03	6.37E-03	5.28E-04	4.16E-04	3.13E-04	8.60E-04	**9.04E-03**
OD	3.69E-07	1.21E-06	1.09E-06	2.17E-07	1.74E-07	1.44E-07	3.20E-07	**2.05E-06**
RI	2.03E+00	7.75E-01	7.74E-01	7.75E-01	7.77E-01	5.49E-02	2.41E-02	**2.88E+00**
POF	3.28E-02	6.03E-02	5.43E-02	1.03E-02	8.21E-03	5.27E-03	1.60E-02	**1.14E-01**
RD	5.19E-05	9.93E-04	9.10E-04	2.19E-04	1.91E-04	3.56E-05	5.01E-04	**1.58E-03**
TE	1.18E-01	2.00E-01	1.80E-01	3.49E-02	2.77E-02	1.65E-02	5.43E-02	**3.89E-01**

WD	3.67E+00	2.77E+01	2.45E+01	1.35E+01	1.30E+01	3.93E+00	4.18E+00	**3.94E+01**
PED	5.09E+01	3.72E+02	3.26E+02	6.81E+01	5.24E+01	4.82E+01	1.17E+02	**5.88E+02**
TFWC	3.78E+01	2.85E+02	2.53E+02	1.39E+02	1.34E+02	4.05E+01	4.30E+01	**4.07E+02**

Table II.10 Environmental impacts of the production from cradle-to-gate of one square meter of finished granite tiles. NOTE: (*) Unit processes considered to define the total environmental impacts per square meter of finished granite tiles

Section A.5.4.2 Potential for environmental improvements to the granite production chain per square meter of finished granite tiles production according to the technological optimization of the unit process of granite sawing.

Environmental indicators	**Life cycle stage**	**Gangsaw tech. mix**	ref.	**MBGS 180**	dif. %	**DMWS 35**	dif. %	**DMWS 100**	dif. %
A	Granite production chain	1.85E-01	-	1.70E-01	-8	9.48E-02	-49	9.00E-02	-51
	Granite processing stage	1.56E-01	-	1.42E-01	-9	6.64E-02	-57	6.16E-02	-61
	Granite sawing	8.36E-02	-	7.28E-02	-13	1.61E-02	-81	1.24E-02	-85
AFWE	Granite production chain	3.40E+02	-	3.29E+02	-3	7.35E+01	-78	6.96E+01	-80
	Granite processing stage	3.33E+02	-	3.21E+02	-3	6.64E+01	-80	6.25E+01	-81
	Granite sawing	2.15E+02	-	2.07E+02	-4	1.46E+01	-93	1.16E+01	-95
FE	Granite production chain	1.39E-02	-	1.32E-02	-5	3.88E-03	-72	3.65E-03	-74
	Granite processing stage	1.36E-02	-	1.29E-02	-5	3.49E-03	-74	3.26E-03	-76
	Granite sawing	8.36E-03	-	7.83E-03	-6	7.84E-04	-91	6.06E-04	-93

HTPc	Granite production chain	6.56E-06	-	6.43E-06	-2	1.29E-06	-80	1.24E-06	-81
	Granite processing stage	6.41E-06	-	6.28E-06	-2	1.14E-06	-82	1.10E-06	-83
	Granite sawing	4.14E-06	-	4.04E-06	-2	1.73E-07	-96	1.40E-07	-97
HTPn-c	Granite production chain	1.24E-05	-	1.17E-05	-5	3.84E-06	-69	3.64E-06	-71
	Granite processing stage	1.19E-05	-	1.13E-05	-5	3.35E-06	-72	3.15E-06	-73
	Granite sawing	7.15E-06	-	6.69E-06	-6	7.42E-07	-90	5.85E-07	-92
IR	Granite production chain	9.42E+03	-	8.38E+03	-11	4.67E+03	-50	4.31E+03	-54
	Granite processing stage	9.06E+03	-	8.02E+03	-12	4.31E+03	-52	3.96E+03	-56
	Granite sawing	4.63E+03	-	3.85E+03	-17	1.06E+03	-77	7.88E+02	-83
GW	Granite production chain	2.89E+01	-	2.72E+01	-6	1.12E+01	-61	1.07E+01	-63
	Granite processing stage	2.58E+01	-	2.42E+01	-6	8.20E+00	-68	7.63E+00	-70
	Granite sawing	1.52E+01	-	1.40E+01	-8	1.96E+00	-87	1.53E+00	-90
ME	Granite production chain	9.04E-03	-	8.72E-03	-4	2.88E-03	-68	2.77E-03	-69
	Granite processing stage	7.87E-03	-	7.54E-03	-4	1.70E-03	-78	1.59E-03	-80
	Granite sawing	5.04E-03	-	4.79E-03	-5	3.98E-04	-92	3.13E-04	-94
OD	Granite production chain	2.05E-06	-	1.92E-06	-6	1.05E-06	-49	1.01E-06	-51
	Granite processing stage	1.68E-06	-	1.55E-06	-8	6.82E-07	-59	6.38E-07	-62
	Granite sawing	9.13E-07	-	8.17E-07	-10	1.64E-07	-82	1.31E-07	-86
RI	Granite production chain	2.88E+00	-	2.88E+00	0	2.88E+00	0	2.88E+00	0
	Granite processing stage	8.54E-01	-	8.53E-01	0	8.54E-01	0	8.56E-01	0

	Granite sawing	5.84E-01	-	5.83E-01	0	5.85E-01	0	5.85E-01	0
POF	Granite production chain	1.14E-01	-	1.08E-01	-5	6.43E-02	-44	6.22E-02	-46
	Granite processing stage	8.15E-02	-	7.56E-02	-7	3.15E-02	-61	2.95E-02	-64
	Granite sawing	4.54E-02	-	4.09E-02	-10	7.74E-03	-83	6.18E-03	-86
RD	Granite production chain	1.58E-03	-	1.50E-03	-5	8.07E-04	-49	7.79E-04	-51
	Granite processing stage	1.53E-03	-	1.45E-03	-5	7.55E-04	-51	7.27E-04	-52
	Granite sawing	7.48E-04	-	6.85E-04	-8	1.65E-04	-78	1.44E-04	-81
TE	Granite production chain	3.89E-01	-	3.68E-01	-5	2.24E-01	-43	2.17E-01	-44
	Granite processing stage	2.71E-01	-	2.50E-01	-8	1.06E-01	-61	9.85E-02	-64
	Granite sawing	1.51E-01	-	1.35E-01	-10	2.63E-02	-83	2.09E-02	-86
WD	Granite production chain	3.94E+01	-	3.63E+01	-8	2.52E+01	-36	2.48E+01	-37
	Granite processing stage	3.58E+01	-	3.26E+01	-9	2.16E+01	-40	2.11E+01	-41
	Granite sawing	2.08E+01	-	1.85E+01	-11	1.01E+01	-51	9.79E+00	-53
PED	Granite production chain	5.88E+02	-	5.41E+02	-8	2.84E+02	-52	2.68E+02	-54
	Granite processing stage	5.37E+02	-	4.91E+02	-9	2.33E+02	-57	2.17E+02	-60
	Granite sawing	2.80E+02	-	2.45E+02	-12	5.14E+01	-82	3.95E+01	-86
TFWC	Granite production chain	4.07E+02	-	3.74E+02	-8	2.60E+02	-36	2.56E+02	-37
	Granite processing stage	3.69E+02	-	3.37E+02	-9	2.22E+02	-40	2.18E+02	-41
	Granite sawing	2.15E+02	-	1.90E+02	-11	1.05E+02	-51	1.01E+02	-53

Table II.11 Potential environmental improvements per square meter of finished granite tiles production by optimizing sawing technology.

Section B. Calculation of the potential for rainwater harvesting for use in granite sawing

Determining factors, variables and criteria considered to characterize the potential for RWH for granite sawing:

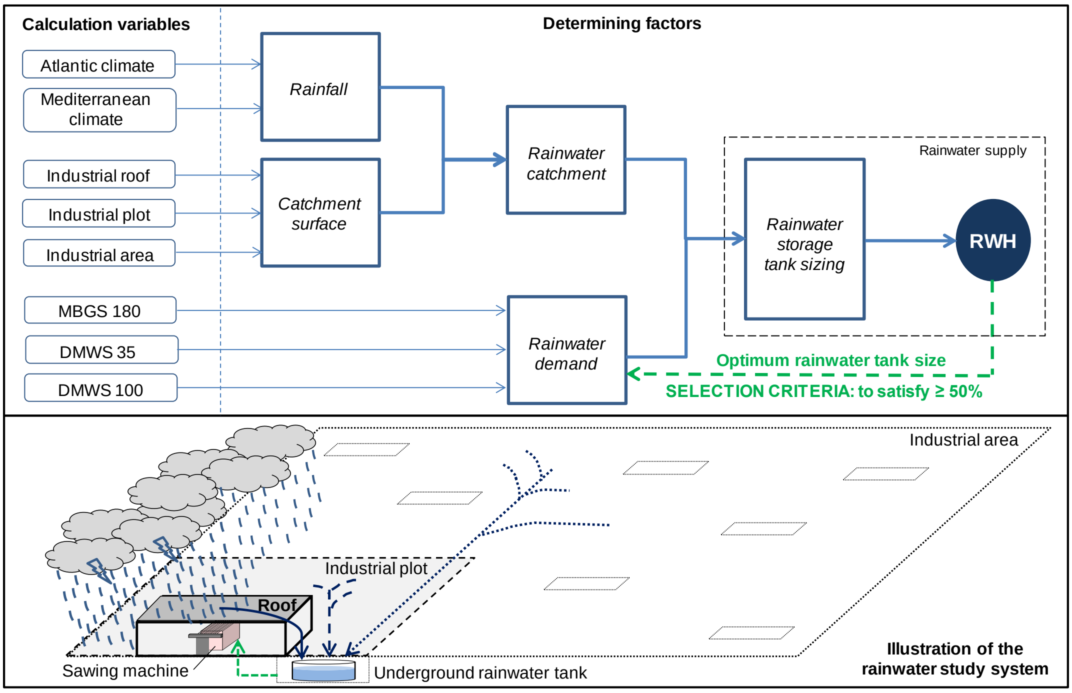


Fig. II.6 Determining factors, variables and criteria considered to characterize the potential for RWH for granite sawing.

Rainfall The first methodological step in modeling the potential for RWH use consists of collecting historical daily rainfall records from the bioclimatic geography of interest. Historical rainfall records are inputs that reproduce past climate conditions, which, under certain assumptions, can be considered representative of future local conditions. In this case study, two different rainfall series are collected and modeled to determine the variability in RWH according to the bioclimatic geography where granite sawing would be addressed. An 11-year rainfall series (2002-2012) from the weather station of Monte Aloia – Tui (meteogalicia, 2013), located close to the industrial area where the processing facilities are located, is used as a representative example of the Atlantic climate (high rainfall). A 20-year rainfall series (1991-2010) from the Barcelona-Fabra weather station (AEMET, 2011) is used as a representative example of the Mediterranean climate (in Barcelona, Spain), which is a low-rainfall scenario.

Catchment surface The catchment surfaces considered correspond to the sawmill roof, below which granite blocks are processed into slabs (≈ 2,000 m^2), the built surface of the industrial plot owned by the processing facilities (≈ 28,500 m^2) and the built surface (i.e., pavements and roofs) of the industrial area (≈ 574,000 m^2) where the processing facilities are located, the so-called A Granxa Industrial Park (http://www.poligonoagranxa.com/). Data related to the sawmill roof and industrial plot surfaces are provided directly by staff from the processing facilities. It is assumed that industrial surfaces are useful for collecting and driving rainwater to storage tanks, and a default constant runoff and filter coefficients of 0.9 are considered. The research does not integrate distribution network requirements or potential water losses.

Rainwater demand by sawing technologies The daily water requirements of the MBGS 180, DMWS 35 and DMWS 100 are considered assuming that 24 h of use per day. An alternative scenario that considers the use of DMWS machines for only one sawing stage per day is also analyzed, given that productivity by the DMWS machines is still competitive compared to MBGS production under this assumption.

Rainwater storage tank sizing The analytical model allows for determining the potential for RWH according to the variability in rainwater storage tank size using a dynamic balance between daily rainwater availability and demand. In this way, the statistically average potential for RWH can be defined.

Rainwater harvesting Overall, 30 scenarios are modeled by combining different calculation variables to determine the optimum rainwater storage tank size. The criteria applied are meant to achieve a rainwater supply equivalent to at least 50% of the daily water requirements of sawing technologies. Harvested rainwater does not require any specific pre-treatment. After filtration, it can be used directly.

Section B.1 General characterization of the Atlantic and Mediterranean rainfall series considered to determine the variability in the RWH potential according to the bioclimatic geography where granite sawing is being addressed.

RAIN	ATLANTIC CLIMATE GEOGRAPHY					MEDITERRANEAN CLIMATE GEOGRAPHY				
Years	Rainfall (L m^{-2} $year^{-1}$)	Rainy days (nº)	Frequency of precipitation (days)	Average rainfall per rainy day (L m^{-2})	Average rainfall per day (L m^{-2})	Rainfall (L m^{-2} $year^{-1}$)	Rainy days (nº)	Frequency of precipitation (days)	Average rainfall per rainy day (L m^{-2})	Average rainfall per day (L m^{-2})
1991	na	na	na	na	na	819.3	84	4.3	9.8	2.2
1992	na	na	na	na	na	595.3	78	4.7	7.6	1.6
1993	na	na	na	na	na	677.6	74	4.9	9.2	1.9
1994	na	na	na	na	na	745.5	67	5.4	11.1	2.0
1995	na	na	na	na	na	483.1	70	5.2	6.9	1.3
1996	na	na	na	na	na	950.3	108	3.4	8.8	2.6
1997	na	na	na	na	na	541.3	77	4.7	7.0	1.5
1998	na	na	na	na	na	485.1	67	5.4	7.2	1.3
1999	na	na	na	na	na	515.3	64	5.7	8.1	1.4
2000	*	*	*	*	*	469.2	87	4.2	5.4	1.3
2001	*	*	*	*	*	486.7	67	5.4	7.3	1.3
2002	2440.4	181	2.0	13.5	6.7	954.4	96	3.8	9.9	2.6
2003	2417.2	142	2.6	17.0	6.6	601.3	81	4.5	7.4	1.6
2004	1861.6	116	3.1	16.0	5.1	577.4	86	4.2	6.7	1.6
2005	2397.6	134	2.7	17.9	6.6	558.6	71	5.1	7.9	1.5

2006	2179.3	122	3.0	17.9	6.0	474.6	69	5.3	6.9	1.3
2007	1821.2	141	2.6	12.9	5.0	493.3	74	4.9	6.7	1.4
2008	1733.7	174	2.1	10.0	4.7	600.1	104	3.5	5.8	1.6
2009	2128.6	171	2.1	12.4	5.8	524.3	87	4.2	6.0	1.4
2010	1812.8	165	2.2	11.0	5.0	720.6	106	3.4	6.8	2.0
2011	1261.8	134	2.7	9.4	3.5	na	na	na	na	na
2012	1404.3	162	2.3	8.7	3.8	na	na	na	na	na
average	**1950.8**	**149**	**2.4**	**13.1**	**5.3**	**613.7**	**81**	**4.5**	**7.6**	**1.7**

Table II.12 Characterization of the Atlantic and Mediterranean rainfall series considered to determine the variability in the RWH potential according to the bioclimatic geography where granite sawing is being addressed. NOTE: na - data not available; *- data not included in calculations due to the high number of days without measurement

Section B.2 Potential daily rainwater availability for industrial use according to the industrial surface dedicated for rainwater catchment. NOTE: Daily water requirements of sawing technologies, considering 24h of use, are indicated in the graphics to visualize the potential for fully coverage with rainwater supply.

Section B.2.1 Potential daily rainwater availability for industrial use by using the sawmill roof (2,000 m²) as rainwater catchment surface.

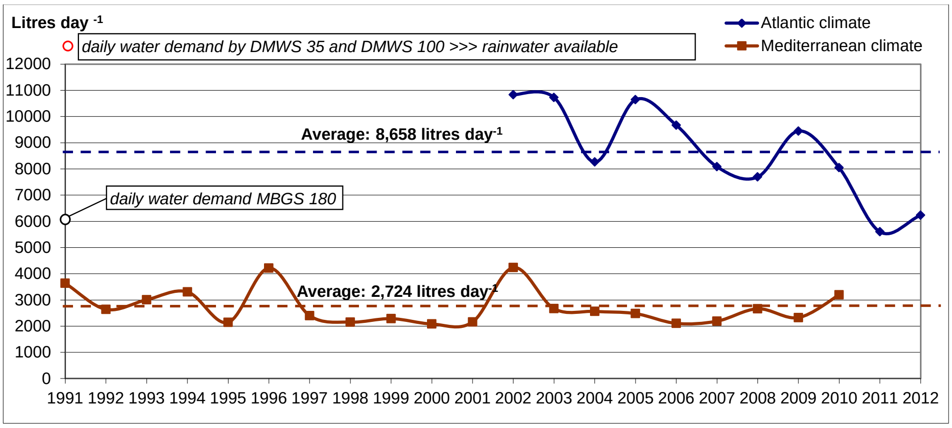


Fig. II.7 Potential daily rainwater availability for industrial use by using the sawmill roof (2,000 m²) as rainwater catchment surface.

Section B.2.2 Potential daily rainwater availability for industrial use by using the industrial plot (28,500 m²) as rainwater catchment surface.

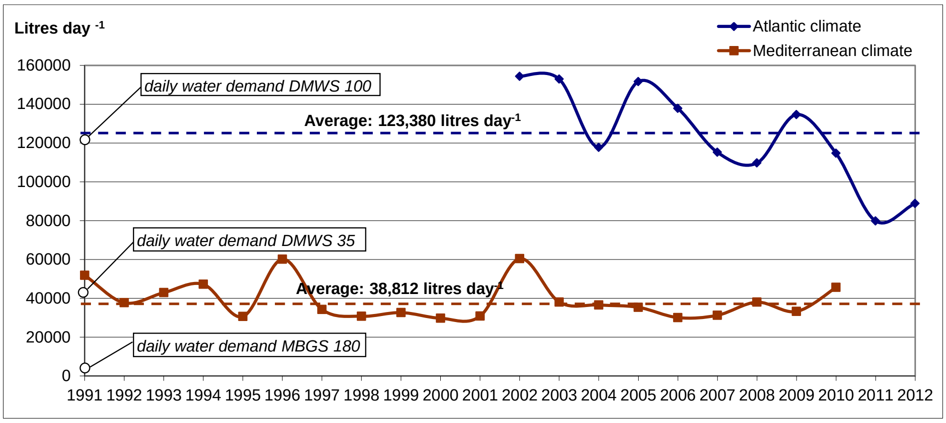


Fig. II.8 Potential daily rainwater availability for industrial use by using the industrial plot (28,500 m²) as rainwater catchment surface.

Section B.2.3 Potential daily rainwater availability for industrial use by using the industrial area (574,100 m²) as rainwater catchment surface.

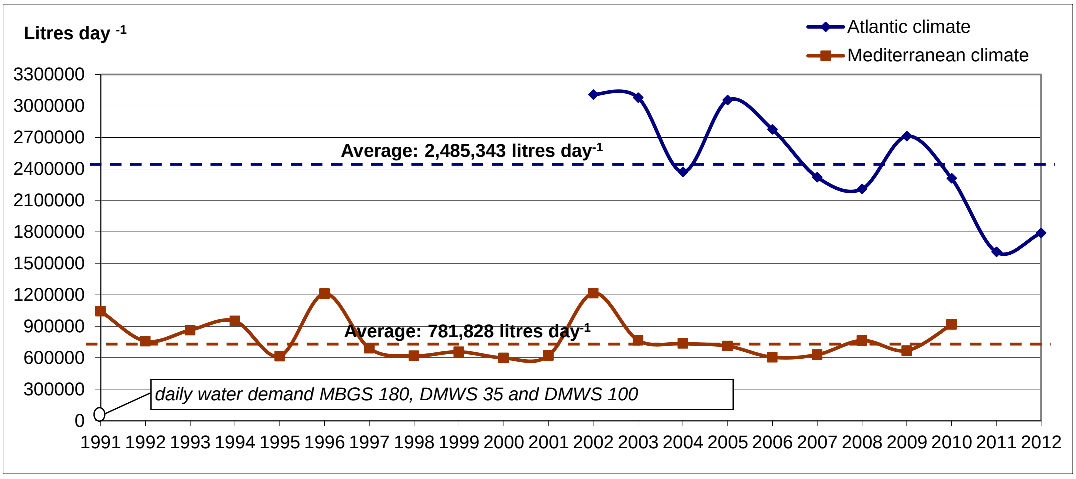


Fig. II.9 Potential daily rainwater availability for industrial use by using the industrial area (574,100 m²) as rainwater catchment surface.

Section B.3 Potential coverage of daily water consumption by sawing technologies if all available rainwater is fully harvested and stored (ideal scenario).

The daily water consumption by sawing technologies is calculated by considering the productivity over 24 h according to each technology's technical specifications. On average, 1.4 granite blocks can be processed daily by employing the MBGS 180, which is equivalent to 415 sawn m². In terms of the DMWS 35 and DMWS 100 technologies, 1.5 and 3 granite blocks can be sawn daily, respectively, when considering a time spent between loading stages. These values correspond to a daily production of 534 m² by the DMWS 35 and 1,530 m² by the DMWS 100. Nevertheless, an alternative scenario is applied for the DMWS technologies considering their use for one sawing stage a day. Under this scenario, the productivity of the DMWS technologies is still competitive compared to the use of the MBGS 180 (see Fig. 6.2 from chapter 6).

Section B.3.1 Potential coverage of daily water consumption by sawing technologies if all available rainwater by using the sawmill roof as catchment surface is harvested and stored.

Daily water demand by sawing technologies	**ATLANTIC CLIMATE GEOGRAPHY**		**MEDITERRANEAN CLIMATE GEOGRAPHY**	
	Potential coverage of water demand by rainwater supply (%)	Potential rainwater surplus (%)	Potential coverage of water demand by rainwater supply (%)	Potential rainwater surplus (%)
MBGS 180 – 6,000 l	100	44	45	0
DMWS 35 – 42,840 l	20	0	6	0
DMWS 100 – 122,400 l	7	0	2	0
DMWS 35* – 28,560 l	30	0	10	0
DMWS 100* – 40,800 l	21	0	7	0

Table II.13 Potential coverage of daily water consumption by sawing technologies if all available rainwater by using the sawmill roof as catchment surface is harvested and stored. NOTE: (*) considers one daily sawing stage.

Section B.3.2 Potential coverage of daily water consumption by sawing technologies if all available rainwater by using the industrial plot as catchment surface is harvested and stored.

