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Eco-innovation of urban elements to support sustainable multimodal mobility

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Abstract.

The provision of an adequate network of urban infrastructures is essential to create clean and energy-efficient urban mobility systems. However, the urban infrastructure to support sustainable mobility can produce a substantial environmental burden if no life cycle environmental criteria are applied in its design and management. This paper demonstrates the potential to support energy-efficient and CO2-free pedestrian and e-bike mobility through the eco-design of urban elements. An eco-design approach is applied to reconceptualize a conventional pergola toward an eco-product (solar pergola). The solar pergola generates surplus photovoltaic electricity that provides a multifunctional character. According to the end-use of this energy, passive and active contributions to sustainability are distinguished for robust decision-making. The deployment of solar pergolas can contribute to save from 2,080 kg to over 47,185 kg of CO2 eq. and from 350,390 MJ to over 692,760 MJ eq. in 10 years, depending on the geographic emplacement and electricity grid system. These savings are equivalent to charging 2 to 9 e-bikes per day using clean energy.

Instead of maximizing infrastructure deployment to shift to environmentally friendly modes of mobility, the implementation of multifunctional urban elements represents a key area of action in the context of smart city development.

Keywords. Eco-design, Multifunction, Pedestrian mobility, Electric mobility, Green electricity, Smart cities.

1. Introduction

The 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 fulfill the demand for mobility with clean and 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 the greenhouse gas (GHG) emissions and more than two-thirds of the local noxious emissions arising from this mode of transport (European Commission, 2007b). The Europe 2020 Strategy for smart, inclusive, and sustainable growth (European Commission, 2010) therefore stresses the importance of addressing the urban dimension of mobility to encourage a modernized and sustainable regional transport system. Consistent with this vision, the European White Paper (European Commission, 2011) highlights the need to make cities and their local transport systems greener and smarter to achieve essentially carbon-free multimodal mobility logistics. In this process, the use of conventionally fuelled vehicles must be reduced by half by 2030, and these vehicles must be phased out in cities by 2050. Thus, the European Union (EU) calls for rethinking urban mobility by undertaking the necessary action to facilitate walking and cycling, improving the quality and efficiency of collective transport services and promoting the substitution of conventional cars with cleaner and energy-efficient passenger vehicles. In this latter case, the electrification of public and private urban vehicle fleets is given first priority in modern sustainable mobility plans developed in the US, Japan, China, Korea and the EU as a promising strategy for significant reduction in oil consumption and GHG emissions by motorized road mobility (ERTRAC, EPoSS and SMARTGRIDS, 2012; IEA, 2013, 2012, 2011).

However, infrastructure shapes mobility; therefore, no major changes in transport sustainability would be possible without the provision of an adequate network of urban infrastructure and its intelligent use (European Commission, 2011). The infrastructure to support urban mobility spans from the basic network of pavement, which forms the shell onto which everything else is embedded and must operate (Kenworthy, 2006), to dedicated buildings and constructed assets, including a set of diversified urban elements and street furniture. All these elements can produce a notable environmental burden to the built space of cities and have a high relative importance to the life-cycle energy and GHG emission footprints of urban mobility modes (Chester et al., 2010; Dave, 2010). Decisions should therefore not be made based on partial considerations acting as indicators for whole system performance. To effectively mitigate environmental impacts from urban mobility, life-cycle environmental performance should be considered, including the different infrastructure and elements required to support mobility (Chester and Horvath, 2009). The incorporation of life-cycle environmental criteria in the planning, design, and management of urban elements related to the support of sustainable modes of mobility is especially relevant. This best practice can contribute to greatly reduce the environmental burden of the built space, thereby increasing the environmental value of greening urban mobility (Mendoza et al., 2014, 2012a, 2012b; Oliver-Solà et al., 2011, 2009).

To accommodate the growing mobility needs and aspirations of a socioeconomically diverse population seeking to follow a sustainable path, there is an urgent need to make mobility-related infrastructures more resource efficient, resilient and smarter. This need requires the application of a wide range of innovative solutions, including the design and deployment of low-carbon and energy-harvesting infrastructures to support a multimodal urban mobility (European Commission, 2013a). In this process, eco-design plays a key role. Eco-design (also known as Design for Environment) involves the consideration of the environmental implications of a product system during the early stage of conceptualization (Harper and Graedel, 2004). Implicitly, eco-design requires detailed analysis of the life-cycle environmental impacts of products (and services). In this manner, comprehensive environmental criteria are placed at the same level and given the same status as the more traditional product values considered in the early stage of design (such as functionality, safety, ergonomics, endurance, image, quality, aesthetics and costs). This early incorporation of environmental criteria is the best strategy for environmental prevention because 80% of total environmental impacts of products are directly conditioned by their design (European Commission, 2012; Kurk and Eagan, 2008). Therefore, eco-design contributes to improve product performance while the life-cycle energy requirements and pollutant releases are minimized.

The application of eco-design principles in the planning, deployment and management of urban elements to support sustainable mobility can provide important environmental benefits at the city scale and play an instrumental role for the development of future smart cities (European Commission, 2013b). In this sense, this paper presents the application of an eco-design methodological framework to reconceptualize an urban pergola to be able to support a clean and energy-efficient multimodal urban mobility. A pergola is one type of urban element implemented in the public space of cities to provide comfort for pedestrian mobility using diurnal shadow and nocturnal lighting. These urban elements also have additional functions such as shelter from the rain, snow and wind; therefore, these elements are implemented in dedicated hot-spots in cities. However, pergolas can produce a substantial environmental burden depending on their design (material inputs) and lifetime energy requirements during operation. In the context of the development of smart cities, it is essential that the urban logistic to support sustainable mobility contribute the minimum energy use and long-term environmental burdens. In this sense, a conventional pergola (CP) is re-designed toward a solar pergola (SP). Because of the eco-product design, the SP generates surplus photovoltaic electricity (spE) that provides a multifunctional character to the urban element. According to the end-use of the spE generation, passive and active contributions to sustainability are distinguished to denote the importance of promoting a smart approach for robust sustainability-based decision-making. The net environmental balance of SP design is geographically dependent. Thus, a total of nine scenarios are defined to determine the potential variability on the life-cycle environmental performance of the eco-product through sensitivity analysis. These scenarios reflect the variability of the hours of solar radiation and carbon intensity of the electricity grid mix.

2. Methods

Fig. 1 presents the eco-design methodological framework applied to reconceptualize a CP toward an eco-product (SP). The eco-design procedure is based on the approaches proposed by González-García et al. (2012a, 2012b) for the eco-innovation of urban elements and Sanyé-Mengual et al. (2014) for the development of eco-products.

Insert here Fig. 1

The eco-design procedure is divided into a series of successive iterative steps. Product definition is the basic step to approach the goals of the eco-design thinking process. A multidisciplinary team is created to cover all the fields of knowledge implied in eco-design. The attributes of the product to be eco-designed are clearly defined, and its life-cycle environmental performance is characterized by applying qualitative and quantitative tools. The Qualitative Assessment of Life Cycle Criteria (QALCC) (CPRAC, 2012) highlights the global perceptions of the multidisciplinary team regarding the incorporation of environmental criteria into product design. The Life Cycle Assessment (LCA) (ISO, 2006) provides a comprehensive evaluation of the product´s contribution to environmental impacts. The data obtained though the QALCC and LCA are used to build an eco-briefing matrix (Smith and Wyatt, 2006) that compiles the most relevant hotspots (life-cycle stages, processes and elements) for the product´s environmental improvement. A series of eco-design strategies are defined, and a feasibility assessment is performed to detect their technical, economic and social constrains. The most feasible eco-design strategies are classified according to their priority of implementation and characterized by the application of the QALCC and LCA. After this process, the most interesting solutions are selected for the conceptual development of the eco-product. Before the eco-product production and marketing, two interactive steps are addressed. First, a prototype of the eco-product is developed for testing purposes. Second, the environmental performance of the eco-product prototype is validated through a conclusive LCA. Based on the results, a series of corrective measures can be proposed to solve potential constraints and minimize costly interventions in the eco-product´s supply chain.

A step-by-step detailed description of the eco-design methodological framework and the different data generated along the process is presented in the Supporting

Information (SI) file (sections A.1-A.7). In the following sections, the basic information needed to understand the case scenarios and the obtained environmental outcomes is presented.

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

A Spanish company located in the city of Barcelona (Catalonia) participated in the research. This company is one of the most important designers of urban elements, such as pergolas. Thus, the product system analyzed is a very representative model of a conventional pergola implemented in many urban public spaces throughout Spain. This pergola model is especially found in the cities of Barcelona, Bilbao, Madrid, and Murcia, which represent the largest market volumes for the company.

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

Insert here Fig. 2

The resulting eco-designed product, a solar pergola, is based on the repetition of a 23 m^2 (4.80 m x 4.80 m) module with a cover composed of twelve high-energy efficient (mc-Si) photovoltaic panels, which supply energy to LED lighting equipment. The SP integrates mobility sensors, which contribute a 50% reduction in the energy consumption in operation through light attenuation. The photovoltaic cover is supported by an extruded mixed aluminum frame and four columns. Fig. 3 presents an exploded illustration with a brief description of the main components of the SP design.