Daily water demand by sawing technology	**ATLANTIC CLIMATE GEOGRAPHY**		**MEDITERRANEAN CLIMATE GEOGRAPHY**	
	Potential coverage of water demand by rainwater supply (%)	Potential rainwater surplus (%)	Potential coverage of water demand by rainwater supply (%)	Potential rainwater surplus (%)
MBGS 180 – 6,000 l	100	1956	100	547

DMWS 35 – 42,840 l	100	188	91	0
DMWS 100 – 122,400 l	100	1	32	0
DMWS 35* – 28,560 l	100	332	100	36
DMWS 100* – 40,800 l	100	202	95	0

Table II.14 Potential coverage of daily water consumption by sawing technologies if all available rainwater by using the industrial plot as catchment surface is harvested and stored. NOTE: (*) considers one daily sawing stage.

Section B.3.3 Potential coverage of daily water consumption by sawing technologies if all available rainwater by using the industrial area as catchment surface is harvested and stored.

Daily water demand by sawing technology	ATLANTIC CLIMATE GEOGRAPHY		MEDITERRANEAN CLIMATE GEOGRAPHY	
	Potential coverage of water demand by rainwater supply (%)	Potential rainwater surplus (%)	Potential coverage of water demand by rainwater supply (%)	Potential rainwater surplus (%)
MBGS 180 – 6,000 l	100	41,322	100	12,930
DMWS 35 – 42,840 l	100	5,701	100	1,725
DMWS 100 – 122,400 l	100	1,931	100	539
DMWS 35* – 28,560 l	100	8,602	100	2,637
DMWS 100* – 40,800 l	100	5,992	100	1,816

Table II.15 Potential coverage of daily water consumption by sawing technologies if all available rainwater by using the industrial area as catchment surface is harvested and stored. NOTE: (*) considers one daily sawing stage.

Section B.4 Complete overview of the variability in the potential for RWH in Atlantic and Mediterranean climate geographies according to variability in rainwater tank sizing depending on the industrial surface dedicated to rainwater catchment and the water demand to be satisfied. Analytical software applied: Plugrisost® (Morales-Pinzón et al., 2012a).

The results presented in Figures II.10 and II.11 indicate that there is a point from where an increase in rainwater tank sizing does not contribute to achieve major improvements in RWH, or it does contribute but at the expense of high infrastructure cost. RWH depends on dynamic balance between daily rainwater availability and demand. To validate this statement, we focus on the following examples related to RWH for granite sawing in an Atlantic climate geography.

- **MBGS 180 (catchment surface_sawmill roof):** a 25-m^3 rainwater tank can contribute to satisfy 51% of daily water consumption. Doubling the size of the tanks would contribute to increse RWH by only 11%.
- **DMWS 35 (catchment surface_industrial plot):** a 150-m^3 rainwater tank can contribute to satisfy 53% of daily water consumption. An increase in the volume of the tanks up to 500 m^3 (+ 220%) would contribute to increase RWH by 24%, which is a relevant increase but at a high infrastructure cost.
- **DMWS 100 (catchment surface_industrial área):** a 300-m^3 rainwater tank can contribute to satisfy 54% of daily water consumption. An increase in the volume of the tanks up to 1000 m^3 (+ 233%) would contribute to increase RWH by 26%, which is a relevant increase but at a high infrastructure cost.

This situation is more prominent for granite sawing in Mediterranean climate geographies due to the reduced water availability. Results justify that a major increase in the size of rainwater storage tanks would contribute to minimal increases in RWH.

It is also important to have a look on RWH according to catchment surfaces. The difference on the RWH values between using the industrial plot or the industrial area rainwater catchment is not much significant (especially for granite sawing in Atlantic climate geographies) compared to magnitude of the increase in the extension of the surface dedicated for rainwater catchment. However, a greater increase on RWH occurs if the surface of the industrial plot is used for rainwater catchment instead of the sawmill roof.

Section B.4.1 Sample of the variability in the potential for RWH in an Atlantic climate geography according to variability in rainwater tank sizing depending on the rainwater catchment surface and sawing technology considered.

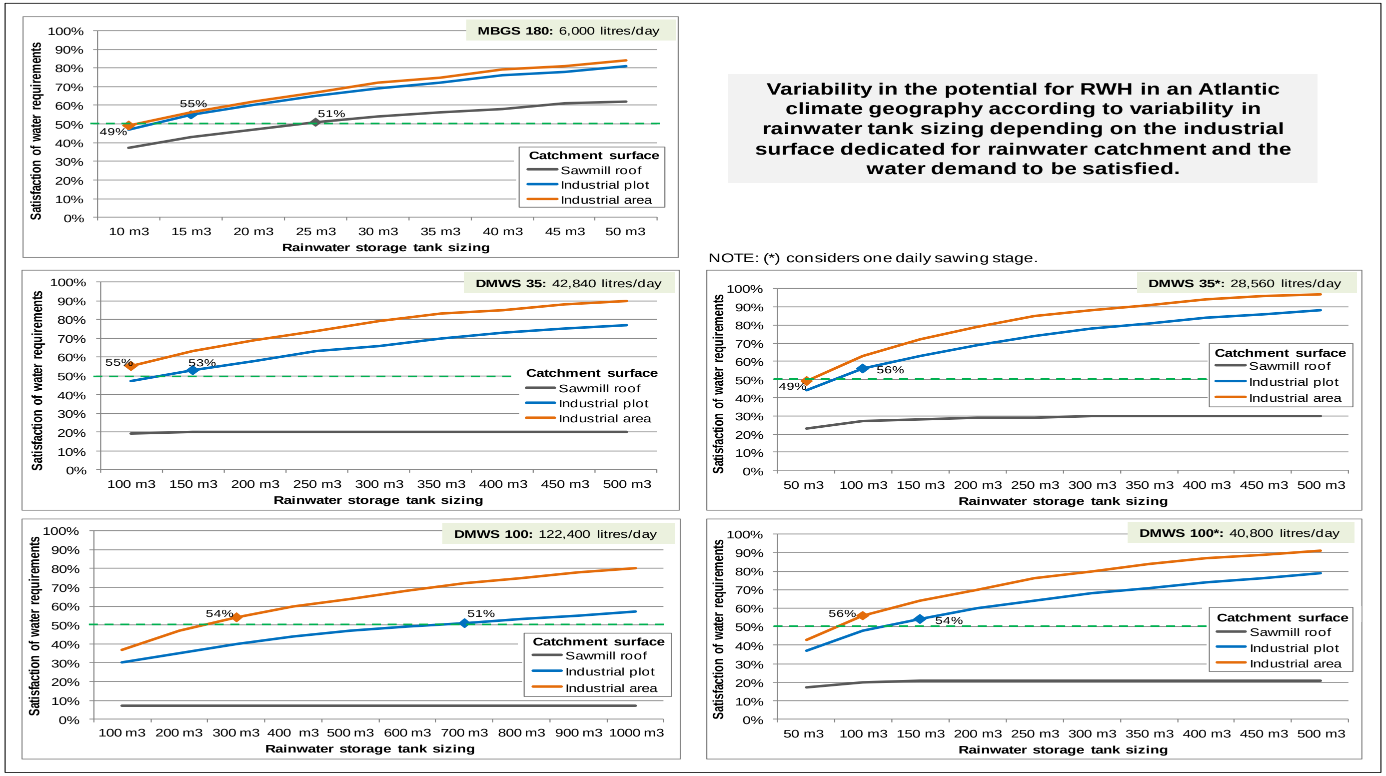


Fig. II.10 Sample of the variability in the potential for RWH in an Atlantic climate geography according to variability in rainwater tank sizing depending on the rainwater catchment surface and sawing technology considered.

Section B.4.2 Sample of the variability in the potential for RWH in a Mediterranean climate geography according to variability in rainwater tank sizing depending on the rainwater catchment surface and sawing technology considered.

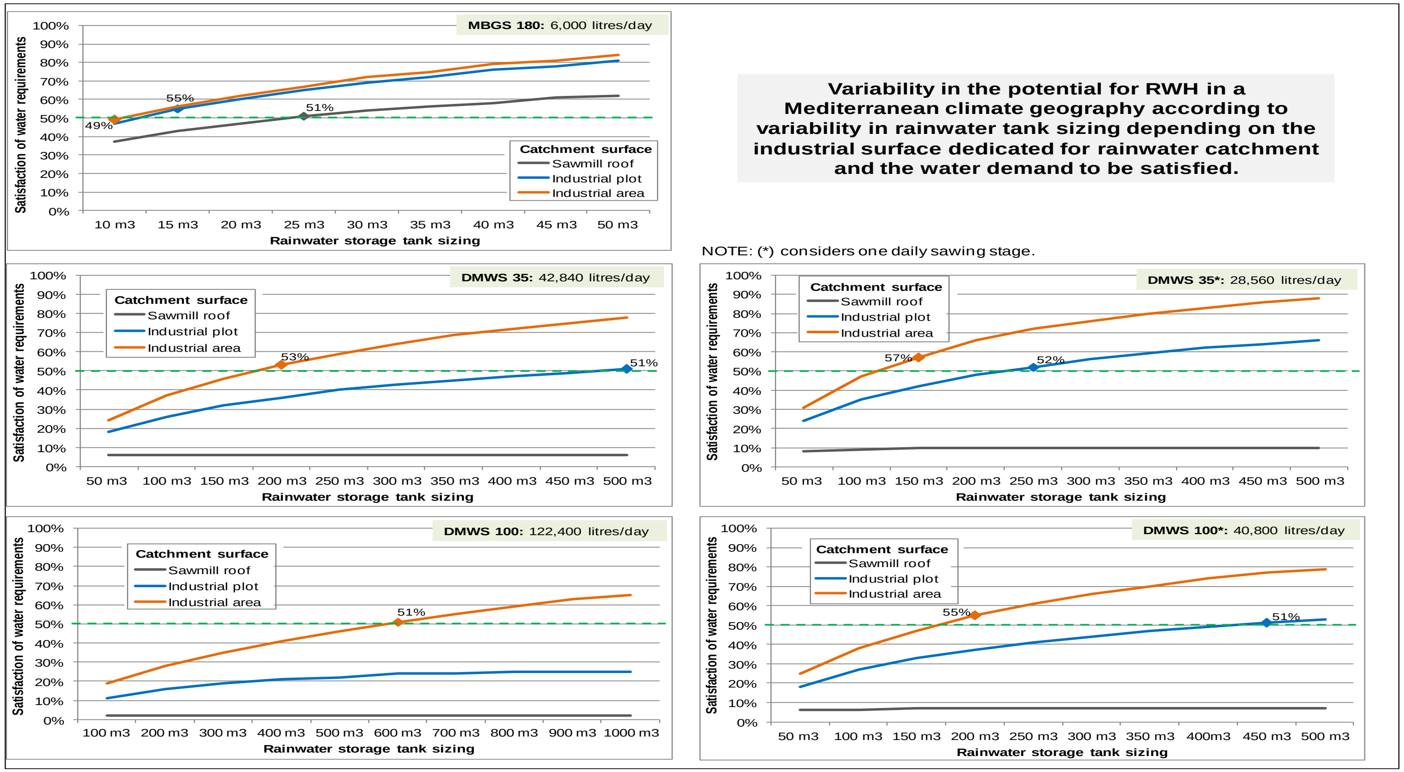


Fig. II.11 Sample of the variability in the potential for RWH in a Mediterranean climate geography according to variability in rainwater tank sizing depending on the rainwater catchment surface and sawing technology considered.

11.3. Appendix III. Supplementary material related to chapter 7.

This file provides additional background information on the extent, diversity and characteristics of the electric vehicle public charging infrastructure implemented in EVI membership countries and EU countries. Complementary descriptions and data (definition of usage conditions, electricity mixes and inventory results) related to the analysis of the life cycle environmental performance of charging infrastructures for electric-two-wheelers are also provided. The information presented in this file is structured as follows:

Section A. Countries approach on the deployment of electric vehicle charging infrastructures.

- **Section A.1** Summary of the present (2012-2013) and future (2020 horizon) extent and diversity of the public EV charging infrastructure implemented in EVI member countries.
- **Section A.2** Summary of the future (2020 horizon) extent and diversity of the public EV charging infrastructure implemented in EU member countries.
- **Section A.3** Brief description of the basic (slow and fast) and complementary charging alternatives available in urban environments for charging EVs.

Section B. Brief description of the product systems and scenarios considered to analyze the life cycle environmental performance of the charging infrastructure for E2Ws.

- **Section B.1** Description of the different components (a-d) and construction work requirements for public installation of ORP2 and ORS6 facilities.
- **Section B.2** Performance of ORP2 and ORS6 facilities according to the variability on their service ratio.
- **Section B.3** Description of the Spanish electricity grid mix for 2011 and 2020 with the corresponding GWP and PED indicators per kWh of low-voltage electricity consumption.

Section C. Life cycle inventory data related to the ORP2 and ORS6 facilities

Section A. Countries approach on the deployment of electric vehicle charging infrastructure.

Section A.1 Summary of the present (2012-2013) and future (2020 horizon) extent and diversity of the public EV charging infrastructure implemented in EVI member countries.

EVI Membership	EVCI stock	EVCI deployment strategy
Austria	1,060 standard AC (level 2) charging stations 6 DC fast charging stations	EVCI are counted by the number of stations rather than the number of plugs in a charging station. One charging station can host several individual charging points. There were 1,066 charging stations installed as of February 2013. It is planned to put 4,500 slow and quick charging points into operation by 2020. *The expected on-road fleet of EVs for 2020 is set as 200,000 EVs. (*) source: http://www.verbund.com/cc/en/news-media/news/2010/04/29/210000-e-vehicles-expected
Belgium	860 charging points (unknown distribution)	Charging points are installed in the public and semi-public domain. It is an open infrastructure (Living Lab program) for testing new e-mobility products and services in real-life conditions in order to stimulate innovation. Most charging points are Level 1 (120 V/12 A) or Level 2 (240 V/40 A), but activity in the direct-current (DC) fast-charging domain is growing. It is estimated that 50 to 80 DC fast chargers will be installed in the short-term. *The potential number of EVs in fleet for 2020 is set as 185,000 vehicles (BAU scenario). (*) source: http://www.cars21.com/news/view/715
Canada	923 standard AC (level 2) charging points 2 DC fast charging points	The three provinces most active in the deployment of EVs — Québec, Ontario, and British Columbia — have also the largest share of EVCI. The rollout of the public charging infrastructure is occurring differently in each province and is highly influenced by the focus of each province's EV program and related funding initiatives. In British Columbia, the largest proportion of public EVCI is

		installed at government or public facilities. In Québec, at least four deployments of charging station networks are in progress. Nevertheless, the largest proportion of charging points is being installed at retail or restaurant locations. In Ontario, public EVCI is being installed across the province organically, without the direct involvement of the provincial government. *The expected on-road fleet of EVs for 2020 is set as 500,000 vehicles. (*) source: Government of Canada (2009); IEA (2011).
Denmark	151 standard (3.7 kW) AC charging (100 posts) 672 semi-fast (11 kW) AC charging (336 posts) 18 fast (22 kW) AC charging (13 posts) 8 DC fast (20 kW) charging (8 posts) 50 DC fast (50 kW) charging (50 posts) 18 Battery Swap Stations	There are a total of 529 charging stations that account for 921 charging points implemented in Denmark. The Danish countrywide EV charging network is dominated by the implementation of fast charging points and battery swap stations. The battery swap process can take only 5 minutes but it required EV to be equipped for a battery swap. However, as of June 2013, Better Place Denmark (the operator of battery swap stations) filed for bankruptcy. This new development can definitely impact Danish EV infrastructure development. DC fast charging stations are implemented at major Danish supermarket chains (i.e. Føtex). The EVs available in Denmark capable of get fast charging include the Nissan Leaf, Mitsubishi iMiEV, Citroën C-Zero, and Peugeot iOn. *The expected EV on-road fleet for 2020 is set as 200,000 vehicles. The public charging network expected account for a total of 20,870 points (20,150 fast, 700 slow and semi-fast and 19 battery swap). (*) source: Trip et al. (2012).
Finland	52 standard AC (level 2) charging points 2 DC fast charging points	Finland´s Nordic climate necessitates preheating of vehicles. There are about 1-1.5 million block heaters in Finland that are used for engine preheating that can also be used for 2 AC (level 2) charging. Plans are underway to increase EVCI numbers and strengthen the existing charging network. Up to 20 new fast charging stations are planned to be implemented in the short-term. Some cities have also announced plans to implement slow-charging stations, i.e. Helsinki has plans for 100, and Vantaa has plans for 70-80.
France	2,418 standard AC (level 2) charging points 143 DC fast charging points	The increase in the number of EVs on French roads is mostly due to the use of the Bolloré Bluecar in the Autolib car-sharing service in Paris. At the end of 2012, there were 752 charging stations in France; they represented 2,564 charging spots (an average of three to four plugs per station).

		The locations used for EVCI and their geographic distribution across France are the following: public road, car dealership, parking, gas station, urban parks, hotels, airports, schools, restaurant, business, home, city hall, movie theatre, shopping mall, organizations, train stations, other. The French government has announced a new mission to organize future EVCI installations in large cities and to harmonize the mapping of charging spots. *The potential number of EVs in fleet for 2020 is set as 2,000,000 vehicles. ** The public urban charging network would account for 400,000 charging points. (*) source: IEA (2011). (**) source: Weeda et al. (2012).
Germany	2,809 standard AC (level 2) charging 12 DC fast charging	There four regions (Baden-Wuerttemberg, Berlin/Brandenburg, Lower Saxony, and Bavaria) as showcases for electric mobility in Germany. These regions will test and demonstrate electric mobility development in everyday life, with a special focus on linking EVs and the electricity system by using information and communication technology (ICT) in the transport system. * The German government estimates that the urban (private and public) EV charging network should be providing a total of 950,000 charging points by 2020, assuming that a ramp-up to one million on-road EVs is achieved. Approximately 800,000 of these 950,000 charging points will be built by private investors (private normal charging). This figure includes some 7,000 fast charging points by 2020. As things currently stand, the figure of 150,000 public charging points will only be achievable if the right framework conditions and appropriate funding models are provided. Consequently, a share of this forecast is described as "uncertain". Therefore this share will be adjusted based on the results from testing in the showcase projects. (*) source: German National Platform for Electric Mobility (2012).
Ireland	530 standard AC (level 2) charging points 30 DC fast charging points	The Irish government aims at monitoring the use of the EVCI to get important information about driving trends, charging patterns, and consumer attitudes in order to testing the usefulness of the planning and design of the charging infrastructure and gaining a better understanding of the characteristics of EVs. Charging points are installed in public, retail/service, commercial and residential locations. * The targeted objective is to have 250,000 on-road EVs and 25,000 public charge points by 2020.

		(*) source: http://www.mobieurope.eu/the-project/ongoing-initiatives/e-car-ireland/
Italy	640 standard AC (level 2) charging 3 DC fast charging	Italy has 1,350 Level 2/standard AC normal charging points (640 in public areas and about 710 in private ones) that is complemented with a few DC fast charging points. Existing charging stations also can have multiple charging points; current statistics do not clearly distinguish between charging stations and charging points. EVCI plans related to running demonstration projects may increase the count beyond the current total by about 30% to 40%. The National Charging Infrastructure Plan, which is under revision and approval, will give clear directions, guidelines, and concerted agreements with local authorities, which could substantially support this expansion.
The Netherlands	2,782 standard AC (level 2) charging points 63 DC fast charging points	The Netherlands focuses on specific market segments where electro-mobility seems promising. These are "heavy user" segments like logistics and distribution; company vehicles; businesses and commuting; and public transportation, including taxis. *The potential number of EVs in fleet for 2020 is set as 200,000 vehicles. The public urban charging network would account for over 11,500 charging points. (*) source: IEA (2011); Weeda et al. (2012); (**) source: Trip et al. (2012)
Portugal	1,117 standard AC (level 2) charging points 9 DC fast charging points	Currently, there are two predominant types of charging stations: normal charging stations, at home for fleets, and on-street and off-street parking, and fast charging stations, on main roads and highways, at service stations, and in strategic urban locations. A public network with 1,126 public charging points in more than 30 cities across the country enables national coverage. By the end of 2012, the network registered a total of 438 regular users, including those operating cars, quadricycles, and two wheelers. *In order to kick-off electric mobility in Portugal, Mobi.E is implementing a pilot recharging infrastructure system. This network comprises over 1,300 normal recharging points and 50 fast recharging points that form a Living Lab for the subsequent design of Local Plans for Electric Mobility. The 50 fast recharging points will be installed in the main motorways in order to make travelling all around the country possible. It is estimated approximately 750,000 EVs will in circulation by 2020. (*) source: MOBI.E (2012).
Spain	771 standard AC (level 2) charging points	MOVELE was an EV demonstration project in three of Spain's major cities between 2009 and early 2011. MOVELE aimed to put 2,000 EVs on the road and install a total of 546 charging stations in Madrid, Barcelona, and Seville.

	11 DC fast charging points	*It is expected the installation of 18,350 publicly available normal charging points. This charging network will be complemented with the installation of 1 fast charging station per every 400 normal (public and private) charging points. It accounts therefore for a total of 160 fast charging stations. The urban public charging network has been planned considering the goal of having 250,000 EVs on-road by 2015. The on-road EV fleet for 2020 is assumed to account for 2,500,000. (*) source: MITC (2010).
Sweden	1,200 standard AC (level 2) charging point 15 DC fast charging points	Swedish authorities have no common EV charging infrastructure plan. Today, the number of EVs has no impact on the electricity grid; hence, there are no official efforts in this area. As in Finland, Nordic winters require the use of block heaters to keep the cooling water in a vehicle's motor block from freezing while the vehicle is parked. Sweden has approximately 800,000 block heater electric outlets that may be used for charging EVs, either directly or with only minor modification. About 600,000 of these outlets are in Swedish homes, and about 200,000 are in corporate parking facilities. * A fleet of 600,000 "eco-cars" are expected on-road in Swedish cities for 2020. At least 94 new charging stations with 240 publicly available charging points will be implemented. (*) source: Trip et al. (2012).
Switzerland	300 standard AC (level 2) charging with 1-2 points each 11 DC fast charging with 1-2 points each	There is still no national legislation concerning EVs in general. Switzerland is one of the first countries in the world to install a nationwide fast charging infrastructure. The national government aims to create a network of 150 public DC fast charging stations throughout Switzerland through 2020. *A fleet of 145,000 on-road EVs are expected for 2020. (*) source: IEA (2011).
Turkey	100-110 charging points (unknown distribution)	Ongoing installation efforts are underway in Turkey to put EVCI in different cities. These efforts are mostly located in Istanbul, which is the country's most populous city. The number of charging points is increasing slowly, keeping pace with EV sales. Although statistics have not been officially kept, the total number of charging points is estimated to be about 100-110. Most of the stations are equipped with standard slow charging; only a few of them are DC fast-charging stations. The charging points are

		located at automotive dealers, parking lots, airports, and shopping centers. Despite the lack of an official announcement about new installations, there are plans to increase the number of charging stations over the next years.
United Kingdom	2,866 charging points (unknown distribution)	Over 2,800 charge points have been provided through eight electric mobility projects by December 2012. About 70% of these charging points are publicly accessible. Nevertheless, around 5,000 public charging points may have been already installed about nationwide. There will be a continued phased installation of 1,300 public charge points on residential streets and off-street locations, such as supermarkets, public car parks, and at shopping and leisure centres in the Source London network. *By 2020, a fleet of 1,550,000 on-road EVs is expected. **The publicly available EVCI stock for 2020 would account for 34,800 points. (*) source: IEA (2011); (**) Trip et al. (2012).
United States	2,789 standard AC (level 1) charging points 10,502 standard AC (level 2) charging points 153 DC fast charging points	EVCI deployment is demonstrated in two separate projects. ECOtality set up the EV Project, so far the largest deployment and evaluation project for electric drive vehicles and charging infrastructure, to deploy approximately 14,000 standard AC (level 2) charging and 300 DC Fast charging stations in 16 major cities across the United States. ChargePoint set up ChargePoint America, to deploy 4,600 public and home networked charging stations at locations throughout the United States. *Over1,000,000 of on-road EVs are expected for 2015. The expected urban EV public charging network corresponds to 22,000 points. (*) source: IEA (2011); (**) source: Weeda et al. (2012).