Insert here Fig. 3

The eco-design efforts related to the SP were focused mainly on taking action at the level of the product´s concept, material use and lifetime energy consumption to solve the most critical environmental aspects related to the CP design (see section 3.1). A detailed description of the most relevant technical aspects of the CP and SP designs is presented in the SI file (sections A.1 and A.5).

2.2.Life cycle environmental impact assessment

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

According to the specifications of the lighting equipment (Fig. 2 and Fig. 3), the energy consumption by the CP design would correspond to 10,480 kWh, whereas it would account for 3,468 kWh for the SP design. Additionally, the photovoltaic electricity production by the SP would account to 33,600 kWh (see section A.6 from the SI file). Only 10% of this energy would be required as input for nocturnal lighting. The generation of surplus photovoltaic electricity (spE) is therefore significant (30,132 kWh). Thus, the environmental performance of the SP design will be highly dependent on the management of its multifunctional character (section 2.3).

The life-cycle inventory (LCI) data required to characterize the environmental performance of each product system was collected and calculated by relying on the information provided by the technical staff from the designer company involved in the research. All the relevant unit processes from cradle to gate, transportation, installation, and lifetime operation were considered. The SI file (sections A.2 and A.6) presents a diagram of the system boundaries of the life cycle of CP and SP designs and describes their complete LCI data disaggregated by stages and unit processes.

The global warming potential (GWP), measured in kg of CO_2 eq. emissions [100 years] according to the IPCC (2007) guidelines and the cumulative energy demand (CED), measured in MJ eq. from renewable and non-renewable resources [net cal. value] according to the Hischier et al. (2010) method were used as indicators to characterize the life-cycle environmental performance of the product systems. However, a complete list of CML midpoint indicators (Guinée et al., 2001) is presented in the SI file (section A.2 and A.6). The software Simapro (PRé Consultants, 2013) and the Ecoinvent v2.2 database (SCLCI, 2010) were employed as supporting analytical tools.

2.3. *Functional equivalence of the product systems for environmental comparison*

Product systems associated with the delivery of additional functions (e.g., SP design) should be characterized in a manner that makes their comparison equivalent with respect to a mono-functional product system (e.g., CP design). ISO 14044 (2006) specifies a hierarchy of approaches to characterize the environmental performance of multifunctional product systems. When multifunctionality cannot be directly subdivided into mono-functional single operation unit processes, the allocation of the environmental impacts between the main functions and co-functions should be avoided by applying system expansion. In practice, there are two alternatives for applying system expansion in LCA (ILCD Handbook, 2010). The first alternative consists of subtracting from the multifunctional product system the environmental burden of the conventional function(s) that is(are) superseded or replaced by the alternative co-function(s) provided. A second alternative consists of adding to the mono-functional product system the unprovided (or missing) co-function(s) that the multifunctional product system provide(s) to make the product systems comparable. Both alternatives are mathematically equivalent but not necessarily in their meaning and interpretation.

In this case study, both system expansion approaches were applied (section 3.2 and section 3.3) to compare the environmental performance of CP and SP product systems. The system expansion approach applied in each case depended on the management of the spE generated by SP design. According to the end-use(r) of the spE, passive and active contributions to sustainability were distinguished (Fig. 4) for robust sustainability-based decision-making.

Insert here Fig. 4

2.3.1. *Passive contribution to sustainability*

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

2.3.2. *Active contribution to sustainability*

Active contribution to sustainability is defined as the implementation of the SP design with encouragement of a specific end-use(r) of the generation of spE. In this case, the spE is proposed to be employed as energy input to support a service of clean electric bike (e-bike) charging.

E-bikes are gaining in popularity in many countries worldwide as environmentally desirable vehicles for urban areas. In some Asian countries, such as China (the biggest e-bike market of the world), e-bikes are replacing gasoline-powered motorcycles and public transit vehicles (The New York Times, 2010; Weinert et al., 2008). Several pioneering Spanish cities in the development of sustainable mobility initiatives are committed to encourage the use of e-bikes among citizens (Fundación ECA - Bureau Veritas, 2012). The City Council of Barcelona, for instance, is running pilot tests for the electrification of a share of the worldwide-known “Bicing” (bike sharing) network to facilitate a sustainable multimodal mobility (Plataforma LIVE, 2013).

Currently, there are various types of e-bikes available in the market, 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). The SI file (section A.7) presents the key technical data of conventional e-bikes used to calculate the number of units that could be charged daily using the net amount of “clean” spE produced by the SP design (see section 3.3).

According to Fig. 4, the boundaries of the CP product system should be expanded to integrate a service of e-bike charging. In this process, the environmental burden of a functionally equivalent conventional charging station (CCS) for e-bikes was added to the life-cycle environmental burden of the CP design. The LCI data and corresponding environmental burden of the functionally equivalent CCS was calculated using the results provided by Mendoza et al. (2014) as a reference; these authors characterized the life-cycle environmental performance of standard public charging facilities for electric two-wheelers. The procedure applied to address this calculation is presented in the SI file (section A.7). However, the values are integrated in Fig. 7. At this stage, the CP product system is re-named CP_CCSeBike, whereas the SP product system is redefined as SP_eBike.

2.3.3. *Sensitivity analysis of the environmental performance of the product systems*

The environmental performance of the SP product system will highly depend on its geographic emplacement, which affects the amount of photovoltaic production and defines the carbon intensity of the avoided production of conventional electricity.

The Spanish (ES) electricity grid mix (REE, 2011) and the photovoltaic production by the SP design emplaced in the city of Barcelona (Spain) were the variables used to define the reference (baseline) scenario.

The Greek (GR) and the French (FR) electricity grid mixes (SCLCI, 2010) were selected as references to determine the effect of replacing the consumption of high and low carbonized electricity grid with photovoltaic production.

The maximum and minimum amount of photovoltaic production were calculated according to the variability of the solar radiation from Mediterranean to Atlantic regions in Spain. These values may also be representative of other countries affected by similar bioclimatic conditions. The lifetime energy consumption in operation of the CP and SP product systems was adjusted according to the average requirements for nocturnal lighting in those geographies. Information provided by the Spanish National Statistical Institute (INE, 2014) about the annual hours of sunlight by provinces (1997-2012) was 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 determine the variability in the photovoltaic production by the SP product system.

Table 1 summarizes the basic data related to each scenario considered to determine the deviation of the environmental performance of the CP and SP designs through sensitivity analysis. Detailed descriptions of the ES, GR and FR electricity mixes and the calculation of the lifetime energy demand of the pergolas and the photovoltaic production by the SP design are presented in the SI file (section A.7).

Insert here Table 1

3. Results and Discussion

3.1.Life-cycle environmental performance of CP and SP designs

Table 2 presents the life-cycle GWP and CED 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 aspect is comprehensively addressed in the next sections. At this point, the products' environmental performance is aimed to be compared by focusing exclusively on their structural design and energy consumption in operation.

Insert here Table 2

The SP design contributes 32% less to GWP (- 2,295 kg CO_2 eq.) and 42% less to CED (- 61,208 MJ eq.) than the CP design. While the operation of the SP does not contribute to environmental impacts, the operation of the CP is the most critical hot-spot. Electricity consumption by CP accounts for 62% of the total GWP and 73% of the total CED. The most relevant environmental aspect of the SP design is the material constituents, which contribute 71% to life-cycle GWP and 76% to life-cycle CED. The materials used in the SP design represent a 2.8 times higher contribution to GWP and 3.4 times higher contribution to CED than the materials employed in the CP design. Fig. 5 shows the relative contribution to GWP and CED by the type of materials employed in each pergola design.

Insert here Fig. 5

The amount of steel used in the structure of the CP design accounts for 65% of the total GWP by the materials, whereas the concrete employed for the installation of the pergola in the public urban space represents 27% of the total GWP. The contribution to GWP by these materials is determined primarily by the primary energy requirements during their industrial processing. Thus, the steel structure and concrete foundation are also the dominant contributors to CED, with contributions of 78% and 10%, respectively.

The photovoltaic cover of the SP design, which contributes to a clean operation stage, contributes the most to GWP and CED amongst all the materials employed. Photovoltaic panels account for 37% of GWP and 39% of CED, which is mainly determined by the energy requirements for the industrial production of the photovoltaic cells. The aluminum structure also strongly contributes to GWP (39%) and CED (34%). Although LED lamps are high-energy efficient lighting products compared with fluorescence lamps, LEDs contribute 24% of GWP and 26% of CED. In this manner, 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 to the operation of the product, which is the most critical stage of energy-related products (European Commission, 2009). Additionally, the SP design requires lower construction requirements and installation efforts compared with the CP design. Overall, the implementation of the SP design in substitution of the CP design would contribute to save 2,295 kg of CO_2 eq. and 61,208 MJ eq., even if the spE generated by the SP is not used for any purpose.

3.2.Passive contribution to sustainability by the implementation of the SP product system

Fig. 6 shows the variability of the life-cycle GWP and CED of the CP and SP product systems according to different geographic emplacements (baseline latitude, Mediterranean latitude, and Atlantic latitude). The lifetime spE generated by the SP design is assumed to be poured into the electricity grid (Fig. 4) in substitution of an equivalent amount of an average-carbonized (ES), high-carbonized (GR) and low-carbonized (FR) electricity grid mix.