General sources: IEA (2013a); IEA (2013b).

Section A.2 Summary of the future (2020 horizon) extent and diversity of the public EV charging infrastructure to be implemented in EU member countries.

Member State	Number of charging points	Number of publicly accessible charging points
BE	207,000	21,000
BG	69,000	7,000
CZ	129,000	13,000
DK	54,000	5,000
DE	1,503,000	150,000
EE	12,000	1,000
IE	22,000	2,000
EL	128,000	13,000
ES	824,000	82,000
FR	969,000	97,000
IT	1,255,000	125,000
CY	20,000	2,000
LV	17,000	2,000
LT	41,000	4,000
LU	14,000	1,000
HU	68,000	7,000
MT	10,000	1,000
NL	321,000	32,000
AT	116,000	12,000
PL	460,000	46,000
PT	123,000	12,000
RO	101,000	10,000
SI	26,000	3,000
SK	36,000	4,000
FI	71,000	7,000
SE	145,000	14,000
UK	1,221,000	122,000
HR	38,000	4,000

Source: European Commission (2013c)

Section A.3 Brief description of the basic (slow and fast) and complementary charging alternatives available in urban environments for charging EVs.

Basic charging modes	Main connection	Voltage/ Amperage	Charging power	Charging time	Urban locations and infrastructure requirements
Slow (Level I and II)	1-phase AC (standard outlet)	120-230V, 10-16A	≤ 3.7 kW	4 - 8 h	Locations: Dwellings, Residential settings, Public parking areas, Workplace, Streets, Civic spaces, Public transport stations, Airports Requirements: *Household/ Workplace: Electric infrastructure is already available. Only a cable from electricity outlet to the vehicle or minimal adaptation of the domestic and workplace electrical circuit are required. *Public space: Stationary charger facilities (pivots/columns) with new dedicated electrical circuit. Electric infrastructure in the urban space is already available. An electrical middle voltage and low voltage network runs under pavements, close to building walls or on elevated cables. Depending on the location, considerable slack in power delivery conditions may exist in some cases that allow charging EVs free of charge. However, in many urban areas, power transformers may already be working at maximum capacity and might therefore require new investments in order to upgrade the delivery capability. Also sometimes there are no open access points available for users to plug in their EVs. In this cases, new electrical constructions are required.
Semi-fast (Level II)	1-phase or 3-phase AC	230-400V, 16-32A	3.7-12 kW	2 - 4 h	Locations: Multi-building office and apartments, Parking's and garages, Commercial areas, Leisure places. Stationary chargers (pivots/columns/boxes) with new dedicated electrical circuit. Variable requirements depending on the location of the charging points (i.e. indoor/outdoor areas from public/private property spaces) The available electric infrastructure consists of the property owner's or user's electrical circuit. It is connected to the municipal power network, normally through a single entry point, and is regulated by a power contract dimensioned to the EVCI´s needs.

					Depending on national legislation, owners may or may not be allowed to resell electricity supplied at their installation to third parties. In most of these locations several power socket outlets are available that can be used for EV charging. However, the electrical system is normally not equipped to charge even a small percentage of the total parking spots without new cables, equipment and an upgrade of the power contract connection and/or supply contract. This is especially true for faster charging modes. In outdoor locations of this kind there are normally no socket outlets available to the public. New electrical constructions are required.
Fast (Level III)	3-phase AC or DC connection	400-600 V, 32-400A	12 - 150 kW	0.17 – 2h	Locations: Heavy traffic corridors, Shopping centres, Designated public spots, Airports. In this case, the construction of dedicated charging stations with collective charging points (such as the petrol station model) is required. The main difference between fast charging and normal charging lies in the additional service for the customer. Fast charging requires that the cables are permanently connected to the EV charging station. Careful should be placed in the planning of the feeding power for the fast charging stations, allowing for proper load management and avoiding problems in the electricity system. Fast charging will most likely be situated in public areas, but might also take place in public areas on public property. It is important to note that there is as of now no universally accepted technical definition of fast charging. Many interpretations are possible, including an AC 3-phase supply up to 43kW, direct DC from 20kW up to hundreds of kW, high power induction charging, etc.

Source: Nemry et al. (2009); Eurelectric 2010; Nemry and Brons (2010); Eurelectric (2011); ERTRAC (2012).

Complementary charging alternatives	Brief description	Urban locations and infrastructure requirements
Battery swapping	It allows an electric car to switch depleted battery packs with those that are fully charged in 5 to 15 minutes. The system to be widely operative requires the standardisation of the EV batteries and the exchange (robotic) technology. Depleted batteries can be re-charged by means of slow, semi-fast or fast charging.	Locations: Inter-urban roads, heavy traffic corridors. Important investment in the construction of dedicated battery swapping stations (robotic technology for battery exchange plus depleted batteries re-charging and storage).
Wireless (inductive) charging	Inductive charging or wireless power transfer delivers electric power to moving vehicles via time varying magnetic fields if transmission system is nearby. Charging equipment buried in the road surface will be able to charge while signal stop or brief parking for shopping. Through the business-concept of occasional short charging there is the benefit of lower weight (battery pack) to move and less space for charging infrastructure is required. For example, at dedicated bus stops, accordingly equipped, battery charging with 10-15% will be done during getting in and out of passengers. The in-between charging would provide enough energy for daily operation, so that the stored energy could be reduced to a minimum.	Locations: Traffic light stops, tool stops, bus stops, dedicated areas on highways. Inductive power transfer technology, i.e. primary coils integrated in concrete structures which will be embedded in the road pavements.
Contact-running charging	There are two possibilities to promote the so called contact-running charging: the implementation of an overhead electric line or facilitating a sliding contact in the street surface. For the overhead option, many years experience is available from the so called 'Trolley-Bus'. Sliding contacts are currently being adapted to using duty electric trucks.	Locations: urban traffic lanes. Construction of an electrical installation with the facilitation of direct contact via a vehicle part to a contact plate. Construction of a robotic connection, e.g. a plug coming from floor or wall connecting with the vehicle or a pick-up connecting to rails in the road or to a contact surface on top of the vehicle (e.g. for city buses and trucks)
Solar-powered	Consist of photovoltaic covers (i.e. roof with solar panels) that provide a charging space for	Locations: designated public spots in cities.

charging stations	use by several electric vehicles. The surplus power generated by the solar charging stations is poured into the electricity grid.	Investment in the construction of a new dedicated electrical installation in specific urban spaces.
Wind-powered charging Station	Consist of charging facilities that combines the energy production capacity of a small cutting-edge vertical wind turbine with electric vehicle charging technology in a single unit.	Locations: designated public spots in cities. Investment in the construction of a new dedicated electrical installation in specific urban spaces.
Multi-functional urban elements	Consist of taking use of the already available urban furniture and mobility elements present in cities in order to integrated, whenever possible, slow-charging points. These elements, currently, include at least: • Public under-used telephone boxes • Pergolas (urban furniture) • Street lighting and traffic light systems	Locations: designated public spots in cities. Minimal adaptation of the already available electrical infrastructure related to these urban elements

Source: Nemry et al. (2009); Eurelectric 2010; Nemry and Brons (2010); Eurelectric (2011); ERTRAC (2012), and internet browsing regarding solar, wind and multi-functional charging options.

Section B. Brief description of the product systems and scenarios considered to analyze the life cycle environmental performance of the charging infrastructure for E2Ws.

Section B.1 Description of the different components (a-d) and construction work requirements for public installation of ORP2 and ORS6 facilities.

The basic features of the ORP2 device include electronic units enclosed by a stainless steel structure that is 214 mm in diameter, 1,230 mm high and 3 mm thick, painted with a polyester coating and fixed on the ground through a concrete bench measuring 500 mm x 500 mm x 400 mm and a template with 4 bolts. In the ORS6 device, the electronic units are enclosed by a stainless steel structure 4,200 mm long, 300 mm high and 2 mm thick and also painted with polyester. The station is fixed on the ground through a concrete bench and fasteners and bolts. Technical information on the charging devices can be obtained from CIRCONTROL (2012). A number of common technical requirements are applicable to both types of charging facilities for public installation. These requirements are specified by the AEB (2011) and in the technical instructions provided by the FECSA-ENDESA (2006) electricity supplier and the MITC (2002). A feeder pillar must be installed together with the charging device for security and control purposes. The charging equipment therefore includes a feeder pillar (b) and a charging device (d). The installation of the charging equipment begins with an electrical connection at the closest point of access to a municipal low-voltage line. A trench approximately 75 cm deep and 35 cm wide is required to house the cables. The average distance between the point of access to the local low-voltage network and the placement of the feeder pillar is 12 m (a), and another 3 m (c) are required from the placement of the feeder pillar to the location of the charging device. The average length of the trench is determined by technical considerations such as the presence of underground services such as gas and water pipes, telecommunications, and security checkpoints. These may be common features in other large cities with complex underground networks. Cables are enclosed in polyethylene tubes over a 5-cm layer of sand along the length of the trench (15 m). After placement, the tubes are covered with up to 25 cm of additional sand. Subsequently, a 30-cm layer of gravel is placed over the sand and compacted, and this gravel layer is covered by a 12-cm layer of lightweight concrete. Finally, a standard pavement of 4-cm-thick concrete slabs is placed on a 2-cm cement mortar layer, and grouting seeps through the slab joints into the mortar. The feeder pillar and charging device are installed manually. The service life of the charging equipment is assumed to be 10 years. The equipment is removed manually, and the ground is sealed using concrete, mortar and slabs.

All the life-cycle stages and unit processes from cradle-to-removal of the product systems have been considered in environmental calculations. Only the waste management scenario is excluded from consideration. According to the information provided by local producers, the charging equipments are recycled into "unspecified" new products after removal from the public space. I t is considered therefore that the additional expenditure for further recycling of the equipment should be assigned to the new product systems. The space required for parking the E2Ws for charging purposes is also excluded from consideration because it is not new construction related to charging facilities.

Section B2. Performance of the ORP2 and ORS6 facilities according to the variability on their service ratio.

Intensity of use	Daily hours	Electricity supplied to E2Ws (kWh/year)	Electricity consumption by (3x)ORP2 (kWh/year)	Electricity consumption by (1x)ORS6 (kWh/year)	Maintenance operations
10%	2.4	19,447	101.6	75.3	Substitution of 10% of electronic units in feeder pillars and 25% in charging devices every 5 years
20%	4.8	38,894	124.3	98.0	
30%	7.2	58,342	147.0	120.7	
40%	9.6	77,789	169.7	143.4	Substitution of 25% of electronic units in feeder pillars and 50% in charging devices every 5 years
50%	12.0	97,236	192.4	166.2	

The scenarios are classified according to the percentage of daytime hours during which the charging facilities are supplying electricity to E2Ws.

The energy consumption by a (1x) ORP2 corresponds to 3 Wh during stand-by time plus 26 Wh during hours of electricity supply (including energy losses). The ORS6 design consumes 6 Wh during stand-by time and 78 Wh during hours of electricity supply. The energy requirements for each type of charging device are accounted for and grouped together. The maintenance operations are estimated by considering the performance of the electronic units in the different use intensity scenarios. The fact that the charging facilities are placed outdoors, where they are exposed to weather conditions and potential vandalism, misuse or poor equipment management, is also considered.

Section B.3 Description of the Spanish 2011 and 2020 electricity mixes with the corresponding global warming potential (GWP) and primary energy demand (PED) indicators per kWh of low-voltage electricity consumption.

% Energy sources	Electricity mix 2011	Electricity mix 2020
Nuclear	21.3%	15.3%
Combined cycle (natural gas)	18.7%	23.5%
Wind	15.4%	20.4%
Hard coal	15.2%	8.2%
Hydropower	12.1%	11.1%
Cogeneration	9.8%	8.4%
Solar	3.3%	7.4%
Biomass	1.1%	2.4%
Fuel oil	0.9%	-
Lignite	0.8%	0.5%
Residual gas	0.6%	-
Incineration (municipal wastes)	0.5%	2.3%
Biogas	0.3%	0.6%
GWP (g CO_2 eq. / kWh)	**422**	**324**
PED (MJ eq. / kWh)	**10.1**	**8.9**

Section C: Life cycle inventory data related to the ORP2 and ORS6 facilities

Unit processes		Elements	(1x) ORP2	(1x) ORS6
Charging Equipment	Connection from LV line to feeder pillar (a)	Cable AL (50 mm^2)	4 x 15 m	4 x 15 m
		PEHD tube (ø 125 mm)	1 x 13.5 m	1 x 13.5 m
	Feeder pillar (b)	Stainless steel envelope (1,920x520x520 mm)	80.2 kg	80.2 kg

		Screws, nuts, hinges, bridles	1.1 kg	2.1 kg
		Plastic envelopes for electronic units (ABS)	7.2 kg	8.5 kg
		Cable CU (various types)	5.1 kg	6.5 kg
		PEHD tube (ø 63 mm)	1 x 2 m	1 x 2 m
		Iron bar	0.2 kg	0.4 kg
		Electronic units	15 kg	18 kg
		Polyester (paint)	1 kg	1 kg
	Connection from feeder pillar to charging device (c)	Cable Cu (10 mm²)	3 x 4.5 m	7 x 4.5 m
		PEHD tube (ø 63 mm)	1 x 4 m	1 x 4 m
	Charging device (d)	Stainless steel envelope	25 kg	60 kg
		Electronic units	5 kg	9 kg
		Cable Cu (various types)	0.55 kg	0.74 kg
		Iron bar	0.2 kg	0.4 kg
		Polyester (paint)	0.5 kg	1.5 kg
Construction materials		Sand (25 cm)	2,077 kg	2,077 kg
		Gravel (30 cm)	2,873 kg	2,873 kg
		Lightweight concrete (12 cm)	1,085 kg	1,085 kg
		Normal concrete (structural)	248 kg	486 kg
		Mortar (2 cm)	143 kg	143 kg
		Concrete slabs (4 cm)	526 kg	526 kg
		Cement grout	10 kg	10 kg
		Water	116 kg	116 kg
		PEHD (cables cover)	36 kg	36 kg
		PELD (signaling tape)	4 kg	4 kg
Transportation of materials		Electrical equipment (lorry 3.5–6 tn)	35 km	35 km
		Construction materials (truck 20–28 tn)	50 km	50 km
		Waste from maintenance and removal operations (lorry 3.5–6 tn)	35 km	35 km
Installation of the charging facility		Excavation and compaction: backhoe equipped with pneumatic hammers and vibrating tamper (diesel)	584 MJ	584 MJ
		Sand dump: backhoe loader (diesel)	34.7 MJ	34.7 MJ
		Gravel placing and compacting: backhoe loader and vibrating tamper (diesel)	149.3 MJ	149.3 MJ
		Concrete pouring: vibratory screed (electricity)	9.4 MJ	9.6 MJ

	Placement of remaining elements		Manual	Manual
Operation and maintenance of the charging facility	Electricity consumption		Data given in section B.2	
	Substitution of electrical units			
Removal of the charging facility	Removal of the charging equipment		Manual	Manual
	Ground sealing	Lightweight concrete	9 kg	9 kg
		Mortar	8.4 kg	9.9 kg
		Concrete slabs	31.0 kg	36.1 kg
		Cement grout	0.6 kg	0.7 kg
		Water	2.5 kg	2.9 kg
		Electricity	0.1 MJ	0.1 MJ

This Table provides inventory data related to each of the individual product systems under study. According to the definition of the FU, references to ORP2 in the discussion of results apply to 3xORP2 designs.

The type and requirements of construction machinery used for these processes have been identified by consulting the ITeC (2012) database, and the operations needed for the transportation of construction materials and electrical equipment have been determined by applying a local market perspective.

11.4. Appendix IV. Supplementary material related chapter 8.

This file contains a step-by-step detailed description of the ecodesign methodological framework among complementary data and environmental results related to the case scenarios presented in the main body of the article. The information presented in this file is structured as follows:

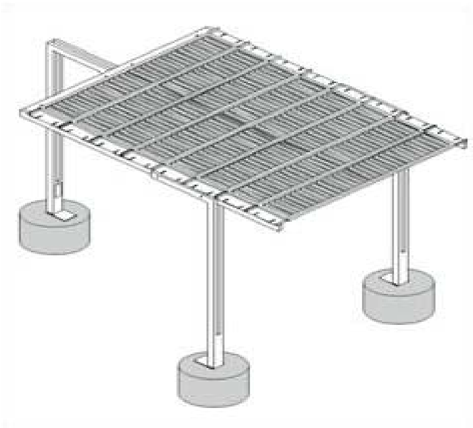
Section A. Ecodesign methodological framework

- **Section A.1.** Conventional product attributes
- **Section A.2.** Environmental assessment of the conventional pergola (CP)
    - **Section A.2.1.** Qualitative Assessment of Life Cycle Criteria of CP product system
    - **Section A.2.2.** Life Cycle Assessment of CP product system
        - **Section A.2.2.1.** System boundaries of the CP product system
        - **Section A.2.2.2.** Life cycle inventory data of CP product system
        - **Section A.2.2.3.** Life cycle impact assessment of CP product system
- **Section A.3.** Eco-briefing
- **Section A.4.** Definition and selection of eco-design strategies
- **Section A.5.** Eco-product attributes
- **Section A.6.** Environmental assessment of the solar pergola (SP)
    - **Section A.6.1.** Life Cycle Assessment of SP product system
        - **Section A.6.1.1.** System boundaries of SP product system
        - **Section A.6.1.2.** Life cycle inventory data of SP product system
        - **Section A.6.1.3.** Life cycle impact assessment of SP product system
    - **Section A.6.2.** Photovoltaic energy production by the SP product system
- **Section A.7.** Description of the variables considered to compare the life-cycle environmental performance between CP and SP product systems
    - **Section A.7.1.** Lifetime energy consumption of CP and SP product systems for different Spanish geographical emplacements
    - **Section A.7.2.** Carbon intensity and embodied energy of conventional Spanish, French and Greek electricity mixes
    - **Section A.7.3.** Environmental burden of a functionally equivalent conventional public charging station for e-bikes to be attributed to the (extended) CP product system

Section A. Ecodesign methodological framework

Section A.1. Conventional product attributes

Conventional pergola (CP)



Basic parts	**Main elements**	**Components**
Structure	Cover	Slatted wood (red pine)
	Support elements	Aluminium (optical reflector group)
		Stainless steel (screws)
		Galvanized steel (columns, joists and auxiliary elements)
		Plastic (armour of the diffuser of the optical group)
	Paint	Autoclave Xylazel impralit kds (wood) Acrylic paint (galvanized steel)
Lighting equipment	Lamps	Fluorescence
		Luminaire
	Electrical components	Lamp-holder
		Cabling
Foundation	Concrete	HM-20
	Fasteners	Steel bolts

Table IV.1 Basic technical information of the conventional pergola under assessment.

The product consists of a simple modular CP with multiple compositional possibilities. It is based on the repetition of a street lamp module originally designed to draw lines of light in the sky. The design of pergola represents the most prominent application of fluorescence in urban areas. The cover of a basic module accounts for 18 m^2 made up of eight slatted wooden panels of red pine treated in autoclave. The cover is supported by a lamppost and two steel support columns. Each module of the CP creates large shaded areas during the day and large illuminated spaces at night.

Section A.2. Qualitative Assessment of Life Cycle Criteria (QALCC)

The QALCC (CPRAC, 2012; Sanyé-Mengual et al., 2014) consists of a first environmental diagnosis of each of the life cycle stages of the product system. Through QALCC the hot-spots that have the largest potential for environmental improvement are detected. By this way, eco-design efforts can be concentrated on those life cycle stages most sensitive to provide significant environmental gains.

The QALCC consist of three main sub-steps: First, definition of all the life cycle stages of the product system; second, definition of environmentally relevant criteria to be considered for each life-cycle stage; third, evaluation of the potential for environmental improvement of each of the product system´s life cycle stages according to the expert judgement (multidisciplinary team) who provides well-defined punctuation. The potential for environmental improvement of each of the life cycle stages of the product system is graded from 1 “enormous room for improvement” to 5 “no room for improvement” according to the level of implementation of the defined environmentally relevant criteria for each case. After the evaluation, punctuation is averaged per type of environmental criteria and life-cycle stage. Results may be represented in a spider diagram that enables an easy identification of the most and least suitable life-cycle stages for potential environmental improvement. This tool allows therefore for an easy initial diagnosis of the potential for environmental improvement of the product system what facilitates to development of the subsequent methodological steps.

In this case study, the life-cycle of the product system has been divided into the stages of concept, materials and production, packaging and distribution, installation, use, maintenance and end-of-life management.