Insert here Fig. 6

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

As a general rule, higher nocturnal lighting requirements correspond to greater electricity consumption by the pergolas (Table 1); in addition, a higher carbon intensity of the electricity grid mix represents a greater environmental impact of the operation stage. However, this rule applies partially to the SP product system. In this case, the environmental burden of the operation stage is always zero given that the energy demand of nocturnal lighting is supplied by photovoltaic production (Table 2). Nevertheless, a greater lifetime spE generation and higher carbon intensity of the conventional electricity grid mix corresponds with larger environmental savings for the operation stage (Fig. 6).

Focusing on the baseline scenario, approximately 11,417 kWh of spE are required to compensate for the entire life-cycle GWP (4,820 kg CO_2 eq.) of the SP design, whereas 8,301kWh of spE are sufficient to compensate the life-cycle CED (83,571 MJ eq.). The payback time of the total life-cycle environmental burden of the SP product system would account for 3 to 4 years of operation. After that, each kWh of spE poured into the electricity grid would contribute to net environmental savings. In this manner, the potential for environmental improvement of the implementation of the SP design in substitution of the CP product system would account for 211% in GWP (- 15,017 kg CO_2 eq.) and 252% in CED (- 364,564 MJ eq.) in a timeframe of 10 years. However, these values might be lower or higher depending on the geographic emplacement of the product system. According to Fig. 6, the minimum potential for environmental improvement of the SP product system accounts for 49% in GWP (- 2,080 kg CO_2 eq.) and 191% in CED (- 350, 394 MJ eq.), which represent notable environmental savings. In contrast, the maximum potential for environmental improvement accounts for 369% in GWP (47,187 kg CO_2 eq.) and 364% in CED (692,764 MJ eq.).

Table 3 summaries the most relevant environmental outcomes related to the life-cycle performance of the SP product system for the different case scenarios.

Insert here Table 3

The SP product system exhibits the lowest potential for environmental improvement in Atlantic regions with a low-carbonized electricity grid mix. In these cases, the life-cycle GWP cannot be completely compensated but is greatly reduced. The life-cycle GWP payback time would be 15 to 18 years and would correspond to pouring an extra amount of 10,580 kWh to over 20,000 kWh of spE into the electricity grid.

The findings therefore demonstrate that the SP product system exhibits a higher potential for environmental improvement in geographic regions with high solar radiation and high-carbonized electricity grid mixes. In these locations, the life-cycle GWP of the SP product system could be amortized after 1 to 4 years of operation. Thus, an important amount of clean spE would be generated, which would contribute to achieve notable net environmental savings over time. Using the total lifetime GWP savings of the SP product system for the baseline scenario (15,017 kg CO_2 eq.) as a reference, the savings can be increased by a maximum of 214%.

Regarding the CED indicator, the savings are remarkable for all the scenarios considered. The life-cycle CED of the SP product system can be amortized after 1 to 3 years of operation. The CED value of the electricity grid mixes considered in the calculations is high (Table 1) even for the low-carbonized mix (FR) due to the input of nuclear power (see section A.7 from the SI file). Therefore, the environmental performance of the SP product system exhibits a different behavior for CED when the system is assumed to be implemented in geographic regions with a low-carbonized electricity grid mix. Using the total lifetime CED savings of the SP product system for the baseline scenario (364,564 MJ eq.) as a reference, the savings can be reduced by only 4% (SP implemented in an Atlantic geography with an average-carbonized electricity grid mix, ES) or by 90% (SP implemented in a Mediterranean geography with a high-carbonized electricity grid mix).

All the findings indicate that the implementation of the 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, the overall environmental savings could be increased if a specific end-use(r) of the spE generation by the SP design is actively promoted.

3.3.Active contribution to sustainability by the implementation of the SP_eBike (concept)

3.3.1. Clean e-bike charging

The amount of clean spE generated by the SP design could be encouraged to be used for providing a sustainable service of public charging of e-bikes. Table 4 lists the number of e-bikes that could be daily charged using clean spE based on the different scenarios considered. At this point, the SP product system is re-defined as the SP_eBike concept.

The minimum, average and maximum number of daily charged e-bikes was determined based on the specificities related to battery capacity and the charging time of conventional e-bikes (section A.7 from SI).

Insert here Table 4

Depending on the geographic emplacement, the electricity grid mix and the model of e-bikes used, a minimum of 2 e-bikes to a maximum of 9 e-bikes could be charged daily per module (23 m^2) of the SP_eBike concept implemented in the urban public space of cities. Only in geographic regions with a very low-carbonized electricity grid mix (e.g., FR), there would be no opportunity to offer clean e-bike charging.

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 an e-bike plug-in (i.e., one plugged e-bike per column). A plug-holder bar can be installed (see Fig. 4) when the number of e-bikes to be charged daily is greater (i.e., more than four). In this manner, 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-bikes. This fact also provides a multifunctional character to the material structure of the product system.