Section A.2.1. Characterization of the multidisciplinary team to address the QALCC

Participants identification	**Discipline**
A	Technical design
B	Editorial
C	Logistic
D	Quality
E	Production
F	Technical support
G	Environmental engineering
H	LCA
I	Environmental Assessment
J	Industrial Ecology
K	Eco-design

Table IV.2 Multidisciplinary team to address the DfE thinking process

Section A.2.2. Product environmental characterization according to the QALCC

Life-cycle stage	**Environmentally relevant criteria**	**Potential for environmental improvement**										
		A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**
Concept	Optimization of the function	2	4	4	2	3	3	4	3	1	4	3
	Product multifunctionallity	2	2	2	1	2	2	2	2	2	1	2
	Timelessness of design	4	5	4	4	3	3	4	4	3	3	5
	Ralationshipt between technical and aesthetical lifetime	4	4	3	2	4	3	3	3	3	3	4
	Design modularity	3	2	3	1	2	3	4	2	3	1	3
	Product eco-innovation	1	2	1	1	1	1	2	1	1	1	1
Materials and Production	Amount of materials	2	4	3	1	3	2	3	2	3	3	2
	Variety of materials	3	4	3	4	4	3	3	3	4	4	4
	Recycled materials	2	1	1	2	1	1	2	1	4	1	3
	Recyclable materials	4	2	4	3	2	2	4	3	4	4	4
	Standard components	2	2	1	1	2	2	3	2	4	2	2
	Production losses	3	4	2	3	3	3	0	4	3	4	3
	Number of productive steps	3	3	2	4	3	3	3	2	4	3	0
	Biodegradable materials	4	2	3	1	1	3	2	2	3	2	2

Transport and Packaging	Optimization of volumen	3	2	1	1	3	2	2	2	2	2	2
	Optimization of the cargo	3	4	2	1	3	2	2	2	3	2	3
	Low environmental impact transportation	2	1	2	2	1	1	2	2	2	4	2
	Amount of packaging material	3	3	2	4	4	3	4	3	3	4	4
	Variety of packaging material	4	3	2	4	3	3	4	3	3	4	4
	Recycled/reciclable packaging material	4	4	3	3	3	3	3	2	2	3	3
	Reusable packaging material	3	3	3	3	3	3	2	1	4	2	3
Installation and Removal	Easy installation	2	4	2	1	3	2	3	2	2	2	2
	Easy removal	2	4	3	2	3	3	5	3	4	4	3
	Construction solution	4	4	3	3	4	3	4	3	3	4	4
	Variety of construction materials	4	4	3	4	3	3	4	3	3	3	4
	Use of local materials	3	4	4	4	4	3	2	4	2	0	4
	Recoverable materials	3	1	4	3	3	2	2	2	1	4	1
	Energy requirements	2	3	3	3	4	2	4	4	1	3	3
Operation	Lamp efficiency	3	3	1	3	2	2	2	2	2	2	3
	Efficiency of electrical components	3	3	3	2	3	3	2	0	0	0	0
	Energy consumption	1	2	2	2	2	2	1	2	1	1	2
	Light pollution	2	4	4	3	3	2	3	3	1	2	3
	Dimming device	1	1	1	1	1	2	2	1	1	2	1
	Use of renewable energy sources	1	1	1	1	1	1	1	1	1	1	1
Maintenance	Communication of maintenance requirements	3	1	1	3	1	2	3	1	1	2	2
	Material requirements for maintenance	4	4	3	4	3	2	4	3	4	3	3
	Minimization of maintenance through design	2	4	3	3	2	2	3	3	2	1	1
	Potential for reparability	4	4	4	4	3	3	4	4	4	3	4
	Availability of spare elements	4	4	4	4	4	3	4	4	4	5	4
	Easy replacement of components	2	3	4	3	3	3	5	4	4	3	4
End-of-life management	Separability of the components	3	4	4	4	4	3	4	3	4	4	4
	Separability of the materials	4	4	4	3	4	3	4	3	3	4	4
	Identification of materials	4	3	4	4	4	4	5	2	5	4	4
	Potential for recyclability	3	3	4	3	3	3	4	4	4	2	4
	Potential for reuse	4	3	3	3	2	2	4	4	0	2	4
	Communication of end-of-life management	1	1	1	3	1	3	2	2	1	1	1

Table IV.3 QALCC punctuation matrix. Punctuation: 5 – No room for improvement (criteria with a 100% of implementation); 4 – Reduced room for improvement (criteria with high level of implementation, 75%); 3 – Improvable (criteria partially implemented, 50%); 2 – High room for improvement (criteria low implemented, 25%); 1 – Enormous room for improvement (criteria with a 0% of implementation); 0 – Not evaluated/Lack of knowledge.

Section A.2.3. Qualitative diagnosis of the life-cycle of the CP product system

Figure IV.1 shows the average qualitative punctuation of the room for environmental improvement per life-cycle stages of the CP product system.

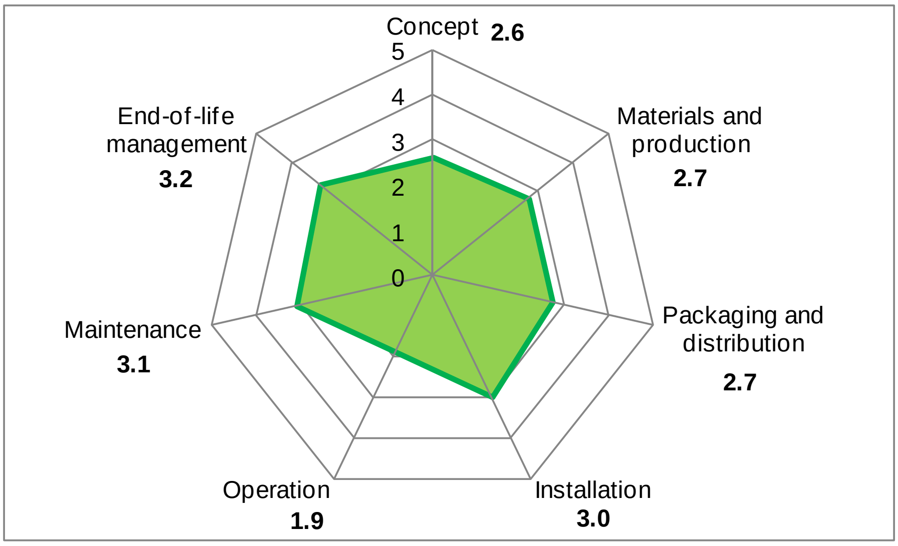


Fig. IV.1 Qualitative diagnosis of the potential for environmental improvement of the life cycle stages of the CP product system.

The area coloured in green (numbers in bold) represents the current perception of the environmental performance of the CP´s life cycle. The lower the qualitative environmental punctuation of a life cycle stage, the greater the room for potential environmental improvement. In this sense, the operation stage of the CP has the greater potential for environmental improvement due to the high energy requirements and lack of use of renewable energy sources. The end-of-life management is considered to have the least potential for environmental improvement since materials are already separable, recyclable and reusable. Nevertheless, the overall qualitative diagnosis of the product indicates that the environmental performance of the product can be improved by acting on design.

The QALCC points out that the life cycle stages of "installation", "maintenance" and "end-of-life management" are the most environmentally-friendly. It means that the environmentally relevant criteria defined for each case have already a medium to high level of implementation in product design. The most sensitive life cycle stages to provide relevant environmental improvement are therefore those related to product "conceptualization" and "operation", "material use and production" and "packaging and distribution".

Concept The low "eco-innovation" and "multifunctionality" of the product are identified as the most significant environmental aspects to be implemented during the early stage of product conceptualization.

Materials and production The use of "recycled materials" and "biodegradable materials" in the design and production of the product system are considered environmentally relevant criteria with high room for implementation to improve the environmental performance of the product.

Operation Product operation is perceived as the most environmentally relevant life cycle stage. The implementation of "renewable energy sources", "energy control devices", and "reduction of energy consumption in operation" is considered to have a high potential for implementation in product design in order to improve the environmental performance of the CP.

Packaging and distribution Promoting the use of "low-environmental impact vehicles" as well as the optimization of the "load capacity (volume and cargo)" for the distribution of materials from factories to the assembly company and from the company to site of emplacement of the CP represent have a high room for implementation in order to improve CP´s environmental performance. The use of "reusable packaging material" is also considered to have a medium room for implementation.

The results from the QALCC provide a first perception of the environmental suitability and potential for environmental improvement of the CP design. However, QALCC results should be complemented with comprehensive quantitative environmental data for the completion of the identification and characterization of the most suitable hot-spots for significant environmental improvement through eco-design. Thus, an LCA is should be subsequently addressed.

Section A.3. Life Cycle Assessment of CP product system

LCA is a powerful scientific-based quantitative tool for sustainability-based decision-making (Baumann and Tillman 2004) thus it is essential for DfE of products. In this way, LCA is applied according to the guidelines specified by the ISO 14044 (2006) in order to complete the environmental characterization of the conventional product.

Section A.3.1. System boundaries of the CP product system

System boundaries in LCA consist of specifying the life cycle stages and unit processes that are considered as part of the product system under study in order to properly compile the related inputs and outputs for a consistent and reliable characterization of life-cycle environmental impacts.

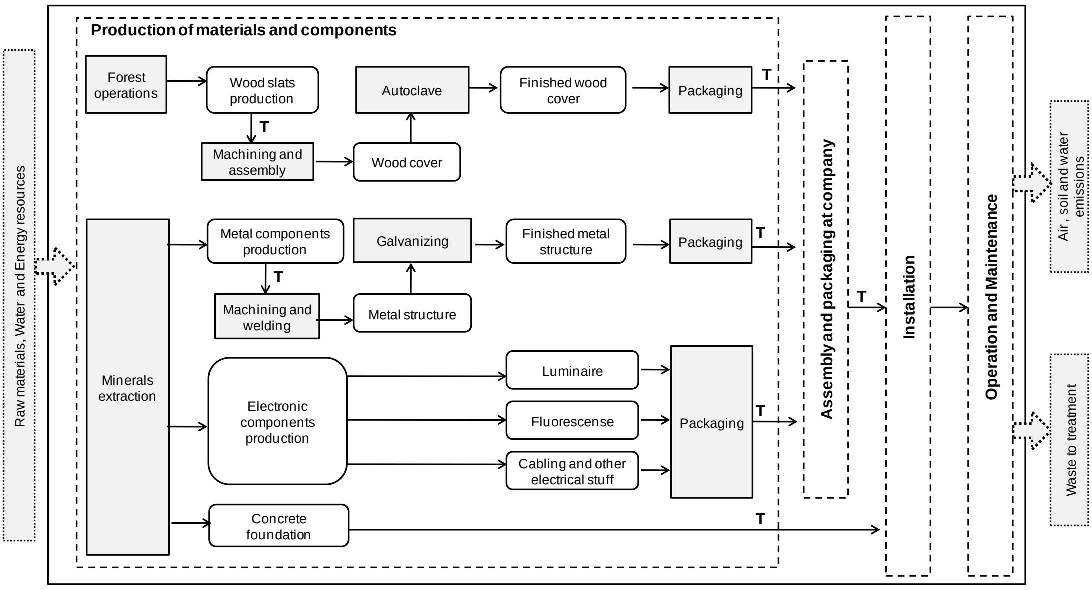


Fig. IV.2 System boundaries of CP product system

All the relevant unit processes related to the product system from the extraction of raw materials for materials and components production to lifespan operation are considered in the compilation and calculation of the life cycle inventory (LCI) data related to the CP.

Section A.3.2. Life cycle inventory data of the CP product system

Life cycle stage	Components	Flows	Amount
Product design	Wooden cover	Wooden (red pine) slabs	175.76 kg
		Xylazel IMPRALIT KDS (autoclave)	0.62 kg
		Electricity consumption in wood processing	104.00 kWh
	Metal structure	Galvanized steel S-275 JR (support columns)	347.06 kg
		Stainless steel (screws)	0.13 kg
		Galvanized carbon steel (joists and	5.04 kg

		auxiliary elements)	
		Electricity consumption in steel processing	372.61 kWh
	Lighting equipment	Anodised aluminium sheet (reflector)	0.60 kg
		Copper wiring (cables)	0.01 kg
		Polycarbonate (diffuser)	4.44 kg
		Fluorescence (2 x 58W)	6.40 kg
		Luminaire HF (2 X 65W)	1.60 kg
	Packaging	Polypropylene (strips)	0.77 kg
		Industrial steel (strips)	1.00 kg
		Wood (pallet)	11.38 kg
		Cardboard (components)	2.05 kg
Materials Transportation	Distribution of the wooden cover	Raw wood to processing plant	2,700 km, train
			200 km, truck 30t
		Wood slabs to assembly plant	111 km, van 3t
	Distribution of the metallic structure	Raw steel to processing plant	1,066 km, truck 20t
		Steel parts to assembly plant	30 km, van 3.5t
		Steel screws	20 km, van 5t
	Distribution of the lighting equipment	Electrical materials	23 km, van 3t
	Distribution of the foundation	Concrete HM-20	30 Km, truck 3.5t
	Distribution of the pergola	Finished product	650 km, truck 3t
Product installation	Foundation	Concrete HM-20	2,990 kg
		Electricity required in installation	420.16 kWh
Product use	Operation (*)	Electricity consumption (10 years operation)	10,480 kWh
Product Maintenance	Electric equipment	Fluorescence replacement (x3) (2 substitutions due to end of life + 1 additional substitution due to incidences)	19.20 kg

Table IV.4 LCI dataset of the CP product system. NOTE: (*) Considering its implementation at the public space of the city of Barcelona in Spain (see section 8.2.2 of the main body of the article).

The LCI data has been directly provided by the company responsible for the design of the product system under assessment. LCI data correspond to a basic module of CP with an estimated lifespan of 10 years. Following, some basic relevant information related to life-cycle stages and unit processes is provided:

Materials and components

- Wooden cover: 8 slatted pine blocks – (2 crossbars of 40x45x3310 mm and 33 slabs of 40x45x500 mm). The density of the wood was assumed to correspond to 500-540 kg/m3.
- Metal structure: The steel bolts used to fix the pergola on the ground are assumed to correspond to "reinforcing steel" as specified by the ecoinvent 2.2 database, whereas the stainless steel related to the use of screws correspond to "chromium steel".
- Lighting equipment: plastic extraction is included in environmental calculations. The fluorescence is assumed to correspond to 60 W bulbs according to the ETH-ESU 96 System Process database (Pré Consultants, 2001) due to the lack of more specific options.

Production

- Machinery used for wood processing: multiple saw, moulder, topping, splitting, and bench mounting. In wood treatment through autoclave, wood drying is not included in calculations given it comes dried from the place of origin.
- The energy consumption related to the processing of materials and components includes the energy use by the suppliers in the pre-treatment of raw material as well as the energy use in materials production.
- All the machinery employed in the different unit processes consume low-voltage electricity, with the exception of the machinery employed in the autoclave and galvanizing processes where medium-voltage is required.

Transport

- The wood used for the design of the CP comes from central Sweden, whereas the galvanized steel comes from Italy. Average distances for wood and steel transportation from Sweden and Italy, respectively, to the designer company are considered in calculations.
- It is considered an average national transportation distance of 650 km from the designer company to the site of emplacement of the CP.

- EURO4 vehicles of variable capacity are employed for materials transportation.

Installation

- It has been estimated that the installation of the CP in the public space requires about 1h 50min. Construction works are addressed by using a 20tn truck-crane, a backhoe and a concrete mixer.

Operation and Maintenance

- The functional unit (FU) used to characterize the life-cycle environmental performance of the product systems has been defined as the prospect of supplying diurnal shadow (45,000 h) and nocturnal light (42,600 h) per module of pergola implemented in the public in the city of Barcelona (Spain) during a timeframe of 10 years (baseline case scenario).
- The fluorescence is estimated to have a service life of around 15,000 hours what corresponds to 3 years of use. A total of 3 replacements are therefore assumed to be required during CP operation (2 due to the end-of-service life and an additional one due to urban incidents). Nevertheless, the service life of the rest of the lighting equipment, including the electric components, are considered to have a service life over 50,000 hours of operation (hence over 10 years)

End-of-life waste management

- The CP is considered to be removable and recyclable by 97%. The potential material recovery of the metal structure consists of smelting and recycling into useful products for the construction industry. The wood cover and plastic components are also recyclable. Only 3% of the material components are components are considered to be sent to incineration or disposal to landfill.
- Waste management is excluded from calculations. On the one hand, the expenditure in further recycling of materials into new products is assumed to be allocated to the new product life-cycles. On the other hand, large part of the CP module has more than 10 years of service life thus it exceeds the timeframe considered in environmental calculations.

Section A.3.3. Life cycle impact assessment of CP product system

A list of CML 2001 environmental indicators (Guinée et al., 2001), including the Primary Energy Demand (PED) indicator (Hischier et al., 2010), are used for the life cycle impact assessment (LCIA) of the CP product system. The CML impact categories considered are abiotic depletion (ADP, kg Sb eq.), acidification (AP, kg SO_2 eq.), eutrophication (EP, kg PO_3^{-4} eq.), global warming (GWP, kg CO_2 eq. /100 years), ozone layer depletion (ODP, kg CFC-11eq.) and human toxicity (HTP, kg 1.4-DB eq.), and photochemical ozone creation potential (kg C_2H_4 eq.). The software Simapro (PRé Consultants, 2013) and the ecoinvent v2.2 database (SCLCI, 2010) were used as supporting analytical tools.

Environmental indicators	Materials	Production	Packaging	Transport	Installation	Operation	TOTAL
ADP	6.49E+00	1.48E+00	6.34E-02	8.24E+00	8.50E-01	3.33E+01	**5.05E+01**
AP	3.68E+00	1.31E+00	2.26E-02	4.75E+00	1.37E+00	2.93E+01	**4.05E+01**
EP	1.83E+00	3.09E-01	1.06E-02	1.09E+00	3.04E-01	6.94E+00	**1.05E+01**
GWP	1.05E+03	1.97E+02	6.33E+00	1.31E+03	1.33E+02	4.42E+03	**7.12E+03**
HTP	2.66E+03	1.17E+02	9.70E+00	1.43E+02	1.82E+01	2.63E+03	**5.58E+03**
ODP	4.74E-05	1.33E-05	3.34E-07	1.93E-04	1.64E-05	3.00E-04	**5.71E-04**
POCP	3.53E-01	8.67E-02	2.07E-03	1.23E-01	4.45E-02	1.95E+00	**2.56E+00**
PED	1.37E+04	4.69E+03	2.13E+02	1.87E+04	1.94E+03	1.06E+05	**1.45E+05**

Table IV.5 Relative contribution to environmental impacts of each life cycle stage of the CP product system.

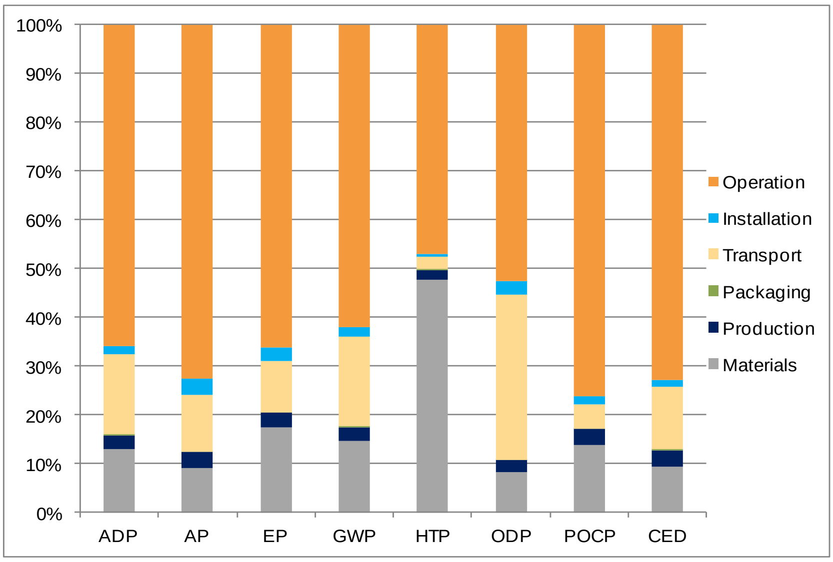


Fig. IV.3 Relative contribution to environmental impacts of each life cycle stage of the CP product system.

The operation stage is the most environmentally relevant hot-spot of the life cycle of the CP product system. It accounts for 52% (ODP) to 76% (POCP) of the total CP´s life cycle environmental burdens. This environmental burden is directly related to the high electricity requirements for nocturnal lighting in the timeframe considered. The second most relevant environmental aspect of the life cycle of the CP product system is materials use. They account from 8% (ODP) to 48% (HTP) of total life cycle environmental burdens. Materials transportation is especially relevant in the contribution to life-cycle GWP (19%) and ODP (34%) environmental impact categories, which is mainly determined by the distribution of the galvanized steel.

The Fig. IV.4 presents the total environmental burdens of materials disaggregated by the relative contribution per type of elements.

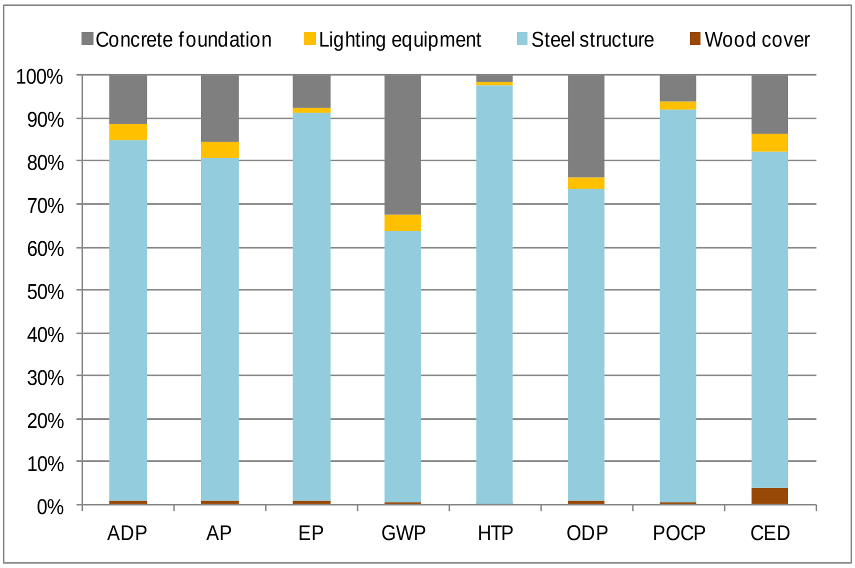


Fig. IV.4 Relative contribution to environmental impacts by the materials used for the design of the CP product system.

The use of steel in the design of the structure of the CP represents the most critical element for the total environmental burden of materials. Steel accounts for 63% (GWP) to 98% (HTP) of the total contribution to environmental impacts by materials. The second most critical element is concrete which is especially relevant in the contribution to environmental impact for GWP (32%) and ODP (24%). The contribution of these materials to environmental impact is mainly related to the energy requirements during their industrial production. However, for the case of steels, the presence of chromium metal highly determines the potential contribution to human toxicity.

In this way, ecodesign efforts should be focused on the operations stage and materials use and transportation:

Operation stage Ecodesign strategies should be focused on increasing the energy efficiency of the lighting equipment, reducing energy consumption by using mobility sensors, and implementing renewable energy sources.

Material use and transportation Steel use represent the most critical element for both the environmental impacts associated with material use and transportation related to the life cycle of the CP product system. The use of alternative structural materials coming from local markets is the key aspect to be considered in the ecodesign of the product system.

Section A.3. Eco-briefing

The main requirements for a conventional briefing are contextualization (general description, market trends), product (objective, range of product), design goals and constraints (available technology, cost, time), project definition and expected results (Sanye-Mengual et al., 2014). An eco-briefing complements this information with the identified environmental critical points for the different life-cycle stages of the product under assessment. In this way, the outputs from the application of both qualitative and quantitative environmental assessment tools are compiled in an eco-briefing matrix (Smith and Wyatt, 2006) in order to communicate to designers the most critical life-cycle environmental hot-spots where ecodesign efforts should be mainly focused to minimize the product´s contribution to environmental impacts. The eco-briefing therefore is a checklist that presents the basic environmental requirements to be considered in the ecodesign thinking process.

Table IV.6 summarizes the most environmentally relevant hot-spots of the life-cycle of the CP product system to be considered in the definition of a set of ecodesign strategies for product´s environmental improvement.

Environmentally relevant life-cycle hot-spots	**Key life cycle stages to their solution**						
	C	**MP**	**TP**	**IR**	**O**	**M**	**EM**
High environmental impact of the materials	●	●	○	○	○	○	○
Use of primary (virgin) materials	○	●	○	○	○	○	○
High electricity requirements	●	○	○	○	●	○	○
Use of non-renewable energy resources	●	○	○	○	●	○	○
Low cargo efficiency for the transportation of materials	●	○	●	○	○	○	○
Use of pollutant transport vehicles	○	○	●	○	○	○	○
Limited functionality of the product system	●	○	○	○	●	○	○

Table IV.6 Eco-briefing matrix of the CP product system. Acronyms: C – Concept; MP – Materials and production; TP – Transport and Packaging; IR – Installation and Removal; O – Operation; M – Maintenance; EM – End-of-Life Management.

The results of the eco-briefing indicate that the DfE solutions should be mainly focused on the concept definition given that it directly defines the potential environmental performance of the rest of the life cycle stages of the product system. Ecodesign strategies should be concentrated on i) the use of environmentally suitable materials (primary materials with reduced environmental burden and/or increase the use of recycled/recyclable material inputs); ii) the increase of energy efficiency and the use of renewable energy inputs for product operation; iii) the promotion of well-considered transportation management, including the use of environmentally-friendly vehicles; and iv) The promotion of multifunctionallity of the material structure and product use through eco-innovation. These issues represent key environmental requirements to be considered in the definition and selection of ecodesign strategies in order to achieve significant environmental improvements by the conceptualization of an eco-product.

Section A.4. Definition and selection of eco-design strategies

Once the most significant hot-spots for environmental improvement have been identified in the product evaluation, eco-design strategies are proposed in order to improve the product´s life cycle environmental performance. Subsequently, a feasibility assessment is performed by the company to observe technical, economic and social constrains. In this way, the most priority and promising ecodesign strategies are selected for the conceptualization of the eco-product and the design of a prototype.

A total of 44 ecodesign actions for potential environmental improvement of the life cycle of the product system have been identified. Table IV.7 presents a description of each of these ecodesign actions with the corresponding technical (T), economical (E) and social (S) feasibility assessment. The viability of each ecodesign action is determined as "Feasible" (F+), "Feasible at mid-term" (F-), "Unfeasible" (Uf) or "Not apply" (NA) when the criterion is not considered. Finally, a priority value is defined as "High", "Medium" or "Low" in order to establish a classification for the subsequent selection of eco-design strategies.

Stage	**Ecodesign strategy**	**Criterion**	**Feasibility**				
			F+	**F-**	**Uf**	**NA**	**Priority**
C.01	Design as multifunctional support	T	●	○	○	○	Not a priority
		E	●	○	○	○	
		S	●	○	○	○	
C.02	Modular design	T	●	○	○	○	High

		E	●	○	○	○	
		S	●	○	○	○	
C.03	Design for customization / multiservice provision	T	●	○	○	○	High
		E	●	○	○	○	
		S	●	○	○	○	
C.04	Design for disassembly	T	●	○	○	○	High
		E	●	○	○	○	
		S	●	○	○	○	
C.05	Component design applicable to different products	T	●	○	○	○	Low
		E	●	○	○	○	
		S	●	○	○	○	
C.06	Design for minimizing maintenance requirements	T	●	○	○	○	High
		E	●	○	○	○	
		S	●	○	○	○	
C.07	Design to avoid light pollution	T	●	○	○	○	High
		E	●	○	○	○	
		S	●	○	○	○	
		E	●	○	○	○	
		S	●	○	○	○	
C.08	Design to minimize the production requirements	T	●	○	○	○	High
		E	●	○	○	○	
		S	●	○	○	○	
C.09	Design adaptable to urban conditions	T	●	○	○	○	High
		E	●	○	○	○	
		S	●	○	○	○	
C.10	Design to provide nocturnal security	T	○	○	○	●	Not a priority
		E	○	○	○	●	
		S	○	○	○	●	
MP.01	Optimization of material use	T	●	○	○	○	High
		E	●	○	○	○	
		S	○	○	○	●	
MP.02	Use of recycled materials	T	●	○	○	○	High
		E	●	○	○	○	
		S	●	○	○	○	
MP.03	Avoid the need of coating on metal surfaces	T	○	○	●	○	Not a

		E	○	○	○	●	priority
		S	○	○	○	●	
MP.04	Sourcing sustainable wood	T	●	○	○	○	High
		E	●	○	○	○	
		S	●	○	○	○	
MP.05	Minimization of treatment requirements for wood	T	○	○	○	●	Not a priority
		E	○	○	○	●	
		S	○	○	○	●	
MP.06	Reduction of the number of components	T	●	○	○	○	High
		E	●	○	○	○	
		S	●	○	○	○	
MP.07	Make informed environmental choices for product suppliers	T	○	●	○	○	Not a priority
		E	○	●	○	○	
		S	○	○	○	●	
MP.08	Priorization of mechanical joints	T	●	○	○	○	High
		E	●	○	○	○	
		S	●	○	○	○	
TP.01	Use of EUROV vehicles	T	●	○	○	○	Low
		E	-	-	-	-	
		S	○	○	○	●	
TP.02	Use of biodiesel-powered vehicles	T	●	○	○	○	Low
		E	-	-	-	-	
		S	○	○	○	●	
TP.03	Prioritize the use of materials from local suppliers	T	●	○	○	○	High
		E	●	○	○	○	
		S	●	○	○	○	
TP.04	Use of recycled and recyclable packaging materials	T	○	●	○	○	High
		E	●	○	○	○	
		S	○	○	○	●	
TP.05	Use of reusable packaging components	T	●	○	○	○	High
		E	●	○	○	○	
		S	●	○	○	○	
IR.01	Adaptation to the terrain features	T	○	○	○	●	Not a priority
		E	○	○	○	●	
		S	○	○	○	●	

IR.02	Lighten the pergola for easy maneuverability	T	●	○	○	○	High
		E	●	○	○	○	
		S	●	○	○	○	
IR.03	Reduction of the construction requirements	T	○	●	○	○	Not a priority
		E	○	●	○	○	
		S	○	○	○	●	
IR.04	Use of environmentally suitable materials for the installation of the pergola in the public space	T	●	○	○	○	Not a priority
		E	●	○	○	○	
		S	○	○	○	●	
O.01	Lighting optimization	T	●	○	○	○	High
		E	●	○	○	○	
		S	●	○	○	○	
O.02	Implementation of photo-sensitive cells	T	●	○	○	○	Not a priority
		E	●	○	○	○	
		S	●	○	○	○	
O.03	Light attenuation	T	●	○	○	○	High
		E	●	○	○	○	
		S	●	○	○	○	
O.04	Implementation of mobility sensors	T	●	○	○	○	Not a priority
		E	●	○	○	○	
		S	●	○	○	○	
O.05	Use of high-efficient lighting equipment	T	●	○	○	○	High
		E	●	○	○	○	
		S	●	○	○	○	
O.06	Improve lighting efficiency	T	●	○	○	○	Not a priority
		E	●	○	○	○	
		S	●	○	○	○	
O.07	Use of high-efficient electronics	T	●	○	○	○	High
		E	●	○	○	○	
		S	●	○	○	○	
O.08	Implementation renewable energy sources	T	●	○	○	○	High
		E	●	○	○	○	
		S	●	○	○	○	
O.09	Promoting energy self-sufficiency	T	○	○	●	○	Not a priority
		E	○	○	●	○	

		S	○	○	○	●	
O.10	Implementation of an energy supply device	T	●	○	○	○	High
		E	●	○	○	○	
		S	●	○	○	○	
M.01	Implementation of low-maintenance covers	T	●	○	○	○	High
		E	●	○	○	○	
		S	●	○	○	○	
M.02	Use of low-maintenance lighting equipment	T	●	○	○	○	High
		E	●	○	○	○	
		S	●	○	○	○	
M.03	Provision of clear information about maintenance requirements over time	T	●	○	○	○	High
		E	●	○	○	○	
		S	●	○	○	○	
M.04	Use of replaceable elements	T	●	○	○	○	High
		E	●	○	○	○	
		S	●	○	○	○	
M.05	Technical improvements	T	●	○	○	○	High
		E	●	○	○	○	
		S	●	○	○	○	
EM.01	Facilitate the recovery of components	T	○	○	●	○	Not a priority
		E	○	○	●	○	
		S	○	○	●	○	
EM.02	Develop a protocol for the disassembly of the pergola and end-of-life management of the components	T	○	●	○	○	Not a priority
		E	○	●	○	○	
		S	○	●	○	○	

Table IV.7 Definition of eco-design strategies for the life-cycle environmental improvement of the CP product system. Acronyms: C – Concept; MP – Materials and production; TP – Transport and Packaging; IR – Installation and Removal; O – Operation; M – Maintenance; EM – End-of-Life Management.

The eco-design strategies arise as environmental answers to the environmental impacts detected in the previous QALCC and LCA studies and from the environmental requirements summarized in the eco-briefing matrix. Considering the results presented in Table IV.7 a total of 27 ecodesign strategies (those classified as high feasible and priority) are selected for QALCC and LCA in order to determine the most suitable alternatives to be implemented in the conceptualization and development of a prototype of eco-product in order to achieve significant environmental improvement. In this process, a series of scenarios are defined by grouping the set of ecodesign alternatives considered. Table IV.8 presents a brief description of each case scenario defined for environmental assessment (QALCC and/or LCA, when it is the case).

Description of case scenarios	Ecodesign alternatives	Environmental assessment
I . Material efficiency	MP.01 MP.02 MP.04	LCA
Ia. Reduction of material inputs		
Ib. Substitution of steel with aluminium		
II. Transport efficiency	TP.01 TP.03	LCA
IIa. Use of EUROV vehicles		
IIb. Use of materials (wood and steel) from local markets		
III. Packaging efficiency	TP.04 TP.05	LCA
IIIa. Substitution of steel strips with plastic strips		
IV. Energy efficiency	O.03 O.05 O.07	LCA
IVa. Reduction in energy consumption by LED technology use		
IVb. Reduction in energy consumption by light attenuation		
IVc. Reduction in energy consumption by LED use and light attenuation		
V. Implementation of renewable energy sources	C.08	LCA
Va. Implementation of photovoltaic panels		
Vb. Adjustment of the inclination and orientation of the photovoltaic panels to optimize PV electricity production		
Vc. Calculation of PV electricity production in different geographical contexts		
VI. Functional rethinking of the concept of pergola	C.02; C.03 C.04; C.08 C.09; MP.06 MP.08; M.04 M.05; IR.02	QALCC
VII. Redesign of the lighting system	C.07; C.02	QALCC
VIII. Implementation of an energy delivery device	O.10	QALCC
IX. Minimization of maintenance requirements	C.06; M.01 M.02; M.03	QALCC

Table IV.8 Case scenarios defined for the environmental assessment (QALCC and/or LCA) of the selected alternatives for the ecodesign of the conventional product.

The final step consists on the design of a prototype of eco-product which integrates the most promising ecodesign aspects. In this way, the improved life-cycle environmental performance of the prototype of eco-product is validated by LCA. In this stage, the total contribution to environmental impacts throughout the life cycle of the CP and prototype of eco-product (SP) is compared. The last adjustments in product design are addressed in this stage for obtaining a more environmentally friendly product.

Section A.5. Eco-product attributes

In accordance to the results obtained from the QALCC and LCA of the different case scenarios defined by relying on the ecodesign requirements, a prototype was designed and an eco-product formulated as a solar pergola (SP). The SP includes a set of specific ecodesign strategies, namely: use of aluminium instead of steel for the structure, implementation of mobility sensors and use of LED technology for reducing energy consumption during operation (nocturnal lighting), implementation of photovoltaic panels on the cover with optimal orientation (10º slope) to maximize solar energy harvesting for (green) energy self-sufficiency of the product system, modular design (adaptable to different urban usage conditions) and minimization of the maintenance requirements over time. The Fig. IV.5 shows a basic exploded illustration of the SP design, which is composed by a cover made up of 12 solar panels and an aluminium frame supported by 4 aluminium columns, which are fixed on the ground by the use of steel anchors. The lighting equipment consists of 4 LED panels.

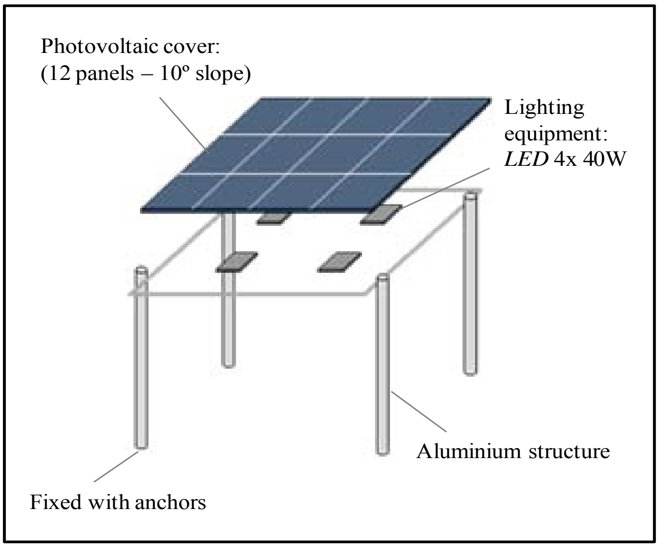


Fig. IV.5 Basic exploded illustration of the solar pergola resulted after the DfE process

The columns and the frame of the cover of the SP product system are made up of mixed extruded aluminium. All the elements employed are modular and independent to optimize their transport, assembly at the company and easy and flexible installation of the product system in the public space. The aluminium columns can be positioned at any point along the perimeter of the cover of the pergola. The photovoltaic cover is multifunctional; panels provide shadow, facilitate the support of the electric lighting equipment and supply green energy for nocturnal lighting. The slop of the photovoltaic cover can be adapted to get the optimum radiation for maximum photovoltaic production. The energy consumption of the product is minimized due to light attenuation through mobility sensors plus the use of LED technology. Lighting provides a better perception of the real colour of the objects thanks to the high colour rendering index associated with LEDs. Light pollution is also minimized; LEDs provide a better concentration of the beam of light than other available lighting technologies.

The design of eco-product aims to solve the most critical environmental aspects associated with the CP design. On the one hand, the qualitative diagnosis of the product system pointed out that the “concept” and “operation” stages were the least environmentally friendly ones. The low eco-innovation and limited functionality of the CP design, with the high energy requirements in operation among the lack of use of renewable energy sources were identified as the most significant environmental hotspots. On the other hand, the quantitative environmental assessment of the product system showed that among the operation stage, materials use are significant contributors to environmental impacts, where the steel is the most critical element.

The SP eco-product represents the commitment of the designer company to introduce in the market a product that can contribute to provide a more comfortable social service (diurnal shadow and nocturnal light) at a reduced environmental cost.

Section A.6. Environmental assessment of the SP

Section A.6.1. Life Cycle Assessment of SP product system

Section A.6.1.1. System boundaries of SP product system

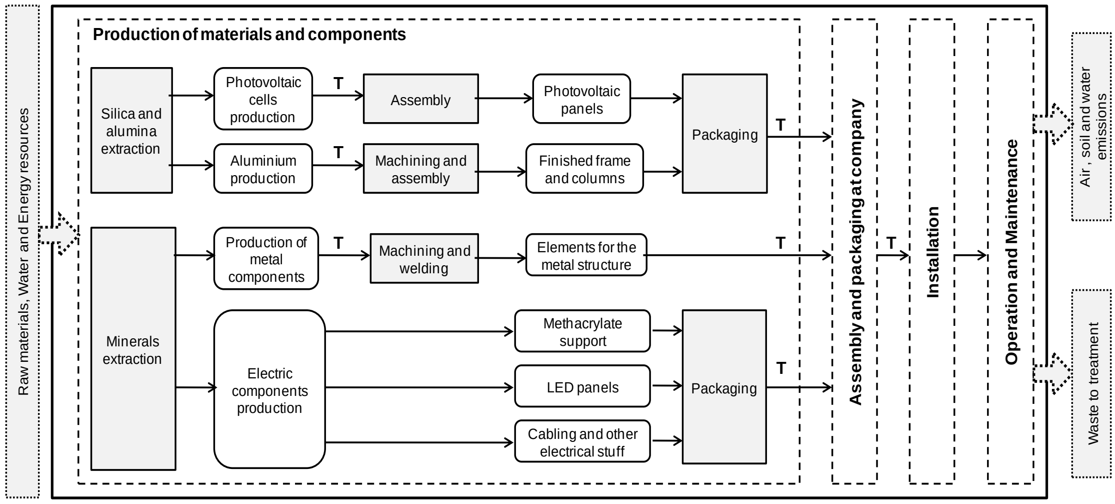


Fig. IV.6 System boundaries of SP product system

All the relevant unit processes related to the product system from the extraction of raw materials for materials and components production to lifespan operation are considered in the compilation and calculation of the life cycle inventory (LCI) data related to the SP.

Section A.6.1.2. Life cycle inventory data of the SP product system

Life cycle stage	Components	Flows	Amount
Product design	Cover	Photovoltaic panels	216 kg
	Metal structure	Extruded aluminium (frame and columns)	330,87 kg
		Stainless steel (screws)	0,13 kg
		Electricity consumption in aluminium processing	325,94 kWh
	Lighting equipment	LED panels	22 kg
		Copper wiring (cables)	22 m
		Methacrylate support	4,44 kg
	Packaging	Wood	11,38 kg
		Cardboard	2,05 kg
Materials transportation	Distribution of the photovoltaic cover	Photovoltaic cells to assembly plant (transoceanic ship freight)	15,000 km
		Photovoltaic panels to designer company	50 km, van 3 t

	Distribution of metal component	Aluminium to assembly plant	1,060 km, truck 20 t
		Metal structure to assembly plant	480 km, truck 3.5 t
	Distribution of the lighting equipment	LED panels to assembly plant (transoceanic ship freight)	18,500 km
		Electrical materials	40 km, van 3 t
	Distribution of the pergola	Finished product	650 km, truck 3t
Product use	Operation (*)	Electricity consumption (10 years operation)	3.467,64 kWh
Product installation	Construction works	Fixed with anchors (bolts)	4 units
		Electricity required in installation	338,12 kWh

Table IV.9 LCI dataset of the SP product system. NOTE: (*) Considering its implementation in the public space of the city of Barcelona in Spain (see section 8.2.2 from chapter 8).

The LCI data has been directly provided by the company responsible for the design of the product system under assessment. LCI data correspond to a basic module of CP with an estimated lifespan of 10 years. Following, some basic relevant information related to life-cycle stages and unit processes is provided:

Materials and components

- The SP weighs 573.44 kg divided by 58% related to the structure and 42% related to the cover.
- Photovoltaic panels (Sunpower Corp.) implemented in the SP design (12 units) have 305 of nominal power and around 18.7% of efficiency.
- The type of LED panels (Lumisheed outdoor, Fawoo, LSL42-2, with methacrylate screen) implemented have an aluminium frame with dimensions 1,230 x 330 x 21 mm. The LED equipment consumes 40.7 W/h and presents a colour temperature of 5,000 – 6,000 K and 265 Lx.
- Moreover, energy consumption in operation is reduced by 50% through light attenuation. Nevertheless, mobility sensors are not included in the LCI data due to the lack of information available to determine their contribution to environmental impact.

Production

- The energy requirements for the production of photovoltaic cells and LED panels are not included in the LCI of the product system due to the lack of information available. Only the data considered in the Ecoinvent dataset related to this elements is used to determine their corresponding contribution to environmental impact.

Transport

- EUROIV vehicles are considered to be used for materials transportation
- Average distances from processing plants to assembly are considered in calculations
- The photovoltaic cells are produced in China, whereas the aluminium is processed in the North of France. LED panels are produced in South Korea. The assembly of the pergola is addressed in Barcelona (Spain).

Installation

- It considers the same energy requirements for the installation of the design of conventional pergola excluding the energy consumption of the construction works related to the foundation.

Operation and Maintenance

- The average lifespan of the LED panels is 50.000 hours therefore no replacements are required for the timeframe considered (10 years = 42,600 h of nocturnal lighting).
- Photovoltaic panels have a lifespan of 25 years, according to the information indicated by the producer. The environmental impact related to photovoltaic panels is adjusted therefore to the timeframe considered in calculations.
- The aluminium structure and the rest of elements embedded in the design of the SP are considered to have a lifespan that exceeds 10 years.

End-of-life waste management

- The potential material recovery of the aluminium frame and structure consists of smelting and recycling into useful products for the construction industry. Part of the electronic equipment can be also recycled.
- Waste management is excluded from calculations. On the one hand, the expenditure in further recycling of materials into new products is assumed to be allocated to the new product life-cycles. On the other hand, a large part of the design of the SP module has more than 10 years of service life thus it exceeds the timeframe considered in environmental calculations.

Section A.6.1.3. Life cycle impact assessment of SP product system

Environmental indicators	Materials	Production	Packaging	Transport	Installation	Operation	TOTAL
ADP	2.29E+01	1.43E+00	2.39E-02	8.04E+00	6.84E-01	0.00E+00	**3.31E+01**
AP	1.55E+01	1.87E+00	1.11E-02	5.30E+00	1.10E+00	0.00E+00	**2.38E+01**
EP	9.24E+00	3.81E-01	6.10E-03	1.09E+00	2.45E-01	0.00E+00	**1.10E+01**
GWP	3.24E+03	1.96E+02	3.07E+00	1.28E+03	1.07E+02	0.00E+00	**4.82E+03**
HTP	6.68E+03	1.02E+02	2.45E+00	1.61E+02	1.46E+01	0.00E+00	**6.96E+03**
ODP	4.55E-04	1.06E-05	2.65E-07	1.88E-04	1.32E-05	0.00E+00	**6.67E-04**
POCP	8.58E-01	6.90E-02	8.68E-04	1.82E-01	3.58E-02	0.00E+00	**1.15E+00**
PED	5.95E+04	3.97E+03	1.37E+02	1.84E+04	1.56E+03	0.00E+00	**8.36E+04**

Table IV.10 Relative contribution to environmental impacts of each life cycle stage of the SP product system.