E-bikes can travel an average range of 30 – 40 km (on a single charge) at the speed of 25 to 45 km/h with a consumption of 1 to 1.5 kWh/100 km (Weinert et al., 2008).

These vehicles thus offer high performance to cover daily urban commuting at a minimum energy and environmental 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). In this manner, one of the most controversial aspects related to the environmental performance of the use of electric vehicles, which relies on the carbon intensity of the electricity grid mix used for daily battery charging (Doucette and McCulloch, 2011), could be easily solved for e-bikes using local photovoltaic production systems. In this process, the implementation of the SP_eBike concept can play an instrumental role in the design of “solar parking networks” for e-bikes.

The deployment of a four-module of the SP_eBike concept (approximately 92 m^2 of “solar parking”) could supply sufficient clean energy to charge 8 to 36 e-bikes by day. These e-bikes would not contribute any environmental impact during their use by riders. These findings demonstrate the viability of promoting the implementation of the SP_eBike concept to support a sustainable service of public e-bike sharing. Much knowledge and expertise on the administration of conventional bike-sharing systems that has already been implemented in many cities worldwide (EPOMM, 2013; OBIS, 2011) could be used for the conceptualization, planning and management of “sustainable e-bike sharing programs.” Tourist areas may represent interesting urban hot-spots for the implementation of the SP_eBike concept to support green tourism initiatives. Tourists can use e-bikes for clean sightseeing instead of using conventional motorized transportation systems. E-bikes can also be very 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 need assistance, as could be the case for elderly citizens, can also take advantage of the use of e-bikes to move throughout the city with the additional incentive of achieving greater health improvements due to softer exercise (Oja et al., 2011). In this manner, steep urban areas with a high density of elderly people can represent another interesting dedicated hot-spot for the deployment of the SP_eBike concept. In all cases, the promotion of sustainable e-bike sharing programs could directly contribute to reduce the use of petrol-fuelled private and public conventional means of transportation and diminish pollutant emissions.

3.3.2. Environmental performance of CP_CCSeBike and SP_eBike product systems

In this scenario, the life-cycle environmental performance of the SP_eBike concept is compared with the CP_CCSeBike product system (section 2.3.2) to determine the extra potential for environmental improvement that can be achieved through smart decision-making in the eco-design of products and services.

Fig. 7 compares the life-cycle GWP and CED of the CP_CCSeBike and SP_eBike product systems for various geographic emplacements with variable carbonized electricity grid mixes. The amount of clean lifetime spE (Table 3) and the corresponding potential number of daily charged e-bikes (Table 4) were taken as references to compare the environmental impacts among product systems under equivalent functional conditions.

Insert here Fig. 7

In this scenario, the life-cycle GWP and CED related to the SP_eBike concept are always zero. The environmental burden of the product system is assumed to be compensated first through the substitution of conventional electricity from the grid mix, except when the electricity grid mix is very clean (e.g., FR). The life-cycle environmental GWP and CED of the CP_CCSeBike product system correspond to the function of providing shadow and nocturnal lighting for pedestrian mobility, including the additional function and infrastructure requirements for supplying conventional electricity for e-bike charging (Fig. 4).

The explanations provided in the scenario of passive contribution to sustainability also apply for this analysis. The main difference in the life-cycle environmental impact of the CP_CCSeBike product system compared with the SP_eBike concept relies on the additional environmental burden of the functionally equivalent conventional public charging station. A slight environmental improvement (less than 1%) would be achieved by the encouragement of the use of the spE generated by the SP product system for e-bike charging. These environmental improvements account for an extra savings of 35 to 71 kg of CO_2 eq. and 710 to 1,281 MJ eq. Although, the 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 sustainable multimodal mobility networks in smart cities. An integral service of comfort for pedestrian mobility and green energy for e-bike use can be supported without environmental burden. Thus, this concept can represent an interesting business and socio-political opportunity for companies and local governments committed to the promotion and management of clean and energy-efficient urban mobility networks. The implementation of these urban elements can contribute to induce cycling mobility to the detriment of conventional high-pollutant motorized vehicles, which is a critical issue for transport sustainability. Additionally, the SP_eBike concept could be used in the planning and management of clean-energy-storage urban networks. The batteries of e-bikes could be used as storage systems for solar energy to supply clean energy to the pergola´s lighting system or to the local lighting network as an alternative to provide energy security. These circumstances could contribute to generate additional environmental savings to be attributed to this urban element.

It is therefore demonstrated that infrastructure design plays a key role in effectively mitigating environmental impacts from urban mobility. Sustainable mobility can be greener than relying only on the promotion of a shift toward more environmentally friendly modes of transportation for vehicle technology improvement.