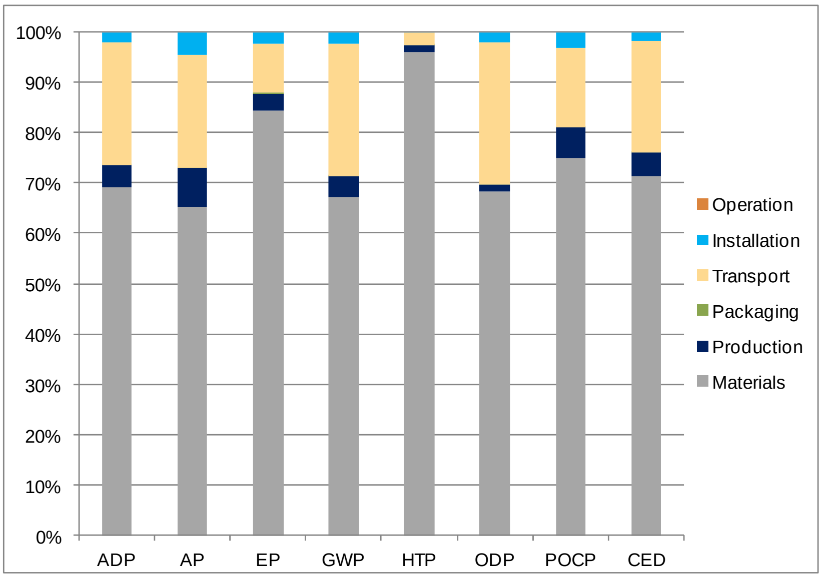


Fig. IV.7 Relative contribution to environmental impacts of each life cycle stage of the SP product system.

Materials represent the most environmentally relevant hot-spot of the life cycle of the SP product system. They account for 65% (AP) to 96% (HTP) of the total SP´s life cycle environmental burdens.. The second most relevant environmental aspect of the life cycle of the SP product system is materials transportation. It accounts from only 2% (HTP) to 28% (ODP) of total life cycle environmental burdens, which is mainly determined by the distribution of the aluminium. The use stage of the SP is considered to have "zero" contribution to environmental impacts given that the energy requirements for nocturnal lighting are supplied by using solar energy inputs.

The Fig. IV.8 presents the total environmental burdens of materials embedded in the SP design disaggregated by the relative contribution per type of elements.

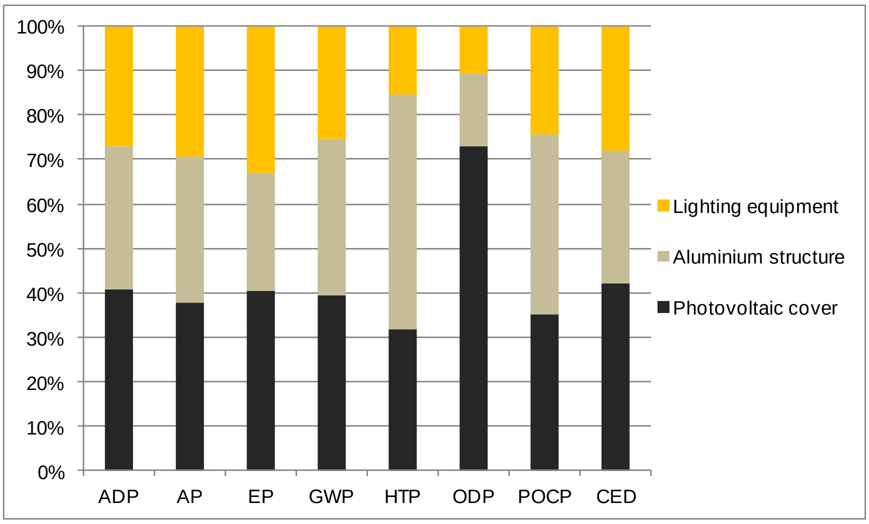


Fig. IV.8 Relative contribution to environmental impacts by the materials used for the design of the SP product system.

The materials employed in the design of the SP have a similar contribution to impact (30%) for some of the categories considered. The photovoltaic cover, which is the key for the clean operation of the product system, is the most critical element of the SP design. It accounts for 32% (HTP) to 73% (ODP) of the total contribution to environmental impacts by materials. The second most critical element is aluminium which contributes from 16% (ODP) to 53% (GWP) of the total environmental impacts. The contribution of these materials to environmental impact is mainly related to the energy requirements during their industrial production, including the production of LED panels that have a low contribution to impact in operation but a relevant environmental burden during production.

Environmental data correspond to the use of the SP according to the functional unit defined in the main body of the article. However, the life-cycle environmental performance of the SP product system is highly dependent on the net production of solar photovoltaic electricity and the carbon intensity of the electricity grid mix used for environmental calculations. The following section presents the basic variables considered to determine the sensitivity of the environmental results related to the lifetime performance of the SP product system.

Section A.6.2. Photovoltaic electricity production by the SP product system

The potential for photovoltaic electricity generation by the SP design along 10 years of operation has been calculated by relying on the useful photovoltaic surface considering 10 ° of slope and a total installed power of 140 Wp/m². According to these considerations, the PV Potential Estimation Utility developed by the Join Research Centre of the European Commission (http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php) has been applied to determine the corresponding amount of photovoltaic electricity production according to the implementation of the SP product system in different Spanish latitudes (Barcelona, Bilbao, Madrid and Murcia). The Spanish latitudes considered represent the cities which account for the largest market volume for the designer company that has participated in the research but provide at the same time a useful representation of the variability of the solar radiation from North to South.

<table>
<tr><th>Photovoltaic cover</th><th colspan="2">Slope (10º)</th></tr>
<tr><td>a (cm)</td><td colspan="2">480</td></tr>
<tr><td>b (cm)</td><td colspan="2">362</td></tr>
<tr><td>Useful photovoltaic surface (m²)</td><td colspan="2">17,38</td></tr>
<tr><td>Installed power (kWp)*</td><td colspan="2">2,43</td></tr>
<tr><td rowspan="4">Potential photovoltaic electricity production (kWh/10years)</td><td>Barcelona</td><td>33,600</td></tr>
<tr><td>Bilbao</td><td>29,600</td></tr>
<tr><td>Madrid</td><td>36,300</td></tr>
<tr><td>Murcia</td><td>37,200</td></tr>
</table>

Table IV.11 Photovoltaic electricity production by the SP design. NOTE: (*) 140 Wp/m².

Section A.7. Description of the variables considered to compare the life-cycle environmental performance between CP and SP product systems

Section A.7.1. Lifetime energy consumption of CP and SP product systems for different Spanish geographical emplacements (latitudes)

Information provided by the Spanish National Statistical Institute (INE, 2014) regarding the average (1997-2012) annual hours of insolation by provinces has been used to adapt the energy consumption of the CP and SP product systems according to the lifetime nocturnal lighting requirements for different Spanish geographical latitudes. Table IV.12 presents the basic information related to each case scenario.

Variables		Barcelona	Bilbao	Madrid	Murcia
Nocturnal lighting requirements (h/10 years)		42,600	58,350	40,350	35,850
Energy consumption (kWh/10 years)	Conventional Pergola (CP)	10,480	14,354	9,926	8,819
	Solar Pergola (SP)	3,468	4,750	3,284	2,918
Surplus photovoltaic electricity generation by the SP design (kWh/ 10 years)		30,132	24,850	33,016	34,282

Table IV.12 Lifetime energy consumption of CP and SP product systems according to the nocturnal lighting requirements for different Spanish geographical latitudes

Section A.7.2. Carbon intensity and embodied energy of conventional Spanish, French and Greek electricity mixes

The carbon-intensity and embodied primary energy of the Spanish (ES) electricity grid mix defined according to Red Eléctrica Española (REE, 2011) represent the baseline electricity mix considered for environmental calculation. The Greek (GR) and the French (FR) electricity grid mixes defined according to ecoinvent 2.2 dataset (SCLCI, 2010) have been chosen as reference to determine the effect of the substitution of the consumption of high carbon and low carbon intensity electricity grid, respectively, by using photovoltaic electricity production.

Electricity mix	ES (%)	FR (%)	GR (%)
Cogeneration, wood	1.1	0.2	0.0
Cogeneration, biogas	0.3	0.1	0.2
Cogeneration 500kWe lean burn	9.8	0.0	0.0
Hard coal	15.2	4.5	0.0
Hydropower	12.1	11.9	8.6

Industrial gas	0.6	0.5	0.0
Lignite	0.8	0.0	54.4
Oil	0.9	1.0	12.9
Production mix photovoltaic	3.3	0.0	0.0
Wind power	15.4	0.2	1.8
Nuclear	21.3	78.5	0.0
Natural gas	18.7	3.2	13.8
Municipal waste incineration	0.5	0.0	0.0
Production mix BG	0.0	0.0	6.1
Production mix CENTREL	0.0	0.0	0.4
Production mix IT	0.0	0.0	0.3
Production mix MK	0.0	0.0	1.4

Table IV.13 Electricity grid mix considered to characterize and compared the lifetime environmental performance of the operation stage of the CP and SP product systems

Section A.7.3. Environmental burden of a functionally equivalent conventional public charging station for e-bikes to be attributed to the (extended) CP product system

Given that there is no information available in scientific literature regarding the environmental characterization of charging facilities for e-bikes, and that it was not possible to get access to specific LCI data provided by industrial designers/producers to determine their corresponding life-cycle environmental burden, the environmental outcomes provided by Mendoza et al. (2014b) related to public charging facilities for electric two-wheelers have been adapted to define the functionally equivalent environmental burden of the e-bike CCS to be integrate as part of the extended CP product system (see section 8.2.3 from chapter 8).

One of the designs of public charging facilities for electric two-wheelers analyzed by Mendoza et al. (2014) consisted on an outdoor recharging station with six outlets available that is a conventional model widely implemented in the city of Barcelona (Spain). The functionally equivalent life-cycle GWP and PED of this charging facility is adjusted by using as reference the amount of surplus photovoltaic generation by the SP design for the different geographical Spanish latitudes. Additionally, a 50% reduction in the related environmental burden is applied given that infrastructure requirements for e-bikes are considered to be much lower than the requirements for bigger electric two-wheel vehicles (large battery pack), as it was the case analyzed by Mendoza et al. (2014). Regarding the additional infrastructure requirements related to the SP product system to support a service of clean e-bike charging using surplus photovoltaic electricity generation, they are considered to be minimal. A line of outlets for e-bike plug-in can be implemented by using the structure and a large portion of the electronic material already available in the design of the SP product system.

Geographical emplacement	**Electricity grid mix**	**GWP**		**PED**	
		CCS	**Electricity supply**	**CCS**	**Electricity supply**
Barcelona (Baseline latitude)	ES	35.8	7901.4	709.8	219785.5
	FR	-	-	778.4	323137.1
	GR	49.6	29657.3	820.9	431716.2
Bilbao (Atlantic latitude)	ES	35.3	5671.3	764.5	166608.6
	FR	-	-	832.0	251843.2
	GR	48.9	23613.6	873.8	341388.9
Murcia (Mediterranean latitude)	ES	57.5	9653.3	1172.0	261560.0
	FR	-	-	1239.5	379143.9
	GR	71.2	34405.2	1281.3	502675.1

Table IV.14 Environmental burden of a functionally equivalent conventional public charging station for e-bikes to be attributed to the (extended) CP product system according to the geographical emplacement and electricity mix considered in calculations. NOTE: (-) not viable case scenario (see section 8.3.3. from chapter 8).

REFERENCES

AEMET, 2011. Series Climatológicas. Agencia Estatal de Meteorología. Estación meteorológica Barcelona-Fabra (Catalonia, Spain), Ministerio de Agricultura, Alimentación y Medio Ambiente, Gobierno de España. Online source: ftp://ftpdatos.aemet.es/series climatologicas/valores diarios/estacion/. Last accessed: Jun, 2013.

Acchar, W., Vieira, F.A., Hotza, D., 2006. Effect of marble and granite sludge in clay materials. Mater. Sci. Eng. A 419, 306 – 309.

ACEA, 2010. ACEA position and recommendations for the standardization of the charging of electrically chargeable vehicles. European automobile Manufacturers Association. Brussels, Belgium.

AEB, 2011. Recomanacions techniques per a la instal·lació i gestió de punts de recàrrega de vehicles elèctrics. Report prepared by the Agència d´Energia de Barcelona (AEB) for the City council of Barcelona.

Almeida, N., Branco, F., Santos, J.R., 2007. Recycling of stone slurry in industrial activities: Application to concrete mixtures. Build. Environ. 42, 810–819.

Amjad, S., Rudramoorthy, R., Neelakrishnan, S., 2011. Assessment of petroleum saving and greenhouse gas emission reduction from two-wheeler segment: 2011–2021. Transportation Res. Part D, 16(3), 265–269.

Angrill, S., Farreny, R., Martinez-Gasol, C., Gabarrell, X., Viñolas, C., Josa, A., Rieradevall, J., 2011. Environmental analysis of rainwater harvesting infrastructures in diffuse and compact urban models of Mediterranean climate. Int. J. Life Cycle Assess. 17 (1), 25 – 42.

Al-Hagla, K., 2008. Towards a Sustainable Neighborhood: The Role of Open Spaces. Int. J. Archit. Res. 2(2), 2162-177.

Ash, C., Jasny, B.R., Roberts, L., Stone, R., Sugden, A., 2008. Reimagining cities - introduction. Science. 319(5864): 739 - 739.

BASST, 2003. Band sawing of natural stone materials for the production of slabs and tiles. European Project. Online source: http://cordis.europa.eu/projects/rcn/52769_en.html. Last accessed: September, 2013.

Balocco, C., Papeschi, S., Grazzini, G., Basosi, R., 2004. Using exergy to analyze the sustainability of an urban area. J. Ecol. Econ. 48, 231 – 244.

Barrientos, V., Delgado, J., Navarro, V., Juncosa, R., Falcón, I., Vázquez, A., 2010. Characterization and geochemical–geotechnical properties of granite sawdust produced by the dimension stone industry of O Porriño (Pontevedra, Spain). Quaterly J. Eng. Geol. Hydrogeol. 43, 141–155.

Barton, H., Daniels, I., Davis, G., Guise, R., 1996. Going Green by Design. Sustain. Urban. Des. 1(57).

Baumann, H., Tillman, A.M., 2004. The Hitch Hiker's Guide to LCA: and orientation in life cycle assessment methodology and application. Studentlitteratur, Lund.

BEAMA, 2012. Guide to electric vehicle infrastructure best practice guidance: modes, plugs/socket-outlets and their domestic, public and commercial application. Association for the British Electrotechnical Industry (BEAMA), London.

Berry, I., Khusid, M., Kasseris, M., Mak, A., 2009. What's the deal with hybrid and electric Cars? Day 1: introduction to electric vehicles. MIT Electric Vehicle Team. Massachusetts Institute of Technology (MIT), US.

Browett, M., Kumar, R. 2004. Diamond Wire Sawing – the way forward, in: Midha, S., Paspaliaris, I. (Eds.), Complementary Technologies for Stone Processing. OSNET Editions (vol. 9), Athens, pp. 31 – 40.

Campbell, K., 2001. Rethinking Open Space, Open space Provision and Management: A Way Forward. Report presented by Scottish Executive Central Research Unit, Edinburgh, Scotland, United Kingdom.

Carosio, S., Parodi, S., 2003. Best Practices for a Cost-Effective Application of Diamond Wire, in: Carosio, S., Paspaliaris, I. (Eds.), Application of diamond technology in the stone sector. OSNET Editions (vol. 4), Athens, pp. 27 – 35.

CBI, 2010. CBI market survey: The natural stone and stone products market in the EU. CBI Market Information Database. Centre for the Promotion of Imports from developing countries, Ministry of Foreign Affairs of the Netherlands. Online source: www.cbi.eu. Last accessed: February, 2013.

CCP, 2009. Life-cycle assessment of cladding products: A comparison of aluminium, brick, granite, limestone, and precast concrete. Center for Clean Products (CCP) of the University of Tennessee, Knoxville, United States.

CEA, 2013. Planning for electric vehicle charging infrastructure: a toolkit. Community Energy Association (CEA), British Columbia.

CEDEX, 2010. La Ciudad Paseable: recomendaciones para la consideración de los peatones en planeamiento, el diseño urbano y la arquitectura. ISBN 978-84-7790-509-7. Centro de Estudios y Experimentación de Obras Públicas, Ministerio de Fomento y Ministerio de Medio Ambiente y Medio Rural y Marino. Gobierno de España, Madrid, España.

CEMBUREAU, BIBM, EFCA, ERMCO, EUROFER, UEPG, 2003. EcoConcrete software tool. CEMBUREAU, Brussels, Belgium.

Centre of Regional Science, 2007. Smart cities ranking of European medium-sized cities. Vienna University of Technology, the Department of Geography at University of Ljubljana and the OTB Research Institute for Housing, Urban and Mobility Studies at the Delft University of Technology.

Chertow, M. R., 2000. Industrial symbiosis: literature and taxonomy. Annu. Rev. Energy Environ. 25, 313–337.

Chertow, M. R., 2004. Industrial Symbiosis. Encyclopedia of Energy, Vol. 3. Elsevier Inc. Publishing.

Chertow, M., 2007. "Uncovering" Industrial Symbiosis. J. Ind. Ecol. 11 (1), 11 – 30.

Chester, M. V., Horvath, A., 2009. Environmental assessment of passenger transportation should include infrastructure and supply chains. Environ. Res. Lett. 4(024008): 1-8.

Chester, M. V., Horvath, A., Madanat, S., 2010. Comparison of life-cycle energy and emissions footprints of passenger transportation in metropolitan regions. Atmospheric Environ. 44, 1071-1079.

CIRCONTROL, 2012. CirCarLife Electric Vehicle Intelligent Charging System. Online source: http://productos.circontrol.com/sites/default/files/docs/circarlife_uk.pdf. Accessed December 2013. Last accessed: December, 2013.

CIRCUTOR, 2013. Electric vehicle smart charge. Online resource: http://circutor.com/docs/CA_V_EN.pdf.

Clean Energy Ministerial, 2010. Electric Vehicles Initiative. Washington, United States.

Contestabile, M., Offer, G., Nort, R., 2012. Electric Vehicles: A Synthesis of the Current Literature with a Focus on Economic and Environmental Viability. Technical Paper, LCA Works. http://www.lcaworks.com/lcaworks_publications.html. Last accessed: December, 2013.

Cooney, G., Hawkins, T.R., Marriott, J., 2013. Life Cycle Assessment of Diesel and Electric Public Transportation Buses. J. Industrial Ecol. 17(5), 689-699.

CPRAC, 2012. Greening the entrepreneurial spirit of Mediterraneans - training program on green entrepreneurship and eco-design. Regional Centre for Cleaner Production, Barcelona, Spain.

CR, 2009. General Reporting, Protocol 1.1. Updates and Clarifications. The Climate Registry (CR). Los Angeles, California. Online source: http://www.theclimateregistry.org/. Last accessed: December 2010.

Crishna, N., Banfill, P.F.G., Goodsir, S., 2011. Embodied energy and CO2 in UK dimension stone. Resour. Conserv. Recy. 55, 1265-1273.

DATEG, 2001. Development of advanced tools for ecological and economic sawing of granite. European project. Online source: http://cordis.europa.eu/projects/rcn/44833_en.html. Last accessed: September, 2013.

Dave, S., 2010. Life cycle assessment of transportation options for commuters. Master thesis. Massachusetts Institute of Technology (MIT), United States.

Davini, P., 2004. Recycling of marble and granite waste, in: Midha, S., Paspaliaris, I. (Eds.), Complementary Technologies for Stone Processing. OSNET Editions (vol. 9), Athens, pp. 125 – 142.

Departament d'Estadística, 2012. Informes Estadístics. Cens de vehicles de la ciutat de Barcelona per a 2011. City Council of Barcelona, Barcelona, Spain.

Dhanapandian, S., Gnanavel, B., 2009. Using Granite and Marble Sawing Power Wastes in the Production of Bricks: Spectroscopic and Mechanical Analysis. Res. J. Appl. Sci. Eng. Technol. 2(1), 73-86.

Decker, E.H., Elliott, S., Smith, F.A., Blake, D.R., Rowland, F.S., 2000. Energy and Material Flow Though the Uban Ecosystem. Annu. Rev. Energy Environ. 25, 685–740.

Delgado, J., Vázquez, A., Juncosa, R., Barrientos, V., 2006. Geochemical assessment of the contaminant potential of granite fines produced during sawing and related processes associated to the dimension stone industry. J. Geochem. Explor. 88, 24-27.

Denkena, B., Mult, E.H., Tonshoff, H.K., Gierse, A. 2004. Band Sawing of Natural Stone, in: Midha, S., Paspaliaris, I. (Eds.), Complementary Technologies for Stone Processing. OSNET Editions (vol. 9), Athens, pp. 15 – 28.

DfT, 2011. Making the Connection: the Plug-In Vehicle Infrastructure Strategy. London: Great Minster House, Department for Transport (DfT), Office for Low Emission Vehicles, London, United Kingdom.

Dhanapandian, S., Gnanavel, B., 2009. Using granite and marble sawing power wastes in the production of bricks: spectroscopic and mechanical analysis. Res. J. Appl. Sci. Eng. Technol. 2 (1), 73 – 86.

Doucette, R. T., McCulloch, M. D., 2011. Modeling the CO_2 emissions from battery electric vehicles given the power generation mixes of different countries. Energy Policy 39(2), 803–811.

ECO-STONE, 2010. Sustainable system implementation for natural stone production and use. European project. Online source: http://www.ecostoneproject.com/. Last accessed: September, 2013.

EIU, 2009. European Green City Index: What makes a city a winner?. Study sponsored by Siemens. First presented in Copenhagen, 8 December 2009. Economist Intelligent Unit (EIU), New York, United States.

Ehrenfeld, J. R., Chertow, M. R., 2002. Industrial symbiosis: the legacy of Kalundborg, in: Ayres, R. U., and Ayres, L. W. (Eds), A handbook of industrial ecology. Edward Elgar Publishing, Cheltenham, United Kingdom, pp. 334-348.

Electrification Coalition, 2009. Electrification Roadmap. Revolutionizing transportation and achieving energy security. United states.

Emery, J., Crump, C., Bors, P., 2003. Reliability and Validity of Two Instruments Designed to Assess the Walking and Bicycling Suitability of Sidewalks and Roads. Am. J. Health Promotion 18(1), 38-46.

Engel-Yan, J., Kennedy, C., Saiz, S., Pressnail, K., 2005. Toward sustainable neighbourhoods: the need to consider infrastructure interactions. Canadian J. Civ. Eng. 32(1), 45-57.

Enrst and Young, 2011. Beyond the plug: finding value in the emerging electric vehicle charging ecosystem. Business strategy analysis. Global Automotive Center - Advanced Powertrain.

ERTRAC, 2012. European Roadmap Infrastructure for Green Vehicles. European Road Transport Research Advisory Council (ERTRAC).

ERTRAC and EPoSS, 2009. The Electrification Approach to Urban Mobility and Transport. Strategy Paper. European Road Transport Research Advisory Council (ERTRACT) and European Technology Platform on Smart Systems Integration (EPoSS).