4. Conclusions and policy implications

A shift to more environmentally friendly modes of mobility is essential to reduce oil consumption and pollutant emissions in cities. In this process, better urban planning and design play a central role in effectively encouraging the creation of clean and energy-efficient mobility networks. However, the provision of infrastructures and urban elements to support sustainable mobility can contribute an important environmental burden if their design lack the integration of comprehensive life cycle environmental criteria.

This research has showed that the deployment of a conventional design of urban pergola and charging station to support pedestrian and e-bike mobility can account for 351 GJ to over 694 GJ of energy consumption and contribute 3.6 tons to over 47 tons of CO_2 eq. emissions in a timeframe of 10 years depending on the geographic emplacement and electricity grid system. However, these environmental burdens can be largely minimized or completely avoided. Findings have demonstrated that there is a great potential to support a carbon-free and high energy-efficient urban multimodal mobility through the eco-design of urban elements. The implementation of solar pergolas with surplus photovoltaic production can provide diurnal shadow, nocturnal lighting and green electricity for pedestrian and e-bike mobility with no environmental cost and only environmental savings. Geographic regions with high solar radiation and a high-carbonized electricity grid mix represent the most suitable hot-spots for the implementation of this type of urban elements.

Although a specific product system has been evaluated, the findings are widely relevant. Instead of solely maximizing infrastructure provision, the deployment of eco-designed (versatile and multifunctional) urban elements in relevant hot-spots of the urban space can play an instrumental role in the support of clean multimodal mobility networks. Given the increasing global investment in urban refurbishment and new infrastructure provision to stimulate a shift in urban mobility patterns, this best practice can contribute to achieve significant energy and environmental savings at the entire city scale. In this sense, eco-design is a high valuable tool for the conceptualization, design, development and management of innovative solutions that lead to achieve carbon-free mobility logistics, which is a key action in the context of the development of future smart cities.

To accomplish energy and environmental targets in cities (i.e. Europe 2020) while satisfying the growing mobility needs and aspirations of citizens, it is essential that policy makers from local and regional governments give proper consideration to the relevance of adequate infrastructure design and provision in the different action plans related to the encouragement of clean mobility and sustainable urban development.

These action plans should integrate a set of guidelines, requirements and recommendations for the eco-design and eco-innovation of urban elements to minimize long-term environmental burdens in cities. The encouragement of the identification of synergies between different urban elements already implemented in cities to support sustainable mobility could bring interesting ideas to stimulate the design of versatile multifunctional products and services, which could provide notably resource savings. In this process, it is essential that public administrations, urban planners, mobility managers and infrastructure providers have access to complete environmental studies and information related to the performance of different urban mobility alternatives and scenarios for a robust sustainability-based decision-making. This environmental studies should also include the effect that the deployment of multifunctional urban elements and infrastructure may have on diversion factors and induced demand related to urban mobility, which are critical issues for transport sustainability. As a result, integrated solutions can be identified to promote strategic and smart infrastructure investment that ensure high environmental performance in cities.

Supplementary Electronic Material

Further descriptions and data related to the eco-design methodological framework, analytical scenarios and environmental outcomes are available in the electronic version of this article.