ERTRAC, EPoSS and SmartGrids, 2010. European Roadmap Electrification of Road Transport. First Edition. European Road Transport Research Advisory Council (ERTRAC), (European Technology Platform on Smart Systems Integration) and SmartGrids European Technology Platform for the Electricity Networks of the Future (SmartGrids).

ERTRAC, EPoSS and SmartGrids, 2012. European Roadmap Electrification of Road Transport. Second Edition. European Road Transport Research Advisory Council (ERTRAC), (European Technology Platform on Smart Systems Integration) and SmartGrids European Technology Platform for the Electricity Networks of the Future (SmartGrids).

ETEC, 2009. Electric Vehicle Charging Infrastructure Deployment Guidelines for British Columbia. This document was prepared for Natural Resources Canada and British Columbia Hydro and Power Authority by Electric Transportation Engineering Corporation (ETEC).

ETRA, 2013. Contribution for the European Commission's stakeholders' consultation on the European Strategy on clean and energy efficient vehicles. The European Two-wheel Retailers' Association (ETRA), Brussels, Belgium.

Eurelectric, 2009. Standardisation of Electric Vehicle Charging Infrastructure. Declaration by the European Electricity Industry. The Union of the Electricity Industry (EURELECTRIC), Brussels, Belgium.

Eurelectric, 2010. Market Models for the Roll-Out of Electric Vehicle Public Charging Infrastructure. A Eurelectric concept paper. The Union of the Electricity Industry (EURELECTRIC), Brussels, Belgium.

Eurelectric, 2011. European electricity industry views on charging Electric Vehicles. A Eurelectric position paper. The Union of the Electricity Industry (EURELECTRIC), Brussels, Belgium.

Eurelectric, 2012. Facilitating e-mobility: Eurelectric views on charging infrastructure. Technical paper, The Union of the Electricity Industry (EURELECTRIC), Brussels, Belgium.

European Commission, 2004. Towards a thematic strategy on the urban environment Communication from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions. COM(2004)60 final, Brussels, Belgium.

European Commission, 2007a. Sustainable Urban Transport Plans. Preparatory Document in relation to the follow-up of the Thematic Strategy on the Urban Environment. Technical Report - 2007/018. ISBN 978-92-79-06955-0. Office for Official Publications of the European Communities, Luxembourg.

European Commission, 2007b. Green Paper: Towards a new culture for urban mobility. Communication from the Commission of the European Communities, COM(2007) 551 final.

European Commission, 2007c. Accelerating the development of the sustainable construction market in Europe. Report of the taskforce on sustainable construction, composed in preparation of the Communication "A lead market initiative in Europe". COM(2007) 860 final.

European Commission, 2007d. Reference Document on Best Available Techniques in the Ceramic Manufacturing Industry. Joint Research Centre (JRC), Institute for Prospective Technological Studies (IPTS).

European Commission, 2008. A European Economic Recovery Plan. Communication from the Commission of the European Council, COM(2008) 800 final.

European Commission, 2009a. Directive 2009/33/EC of the European Parliament and of the Council on the promotion of clean and energy-efficient road transport vehicles. Official Journal of the European Union L 120/5, Luxembourg.

European Commission, 2009b. Establishing the ecological criteria for the award of the Community eco-label to hard coverings. Commission Decision 2009/607/EC.

European Commission, 2009c. Directive 2009/125/EC of the European Parliament and of the Council establishing a framework for the setting of ecodesign requirements for energy-related products. Official Journal of the European Union, L 285/10-35.

European Commission, 2010a. Europe 2020: A strategy for smart, sustainable and inclusive growth. Communication from the Commission, COM(2010) 2020.

European Commission, 2010b. Analysis of existing environmental impact assessment methodologies for use in life cycle assessment. The International Reference Life Cycle Data System (ILCD) Handbook. Institute for Environment and Sustainability (IES), Joint Research Centre (JRC), European Commission.

European Commission, 2010c. Analysis of options to move beyond 20% greenhouse gas emission reductions and assessing the risk of carbon leakage. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. COM(2010)265 final, Brussels, Belgium.

European Commission, 2010d. General guide for life cycle assessment – detailed guidance. International Reference Life Cycle Data System. Institute for Environment and Sustainability, Joint Research Centre, European Commission.

European Commission, 2011a. WHITE PAPER : Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system, COM(2011)144 final.

European Commission, 2011b. Synthesis report on the public consultation on the European Innovation Partnership on Active and Healthy Ageing. European Commission, Brussels, Belgium.

European Commission, 2012. Ecodesign your future – how ecodesign can help the environment by making products smarter. Brochure available in: http://ec.europa.eu/enterprise/policies/sustainable-business/ecodesign/index_en.htm. Last accessed: February 2014.

European Commission, 2013a. European Innovation Partnership on Smart Cities and Communities - Strategic Implementation Plan. An Initiative of the European Commission.

European Commission, 2013b. Together towards competitive and resource-efficient urban mobility. Communication from the Commission to the European Parliament, The council, The European Economic and Social Committee and The Committee of the Regions, COM(2013) 913 final.

European Commission, 2013c. Proposal for a Directive of the European Parliament and the Council on the deployment of alternative fuels infrastructure. Communication from the Commission, COM(2013) 18 final. Brussels, Belgium.

European Commission, 2013d. Building the Single Market for Green Products - Facilitating better information on the environmental performance of products and organisations. COM(2013) 196 final.

European Commission, 2013e. Commission recommendation on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations (2013/179/EU). Official Journal of the European Union, L 124, volume 56.

European Commission, 2013f. Horizon 2020 – Work Programme 2014-2015: Smart, green and integrated transport. European Commission Decision C (2013)8631 of 10 December 2013.

European Union, 2011. Cities of tomorrow: challenges, visions, ways forward. Report KN-31-11-289-EN-C. Unit C.2 - Urban Development, Territorial Cohesion, Directorate General for Regional Policy, Publications Office of the European Union, Luxembourg.

Eurostat, 2011. Eurostat regional yearbook 2011. ISSN 1830-9674. Cat. No: KS-HA-11-001-EN-C. Publications Office of the European Union, Luxembourg.

FAD, 2009. La U urbana: el libro blanco de las calles de Barcelona. Fomento de las Artes y del Diseño (FAD) con la colaboración del Ayuntamiento de Barcelona.

Farreny, R., Oliver-Solá, J., Montlleó M., Escriba, E., Gabarrel, X., Rieradevall, J., 2011a. Transition towards sustainable cities: opportunities, constraints and strategies in planning. A neighbourhood eco-design case study in Barcelona (Spain). Environ. Plan. A, 43, 1118-1134.

Farreny, R., Gabarrell, X., Rieradevall, J., 2011b. Cost-efficiency of rainwater harvesting strategies in dense Mediterranean neighbourhoods. Resour. Conserv. Recycl. 55 (7), 686 – 94.

FCM/NRC, 2004. Sidewalk Design, Construction and Maintenance: A Best Practice by the National Guide to Sustainable Municipal Infrastructure. Issue No 1.0, ISBN 1–897094-64–7. Federation of Canadian Municipalities (FCM) and National Research Council (NRC), Ottawa, Canada.

FDP, 2005. Manual del Granito. Federación Española de la Piedra Natural (FDP). Madrid, Spain.

FECSA-ENDESA, 2006. Condiciones técnicas y de seguridad de las instalaciones de distribución de FECSA-ENDESA. Norma técnica particular de acometidas de enlace en baja tensión (NTP-IEBT), Barcelona, Spain.

Founti, M.A., Giannopoulos, D., Laskaridis, K., 2010. Environmental management aspects for energy saving in natural stone quarries. Proceeding from the Global Stone Congress 2010, Alicante, Spain.

Franzitta, V., La Gennusa, M., Peri, G., Rizzo, G., Scaccianoce, G., 2011. Toward a European Eco-label brand for residential buildings: Holistic or by-components approaches? Energy 36, 1884-1892.

Frischknecht, R., Steiner, R., Jungbluth, N., 2008. The Ecological Scarcity Method – Eco-Factors 2006. A method for impact assessment in LCA. Environmental studies no. 0906. Federal Office for the Environment (FOEN), Bern.

Frosch, R. A., and Gallopoulos, N. E., 1989. Strategies for manufacturing (special issue on "Managing Planet Earth"). Scientific Am. 261(3): 94-102.

Fundación ECA - BUREAU VERITAS, 2012. Balance General de la Bicicleta Pública en España. Corominas, X., Anaya, E., Castro, A. ISBN: 978-84-940098-7-7.

Gabarrell, X., Morales-Pinzón, T., Rieradevall, J., Rovira, M.R., Villalba, G., Josa, A., Martínez-Gasol, C., 2013a. Plugrisost: A model for design, economic cost and environmental analysis of rainwater harvesting in urban systems, in: Stamatelatou, K., (Ed.), Asset management for enhancing energy efficiency in water and wastewater systems. Marbella, pp. 199 – 206.

Gabarrell, X., 2013b. Workshop on Ecotech-Sudoe: an international network in life-cycle analysis and eco-design of innovative environmental technologies. Symposium on

Ecoinnovation in the Sudoe Region. Final presentations of the Ecotech-Sudoe project (SOE2/P2/E377), Tolouse. Online resource:

Gabarrel, X., 2013c. Workshop on the creation and Implementation of an LCA Database for the Sudoe region: creation of datasets for users and review datasets process for editors and reviewers – LCABD.sudoe® user guide. Symposium on Ecoinnovation in the Sudoe Region. Final presentations of the Ecotech-Sudoe project (SOE2/P2/E377), Tolouse.

Gandolfi, G., Carosio, S., Marcellino, M., 2003. Processing equipment, in: Carosio, S., Paspaliaris, I. (Eds.), Machines and tools for stone quarrying and processing. OSNET Editions (vol. 1), Athens, pp. 22 – 116.

Garg, A., Kazunari, K., Pulles, T., 2006. IPCC guidelines for national greenhouse gas inventories. Intergovernmental Panel on Climate Change (IPCC).

Gasol, C.M., Farreny, R., Gabarrell, X., Rieradevall, J., 2008. Life cycle assessment comparison among different reuse intensities for industrial wooden containers. Int. J. Life Cycle Assess. 13, 421-431.

Gazi, A., Skevis, G., Founti, M.A., 2012. Energy efficiency and environmental assessment of a typical marble quarry and processing plant. J. Clean. Prod. 32, 10-21.

German National Platform for Electric Mobility, 2012. Progress Report of the German National Platform for Electric Mobility (Third Report). German Federal Government Joint Unit for Electric Mobility (GGEMO), Berlin, Germany

Gertler, M.S., 2004. Creative Cities: What Are They For, How Do They Work, and How Do We Build Them? Canadian Policy Research Networks Inc. (CPRN). Background Paper F/48 Family Network.

GFEI, 2014. Global Fuel Economy Initiative. United Nations Environmental Program (UNEP), Nairobi, Kenya. Online source: http://www.unep.org/transport/gfei/autotool/approaches/information/labeling.asp. Last accessed: March, 2014.

González-García, S., Gasol, C.M., García-Lozano, R., Moreira, M.T., Gabarrell, X., Rieradevall, J., Feijoo, G., 2011. Assessing the global warming potential of wooden products from the furniture sector to improve their eco-design. Sci. Total Environ. 410–411, 16–25.

González-García, S., García-Lozano, R., Buyo, P., Pascual, R.C., Gabarrell, X., Rieradevall, J., Moreira, M. T., Feijoo, G., 2012a. Eco-innovation of a wooden based modular social playground: application of LCA and DfE methodologies. J. Cleaner Prod. 27, 21-31.

González-García, S., García-Lozano, R., Moreira, M.T., Gabarrell, X., Rieradevall, J., Feijoo, G., Murphy, R. J., 2012b. Eco-innovation of a wooden childhood furniture set: An example of environmental solutions in the wood sector. Sci. Total Environ. 426, 318–326.

Government of Canada, 2009. Electric Vehicle Technology Roadmap for Canada: A strategic vision for highway-capable battery-electric, plug-in and other hybrid-electric vehicles. Report prepared by the Government of Canada.

Graedel, T. E., Allenby, B. R., 2010. Industrial ecology and sustainable engineering. Prentice Hall Publishing.

GRI, 1999. Handbook for estimating combustion emissions from the operation and construction of Canadian natural gas systems. Prepaped for GRI Canada by Picard, D.J., Stribrny, M., Harrison, M.R. of Clearstone Engineering Ltd., Enerco Engineering Ltd. and Radian International.

Guinée, J.B., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., de Koning, A., van Oers, L., Sleeswijk, W. A., Suh, S., Udo de Haes, H. A., de Bruijn, H., van Duin, R., Huijbregts, M. A. J., Lindeijer, E., Roorda, A. A. H., Weidema, B. P., 2001. Life cycle assessment - an operational guide to the ISO standards. Parts 1 and 2. Ministry of Housing, Spatial Planning and Environment (VROM) and Centre of Environmental Science (CML), The Netherlands.

Hacker, F., Harthan, R., Matthes, F., Zimmer, W., 2009. Environmental impacts and impact on the electricity market of a large scale introduction of electric cars in Europe. Critical Review of Literature. ETC/ACC Technical Paper 2009/4. The European Topic Centre on Air and Climate Change (ETC/ACC), Copenhagen.

Häkkinen, T., Mäkelä, K., 1996. Environmental adaptation of concrete. Environmental impact of concrete and asphalt pavements. VTT, Tiedotteita-Meddelanden-research-notes 1752. Technology Research Centre of Finland.

Hamza, R.A., El-Haggar, S., Khedr, S., 2011. Marble and Granite Waste: Characterization and Utilization in Concrete Bricks. Int. J. Biosci. Biochem. Bioinforma. 1(4), 286-291.

Harper, E.M., Graedel, T.E., 2004. Industrial ecology: a teenager's progress. Technol. Soc. 26(2–3), 433–445.

Hawkins, T.R., Singh, B., Majeau-Bettez, G., Strømman, A.H., 2013. Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles. J. Industrial Ecology 17(1), 53-64.

Hendrickson, C. T., Horvath, A., Lave, L. B., and McMichael, F. C., 2002. Industrial ecology and green design, in: Ayres, R. U., and Ayres, L. W. (Eds), A handbook of industrial ecology. Edward Elgar Publishing, Cheltenham, United Kingdom, pp. 457-466.

Herzog, T., 2009. World Greenhouse Gas Emissions in 2005. WRI Working Paper. World Resources Institute, Washington, D.C. Online source: http://pdf.wri.org/working_papers/world_greenhouse_gas_emissions_2005.pdf.

Hischier, R., and Weidema, B. P., (Eds), Althaus, H. J., Bauer, C., Doka, G., Dones, R., Frischknecht, R., Hellweg, S., Humbert, S., Jungbluth, N., Köllner, T., Loerincik, Y., Margni, M., Nemecek, T., 2010. Implementation of Life Cycle Impact Assessment Methods. Data 2.2. Ecoinvent report ecoinvent No. 3. Swiss Centre for Life Cycle Inventories, Dübendorf, Switzerland.

Hojamberdiev, M., Eminov, A., Xu, Y., 2011. Utilization of muscovite granite waste in the manufacture of ceramic tiles. Ceram. Int. 37, 871–876.

Howey, D. A., Martinez-Botas, R. F., Cussons, B., Lytton, L., 2011. Comparative measurements of the energy consumption of 51 electric, hybrid and internal combustion engine vehicles. Transportation Res. 16, 459–464.

IDAE, 2011. Plan de Energías Renovables 2011-2020 [Renewable Energy Plan 2011-2020]. Instituto de Diversificación y Ahorro de la Energía (IDAE), Madrid, Spain.

IEA, 2008. Energy Technology Perspectives 2008 – Scenarios and Strategies to 2050. Organisation for Economic Cooperation and Development (OECD)/International Energy Agency (IEA), Paris, France.

IEA, 2009. Transport, Energy and CO_2 – Moving Towards Sustainability. Organisation for Economic Cooperation and Development (OECD)/International Energy Agency (IEA), Paris, France.

IEA, 2010. Energy Technology Perspectives. Scenarios and Strategies to 2050. Organisation for Economic Cooperation and Development (OECD)/International Energy Agency (IEA), Paris, France.

IEA, 2011. Technology Roadmap: electric and plug-in hybrid electric vehicles. Organisation for Economic Cooperation and Development (OECD)/International Energy Agency (IEA), Paris, France.

IEA, 2012. EV city casebook: a look at the global electric vehicle movement. Organisation for Economic Cooperation and Development (OECD)/International Energy Agency (IEA), Paris, France.

IEA, 2013. Global EV Outlook: understanding the Electric Vehicle Landscape to 2020. Organisation for Economic Cooperation and Development (OECD)/International Energy Agency (IEA), Paris, France.

IEA, 2013b. Hybrid and Electric Vehicles: The electric drive gains traction. Implementing Agreement for co-operation on Hybrid and Electric Vehicle Technologies and Programmes (IA-HEV). Organisation for Economic Cooperation and Development (OECD)/International Energy Agency (IEA), Paris, France.

INE, 2014. Average annual number of hours of sun light by region and season. Series from 1997 to 2012. Spanish National Statistical Institute, Madrid. Online source: http://www.ine.es/jaxi/tabla.do?path=/t43/a012/a1998/l0/&file=t200111b.px&type=pcaxis. Last accessed: April, 2014.

INHABITAT, 2010. Sanyo Installs Solar Parking Lots in Japan for Electric Hybrid Bicycles. Press release 03/16/10. Online source: http://inhabitat.com/sanyo-installs-solar-parking-lots-in-japan-for-electric-hybrid-bicycles/. Last accessed: April, 2014.

INSPRA, 2009. Hard coverings EU Ecolabel Award scheme user manual. Istituto Superiore per la Protezione e la Ricerca Ambientale (INSPRA), Roma.

IPCC, 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Prepared by Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T., and Tanabe, K. (eds). Intergovernmental Panel on Climate Change (IPCC), Institute for Global Environmental Strategies (IGES), Hayama, Japan. Report available in: http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html. Last accessed: February 2014.

IPCC, 2007. IPCC Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, USA.

ISO 14040, 2006. Environmental management — Life cycle assessment — principles and framework. International Organisation for Standardisation (ISO), Geneva, Switzerland.

ISO 14044, 2006. Environmental management—life cycle assessment—requirements and guidelines. International Organisation for Standardisation (ISO), Geneva, Switzerland.

ISO 15686-1, 2011. Buildings and constructed assets – Service life planning - Part 1: General principles and framework. International Standardization Organization (ISO), Geneva, Switzerland.

ISO 15686-6, 2004. Buildings and constructed assets - Service life planning - Part 6: Procedures for considering environmental impacts. International Standardization Organization (ISO), Geneva, Switzerland.

I-STONE, 2008. Re-Engineering of Natural Stone Production Chain through Knowledge Based Processes, Eco-Innovation and new Organisational Paradigms. European project. Online source: http://www.istone.ntua.gr/. Last accessed: September, 2013.

ITeC, 2010. Institut de Tecnologia de la Construcciò de Catalunya. Banco de datos BEDEC. http://www.itec.es/nouBedec.e/bedec.aspx. Last accessed : September 2010.

ITeC, 2011. Institut de Tecnologia de la Construcció de Catalunya. BEDEC database. http://www.itec.es/noumetabase2.e/Presentacio.aspx?page=bancbedec. Last accessed: Jun, 2011.

ITeC, 2012. Institut de Tecnologia de la Construcciò de Catalunya. Banco de datos BEDEC. Online source: http://www.itec.cat/nouBedec.c/bedec.aspx. Last accessed: December, 2013.

Jolliet, O., Margni, M., Charles, R., Humbert, S., Payet, J., Rebitzer, G., Rosenbaum, R., 2003. IMPACT 2002+: A New Life Cycle Impact Assessment Methodology. Int. J. Life Cycle Assess. 8(6), 324-330.

Josa, A., Aguado, A., Gettu, R., 2001. Construcción y medio ambiente. 2ª parte: Comportamiento medioambiental de productos con base cemento. Aplicación a pavimentos de hormigón. Cemento Hormigón nº 828, pp. 985-1004

Josa, A., Aguado, A., Heino, A., Byars, E., Cardim, A., 2004. Comparative analysis of available life cycle inventories of cement in the EU. Cem. Concr. Res. 34(8), 1313-132.

Kamal-Chaoui, L., Robert, A., 2009. Competitive cities and climate change. OECD Regional Development Working Papers 2009/2. Organisation for Economic Cooperation and Development (OECD), Directorate for Public Governance and Territorial Development.

Kenworthy, J.R., 2006. The eco-city: ten key transport and planning dimensions for sustainable city development. Environ. Urbanization 67, 18(1): 67–85.

Kellenberger, D., Althus, H.J., Jungbluth, N., Kunninger, T., Lehmann, M., Thalmann, P., 2007. Life cycle inventories of building products. Final report ecoinvent data v2.0 No. 7. EMPA, Swiss Center for Life Cycle Inventories (SCLCI), Dubendors, Switzerland.

Kurk, F., Eagan, P., 2008. The value of adding design-for-the-environment to pollution prevention assistance options. J. Clean. Prod. 16(6), 722-726.

Lazaroiu, G.C., Roscia, M., 2012. Definition methodology for the smart cities model. Energy 47: 326 – 332.

Lifset, R., Graedel, T. E., 2002. Industrial ecology: goals and definitions, in: Ayres, R. U., and Ayres, L. W. (Eds), A handbook of industrial ecology. Edward Elgar Publishing, Cheltenham, United Kingdom, pp. 3-15.

Liguori, V., Rizzo, G., Traverso, M., 2008. Marble quarrying: An energy and waste intensive activity in the production of building materials. WIT Transactions on Ecol. Environ. 108, 197-207.

LIVE, 2009. Logística per a la Implementació del Vehicle Elèctric a Barcelona. City Council of Barcelona, Barcelona, Spain.

Lucas, A., Silva, C.A., Neto, R.C., 2012. Life cycle analysis of energy supply infrastructure for conventional and electric vehicles. Energy Policy 41, 537–547.

MacPherson, N. D., Keoleian, G.A., Kelly, J.C., 2012. Fuel Economy and Greenhouse Gas Emissions Labeling for Plug-In Hybrid Vehicles from a Life Cycle Perspective. J. Industrial Ecology 16(5), 761-773.

Maponga, O., Munyanduri, N., 2001. Sustainability of the dimension stone industry in Zimbabwe: challenges and opportunities. Nat. Resour. Forum 25, 203-213.

Mármol, I., Ballester, P., Cerro, S., Monros, G., Morales, J., Sanchez, L., 2010. Use of granite sludge wastes for the production of coloured cement-based mortars. Cem. Concr. Composite 32, 617 – 622.

Marshall, J.D., 2008. Energy-efficient urban form. Environ. Sci. Technol. 42(9): 3133–3137.

Mateo-Babiano, I., Hitoshi, I., 2005. Theoretical Discourse on Sustainable Space Design: Towards Creating and Sustaining Effective Sidewalks. Bus. Strat. Env. 14, 300-314.

Mateo-Babiano, I., Ieda, H., 2007. Streets pace sustainability in Asia: The role of the Asian pedestrian and street culture. J. East. Asia Soc. Transportation Stud. Vol. 7: 1915-1930.

Mateo-Babiano, I., 2009. Redefining the Asian space: a comparative view of evolving street culture and pedestrian space development in Bandung, Bangkok and Manila, in: Asian Transformations in Action. The Work of the 2006/2007 API Fellows, The Nippon Foundation, Japan, pp. 214-223.

Mendoza, J.M., Oliver-Solà, J., Gabarrell, X., Josa, A., Rieradevall, J., 2012a. Life Cycle Assessment of Granite Application in Sidewalks. Int. J. Life Cycle Assess. 17, 580–592.

Mendoza, J.M., Oliver-Solà, J., Gabarrell, X., Rieradevall, J., Josa, A., 2012b. Planning strategies for promoting environmentally suitable pedestrian pavements in cities. Transportation Res. D 17, 442-450.

Mendoza, JM., Feced, M., Feijoo, G., Josa A., Gabarrell, X., Rieradevall, J., 2014. Life cycle inventory analysis of granite production from cradle to gate. Int. J. Life Cycle Assess. 19, 153 – 165.

Mendoza, J.M., Josa, A., Rieradevall, J., Gabarrell, X., 2014. Environmental significance of public charging facilities for electric two-wheelers. *Paper under review in an international scientific journal.*

Menezes, R.R., Neves, G.A., Ferreira, H.C., Lira, H. L., 2002. Recycling of granite industry waste from the northeast region of Brazil. Env. Manag. Health 13 (2), 134 – 141.

Meteogalicia, 2013. Estacións meteorolóxicas, datos históricos das redes de estacións automáticas, Monte Aloia (Tui) – Pontevedra (Galicia, Spain). Xunta de Galicia, Consellería de Medio Ambiente, Territorio e Infraestructuras. Online source: http://www2.meteogalicia.es/galego/observacion/estacions/estacionsHistorico.asp?Nest=19045&prov=Pontevedra&red=102109&tiporede=agro&idprov=3#. Last accessed: Jun, 2013.

MITC, 2002. Reglamento electrotécnico para baja tensión. Real Decreto 842/2002. Ministerio de Industria, Turismo y Comercio. Gobierno de España (MITC), Madrid, Spain.

MITC, 2010. Mapa Tecnológico de la Movilidad Eléctrica. Observatorio Tecnológico de la Energía. Report prepared by the Instituto para la Diversificación y Ahorro de la Energía (IDAE) for the Ministerio de Industria, Energía y Turismo. Gobierno de España (MITC), Madrid, Spain.

MOBI. E, 2012. The Portuguese Program for Electric Mobility. GAMEP, Gabinete para a Mobilidade Eléctrica em Portugal. European Transport Conference 2010, Glasgow, Scotland, United Kingdom.

Monteiro, S.N., Peçanha, L.A., Vieira, C.M.F., 2004. Reformulation of roofing tiles body with addition of granite waste from sawing operations. J. Eur. Ceram. Soc. 24, 2349 – 2356.

Morales-Pinzón, T., Rieradevall, J., Martinez-Gasol, C., Gabarrell, X., 2012a. Plugrisost v1.0. Dynamic rainwater and greywater flow analytical model. Software (Spanish version) available at http://sostenipra.ecotech.cat/.

Morales-Pinzón, T., Lurueña, R., Rieradevall, J., Martinez-Gasol, C., Gabarrell, X., 2012b. Financial feasibility and environmental analysis of potential rainwater harvesting systems: A case study in Spain. Resour. Conserv. Recycl. 69, 130 – 140.

Morrow, K., Karner, D., Francfort, J., 2008. Charging Infrastructure Review. Report prepared for the U.S. Department of Energy, Assistant Secretary for Energy Efficiency and Renewable

Energy. U.S. Department of Energy Vehicle Technologies Program – Advanced Vehicle Testing Activity Plug-in Hybrid Electric Vehicle. United States.

NACTO, 2013. Urban street design guide. National Association of City Transportation Officials (NACTO), New York.

Nemry, F., Leduc, G., Muñoz, A., 2009. Plug-in Hybrid and Battery-Electric Vehicles: State of the research and development and comparative analysis of energy and cost efficiency. Technical Note: JRC 54699. Institute for Prospective Technological Studies (IPTS), Joint Research Centre (JRC), European Commission, Seville, Spain.

Nemry, F., Brons, M., 2010. Plug-in Hybrid and Battery Electric Vehicles Market penetration scenarios of electric drive vehicles. Technical Note: JRC 58748. Institute for Prospective Technological Studies (IPTS), Joint Research Centre (JRC), European Commission, Seville, Spain.

Nicoletti, G.M., Notarnicola, B., Tassielli, G., 2002. Comparative Life Cycle Assessment of flooring materials: ceramic versus marble tiles. J. Clean. Prod. 10, 283–296.

NSC, 2009. A life-cycle inventory of granite dimension stone quarrying and processing. Version 2. A report prepared by the Centre of Clean Products (CCP) of the University of Tennessee for The Natural Stone Council (NSC) of United States.

NSC, 2012. Sustainability Assessment for Natural Dimension Stone. Draft 1.9. Creation of new Standard - NSC 373. Tracking number 373i1r1.9. Natural Stone Council, United States.

Oliver-Solà, J., Josa, A., Rieradevall, J., Gabarrell, X., 2009a. Environmental optimization of concrete sidewalks in urban areas. Int. J. Life Cycle Assess. 14: 302–312.

Oliver-Solà, J., Gabarrell, X., Rieradevall, J., 2009b. Environmental impacts of natural gas distribution networks within urban neighbourhoods. Applied Energy 86(10), 1915-1924.

Oliver-Solà, J., Rieradevall, J., Gabarrell, X., 2009c. Environmental impacts of the infrastructure for district heating in urban neighbourhoods. Energy Policy 37(11), 4711-4719.

Oliver-Solà, J., 2009d. Industrial ecology as a discipline for the analysis and design of sustainable urban settlements. PhD thesis. ISBN 978-84-693-2059-4.

Oliver-Solà, J., Josa, A., Arena, A.P., Gabarrell, X., Rieradevall, J., 2011. The GWP-Chart: An environmental tool for guiding urban planning processes. Application to concrete sidewalks. Cities 28, 245–250.

OMPN, 2009. Informe sectorial de la piedra natural en España 2008. Observatorio del Mercado de la Piedra Natural (OMPN), Instituto Tecnológico de la Construcción (AIDICO), Madrid, Spain.

OMPN, 2010. Informe sectorial de la piedra natural en España 2009. Observatorio del Mercado de la Piedra Natural (OMPN), Instituto Tecnológico de la Construcción (AIDICO), Madrid, Spain.

OMPN, 2011. Informe sectorial de la piedra natural en España 2010. Observatorio del Mercado de la Piedra Natural (OMPN), Instituto Tecnológico de la Construcción (AIDICO), Madrid, Spain.

Pacione, M., 2009. Urban geography. A global perspective. Oxon (UK): Routledge.

Papantonopoulos, G., Taxiarchou, M., Bonito, N., Adam, K., Christodoulou, 2007. A study on best available techniques for the management of stone wastes. Proceeding from the 3rd International Conference on Sustainable Development Indicators in the minerals industry, Milos island, Greece.

Pauleit, S., Duhme, F., 2000. Assessing the environmental performance of land cover types for urban planning. Landsc. Urban. Plan. 52, 1-20.

PBSME, 2010. Pedestrian and Bicyclist Safety and Mobility in Europe. International Technology Scanning Program in cooperation with the American Association of State Highway and Transportation Officials and the National Cooperative Highway Research Program.

Petit-Boix, A., Sanjuan-Delmás, D., Gasol, C.M., Villalba, G., Suárez-Ojeda, M.E., Gabarrell, X., Josa, A., Rieradevall, J., 2014. Environmental Assessment of Sewer Construction in Small to Medium Sized Cities Using Life Cycle Assessment. Water Res. Manag. 28(4), 979-997.

PE International, 2008. GaBi software version 4.3, released on July 2008. Online source: http://www.pe-international.com.

PE International, 2010. GaBi software version 4.4, released on 2010. Online source: http://www.pe-international.com.

PE International, 2013. GaBi software. Online source: http://www.gabi-software.com/spain/index/.

Pereira, J., Coitinho Dal Molin, D.C, Moura, W.A., 2000. Utilização do resíduo de corte de granito como adição para a produção de concretos. PhD thesis. Online source: http://www.lume.ufrgs.br/handle/10183/1676. Last accessed: September, 2013.

Pfister, S., Koehler, A., Hellweg, S., 2009. Assessing the Environmental Impacts of Freshwater Consumption in LCA. Environ. Sci. Technol. 43 (11), 4098 - 4104.

Plataforma LIVE, 2013. Mou-te en vehicle elèctric: Guia pràctica de la mobilitat eléctrica. Logística per a la Implementació del Vehicle Elèctric (LIVE), Barcelona, Spain.

Pliz, A., Matos, M.J., Saude, N., Bonito, N., Lazi, K., 2003. Ornamental stones: sector and the environment, in: Peppas, A., Paspaliaris, I. (Eds.), Health and safety in the Ornamental Stone industry: current situation – Risk assessment and Safety on quarries and processing plants. OSNET Editions (vol. 3), Athens, pp. 191 – 211.

PMP, 2002. Pedestrian Master Plan. The City of Oakland. Part of the Land Use and Transportation Element of the City of Oakland's General Plan.

PMUB, 2006. Pla de Mobilitat Urbana de la Ciutat de Barcelona 2006-2018. Ayuntamiento de Barcelona.

PRé Consultants, 2013. SimaPro 7. Online source: http://www.pre-sustainability.com/simapro.

PRé Consultants and ESU-services (2001). Database Manual: The ETH-ESU 96 Library, PRé Consultants. Online source: www.pre.nl/simapro/inventory_databases.htm.

PV Potential Estimation Utility, 2011. Joint Research Centre (JRC), European Commission. Online source: http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php. Last accessed: April, 2014.

RACC, 2012. El Real Automóvil Club de Catalunia (RACC) prevé que 21.000 motos eléctricas circulen por Barcelona para el año 2014. [The Royal Automobile Club of Catalunya (RACC) expect 21,000 electric motorcycles on road in Barcelona for 2014]. Press release. Online source: http://w3.racc.es/index.php?mod=fundacion&mem=novedad&id=1013&relcategoria=1131&relmenu=23. Last accessed: December, 2013.

RAE, 2010. Electric Vehicles: charged with potential. The Royal Academy of Engineering (RAE), London.

Rajendran, S., Gambatese, J.A., 2007. Solid waste generation in asphalt and reinforced concrete roadway life cycles. J. Infrastruct. Syst. 13(2), 88-96.

REE, 2011. El sistema eléctrico español [The Spanish electric system]. Red Eléctrica Española (REE), Madrid, Spain.

Rieradevall, J., Farreny, R., García-Lozano, R., Oliver-Solà, J., 2011. Urban Ecodesign in the City of Barcelona. Design for the XXI century. The form of the future. ELISAVA, Barcelona, Spain.

Rose, C. M., 2000. Design for Environment – a method for formulating product end-of-life strategies. PhD thesis available in: http://www.seas.columbia.edu/earth/RRC/documents/2000.dfe.diss.rose.pdf. Last accessed: February 2014.

Sáenz de Miera, G., 2011. Un análisis prospectivo de la electricidad en España. Papeles de cuadernos de energía. [A prospective analysis of electricity in Spain. Paper notebooks about energy]. Club Español de la Energía (CEE). Instituto Español de la Energía (IEE), Madrid, Spain.

Santero, N.J., Horvath, A., 2009. Global warming potential of pavements. Environ. Res. Lett. 4(034011), 1-8.

Santero, N.J., Harvey, J., Horvath, A., 2011a. Environmental policy for long-life pavements. Transportation Res. Part D, 16(2), 129-136.

Santero, N.J., Masanet, E., Horvath, A., 2011b. Life-cycle assessment of pavements. Part I: Critical review. Res. Conserv. Recy. 55, 801-809.

Segadaes, A.M., Carvalho, T.M.A., Acchar, W., 2005. Using marble and granite rejects to enhance the processing of clay products. Appl. Clay Sci. 30, 42 – 52.

SCLCI, 2006. The Ecoinvent Life Cycle Inventory Data Version 1.2. Swiss Centre for Life Cycle Inventories (SCLCI). Online source: http://www.ecoinvent.ch/.

SCLCI, 2009. The Ecoinvent Life Cycle Inventory Data Version 2.1. Swiss Centre for Life Cycle Inventories (SCLCI). Online source: http://www.ecoinvent.ch/.

SCLCI, 2010. The Ecoinvent Life Cycle Inventory Data. Version 2.2. Swiss Centre for Life Cycle Inventories (SCLCI). Online source: http://www.ecoinvent.ch/ .

Sanyé-Mengual, E., García-Lozano, R., Farreny, R., Oliver-Solà, J., Gasol, C. M., Rieradevall, J., 2014. Introduction to the Eco-Design methodology and the role of product carbon footprint, In: Muthu, S. S. (Ed), Assessment of carbon footprint in different industrial sectors, Vol. 1. Springer Publishing, Singapore, pp. 1–24.

Sanjuan-Delmás, D., Petit-Boix, A., Gasol, C.M., Villalba, G., Suárez-Ojeda, M.E., Gabarrell, X., Josa, A., Rieradevall, J., 2014. Environmental assessment of different pipelines for drinking water transport and distribution network in small to medium cities: a case from Betanzos, Spain. J. Cleaner Prod., 66(1), 588-598.

Silva, M.T.B., Hermo, B.S., García-Rodeja, E., Vázquez, F., 2005. Reutilization of granite powder as an amendment and fertilizer for acid soils. Chemosphere 61, 993–1002.

Smith, J., and Wyatt, R., 2006. Project Inception – a performance brief approach, in: Proceedings of CRIOCM 2006 International Research Symposium on Advancement of Construction Management and Real Estate 1&2, pp. 29–38.

Sostenipra, 2013. Protocol of Life Cycle Assessment Database Sudoe: User´s manual. Draft v.2. Sostenibilitat i prevenció ambiental (Sostenipra) Research group, Barcelona.

Stripple, H., 2005. Life cycle assessment of road: a pilot study for inventory analysis. Report for the Swedish national road administration. IVL Swedish Environmental Research Institute Ltd.

Sung, Y.C., 2010. Consumer learning behavior in choosing electric motorcycles. Transportation Plan. Tech. 33(2), 139-155.

TfL, 2010. Guidance for implementation of electric vehicle charging infrastructure. Transport for London (TfL), London, United Kingdom.

The New York Times, 2010. An Electric Boost for Bicyclists. Online source: http://www.nytimes.com/2010/02/01/business/global/01ebike.html?_r=0. Last accessed: April, 2014.

Torres, P., Fernandes, H.R., Agathopoulos, S., Tulyaganov, D.U., Ferreira, J.M.F., 2004. Incorporation of granite cutting sludge in industrial porcelain tile formulations. J. Eur. Ceram. Soc. 24, 3177 – 3185.

Torres, P., Manjate, R.S., Quaresma, S., Fernandes, H.R., Ferreira J.M.F., 2007. Development of ceramic floor tile compositions based on quartzite and granite sludge. J. Eur. Ceram. Soc. 27 (16), 4649 – 4655.

Torres, P., Fernandes, H.R., Olhero, S., Ferreira, J.M.F., 2009. Incorporation of wastes from granite rock cutting and polishing industries to produce roof tiles. J. Eur. Ceram. Soc. 29, 23 – 30.

Traut, E., Hendrickson, C., Klampfl, E., Liu, Y., Michalek, J. J., 2012. Optimal design and allocation of electrified vehicles and dedicated charging infrastructure for minimum life cycle green house gas emissions and cost. Energy Policy 51, 524–534.

Traverso, M., Rizzo, G., Finkbeiner, M., 2010. Environmental performance of building materials: life cycle assessment of a typical Sicilian marble. Int. J. Life Cycle Assess. 15, 104–114.

Trip, J. J., Lima, J., Bakker, S., 2012. Electric mobility policies in the North Sea Region countries. Report written within the framework of Activity 3.3 of the Interreg IVB project E-Mobility NSR, file nr. 35-2-6-11. North Sea Region Electric Mobility Network (e-mobility NSR). Delft University of Technology, The Netherlands.

Tukker, A., Haag, E., Eder, P., 2000. Eco-design: European state of the art. Part I: Comparative analysis and conclusions. An ESTO project report Prepared for the European Commission — Joint Research Centre (JRC) from the Institute for Prospective Technological Studies (IPTS), Seville, Spain.

UN, 2013. Towards sustainable cities. World Economic and Social Survey 2013. Sustainable Development Challenges. United Nations (UN), Department of Economic and Social Affairs, New York, United States.

UNE-EN 12670, 2003. Natural stone – Terminology. Natural Stone for Construction. AEN/CTN 22 - Mining and Explosives Committee.

UNEP/SETAC, 2007. Life Cycle Management – a business guide to sustainability. United Nations Environment Programme (UNEP) and Society of Environmental Toxicology and Chemistry (SETAC), Nairobi, Kenya.

UNEP, 2010. Share the road: Investment in Walking and Cycling Road Infrastructure. United Nations Environment Programme (UNEP), Division of Technology, Industry and Economics, Nairobi, Kenya.

UNEP, 2011a. Cities: Investing in energy and resource efficiency. Towards a green economy. United Nations Environment Programme (UNEP), Division of Technology, Industry and Economics, Nairobi, Kenya.

UNEP, 2011b. Transport: Investing in energy and resource efficiency. Towards a green economy. United Nations Environment Programme (UNEP), Division of Technology, Industry and Economics, Nairobi, Kenya.

UNEP/SETAC, 2011. Global Guidance Principles for Life Cycle Assessment Databases – a basis for greener processes and products – "Shonan Guidance Principles". United Nations Environment Programme (UNEP) and Society of Environmental Toxicology and Chemistry (SETAC), Nairobi, Kenya.

UNEP, 2012. Sustainable, resource efficient cities: making it happen!. United Nations Environment Programme (UNEP), Nairobi, Kenya.

UNEP/SETAC, 2012. Greening the economy through life cycle thinking - ten years of the UNEP/SETAC Life Cycle Initiative. United Nations Environment Programme (UNEP) and Society of Environmental Toxicology and Chemistry (SETAC), Nairobi, Kenya.

UN-HABITAT, 2010. Urban World: A new chapter in urban development. Vol. 2, issue 2, p. 6.

UN-HABITAT, 2013a. The relevance of street patterns and public space in urban areas. UN-Habitat Working Paper. United Nations Human Settlements Programme (UN-Habitat), Nairobi, Kenya.

UN-HABITAT, 2013b. Streets as public spaces and drivers of urban prosperity. United Nations Human Settlements Programme (UN-Habitat), Nairobi, Kenya.

UN-HABITAT, 2013c. Urban planning for city leaders. United Nations Human Settlements Programme (UN-Habitat), Nairobi, Kenya.

UN-HABITAT, 2013d. Revised compilation for sustainable cities and human settlements in the sustainable development goals (SDGs) within the Post-2015 development agenda. United Nations Human Settlements Programme (UN-Habitat), Nairobi, Kenya.

UN-HABITAT, 2014. Public Space in the global agenda for sustainable urban development: the "global public space toolkit". Urban Planning and Design Branch, United Nations Human Settlements Programme (UN-Habitat), Nairobi, Kenya.

UN Population Division, 2007. World Urbanization Prospects: The 2007 Revision, United Nations, Department of Economic and Social Affairs, Population Division, New York, United States.

UN Population Division, 2010. World urbanisation prospects: The 2009 revision. United Nations (UN), Population division, Department of Economic and Social Affairs, New York, United States.

Urban Foresight Limited, 2013. Future of Markets for Electric Vehicles: Expectations, Constraints and Long-Term Strategies. Report of a roadmapping workshop facilitated by Urban Foresight for the International Energy Agency Hybrid & Electric Vehicle Implementing Agreement and the Austrian Institute of Technology EV Ecosystems. IEA Hybrid and Electric Vehicle Implementing Agreement, Task 18. Document ref: IEA130228. United Kingdom.

van Oers, L., Koning, A., Guinée, J.B., Huppes, G., 2002. Abiotic resource depletion in LCA. Improving characterisation factors for abiotic resource depletion as recommended in the new Dutch LCA Handbook. Road and Hydraulic Engineering Institute. Ministerie van Verkeer en Waterstaat. Directoraat-Generaal Rijkswaterstaat.

Vieira, C.M.F., Soares, T.M., Sánchez, R., Monteiro, S.N., 2004. Incorporation of granite waste in red ceramics. Mater. Sci. Eng. 373, 115 – 121.

Weeda, M., Kroon, P., Appels, D., 2012. An international perspective on electric transportation. Survey on electric road transport for 2012. Report ref.: ECN-E-12-043. ECN, The Netherlands.

Weidema, B. P., 2003. Market information in life cycle assessment. Environmental Project No. 863. Danish Environmental Protection Agency, Danish Ministry of the Environment.

Weinert, J., Ogden, J., Sperling, d., Burke, A., 2008. The future of electric two-wheelers and electric vehicles in China. Energy Policy 36, 2544– 2555.

WEO, 2009. World Energy Outlook 2009. International Energy Agency and Organisation for Economic Co-operation and Development (OECD/IEA). ISBN: 978-92-64-06130-9.

WPPP, 2002. Wisconsin Psdestrian Policy Plan 2020. Wisconsin Department of Transportation, Division of Transportation Investment Management, Bureau of Planning. Citizens Advisory Committee.

WWF, 2008. Reinventing the city: three prerequisites for greening urban infrastructures, World Wildlife Fund (WWF) International, produced in cooperation with Booz and Company, Gland, Switzerland.

Zabalza, I., Valero, A., Aranda, A., 2011. Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. Build. Environ. 46, 1133-1140.

Zapata, P., Gambatese, J.A., 2005. Energy consumption of asphalt and reinforced concrete pavement materials and construction. J. Infrastruct. Syst. 11(1): 9–20.

Zografidis, C., Adam, K., Christodolou, I., Orfanoudakis, J., 2007. Evaluation of the environmental performance of the natural stone industry based on sustainable indicators. Proceeding from the 3rd International Conference on Sustainable Development Indicators in the minerals industry, Milos island, Greece.

Zubaryeva, A., Thiel, C., 2013. Paving the way to electrified road transport: publicly funded research, development and demonstration projects on electric and plug-in vehicles in Europe. Office of the European Union, Report EUR 25832 EN. Institute for Energy and Transport (IET), Joint Research Centre (JRC), European Commission, Luxembourg.