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FIGURES

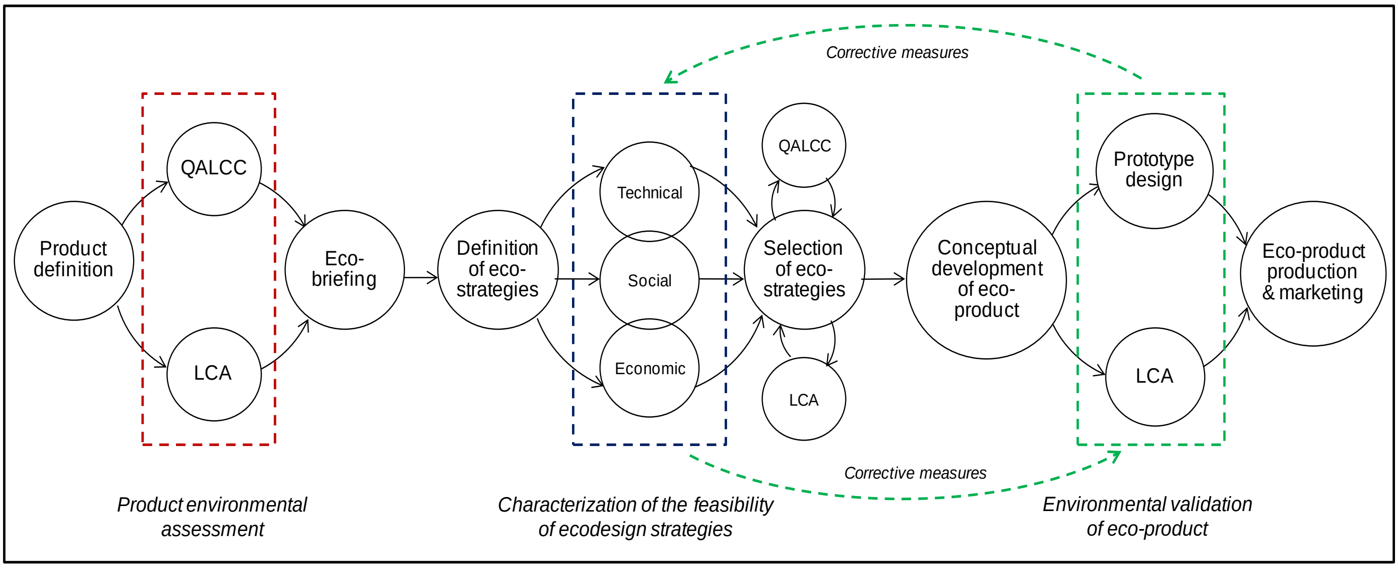
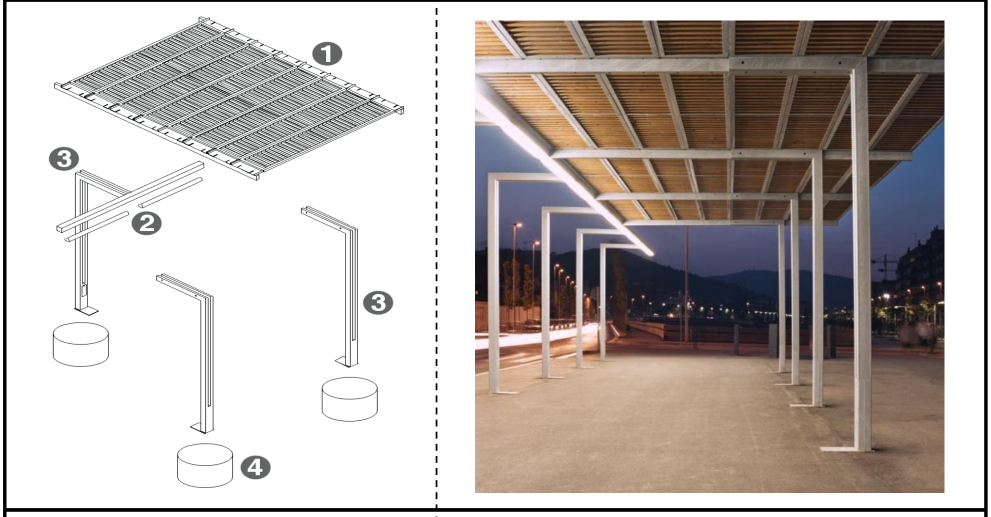
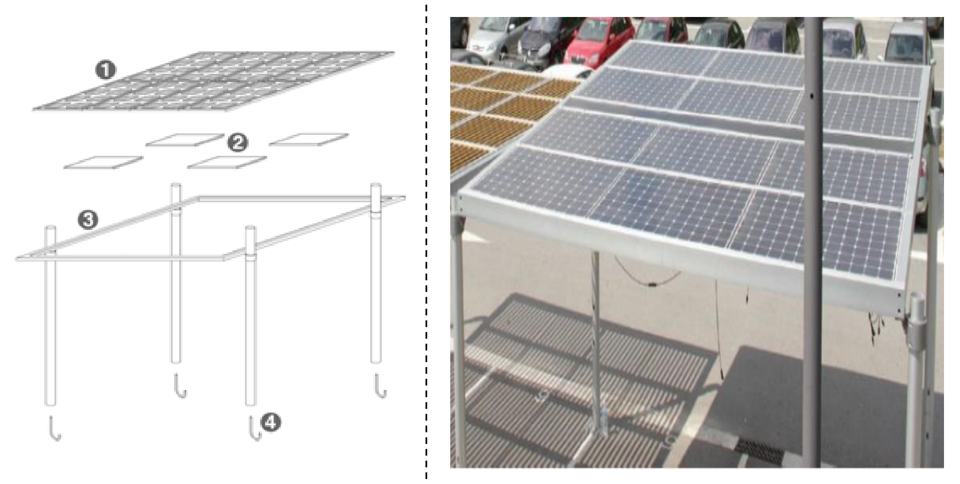


Fig. 1. Ecodesign methodological framework. Acronyms: QALCC - Qualitative Assessment of Life Cycle Criteria; LCA - Life Cycle Assessment.



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. 2. Exploded illustration and brief description of the CP product system.



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

Fig. 3. Exploded illustration and brief description of the SP product system.

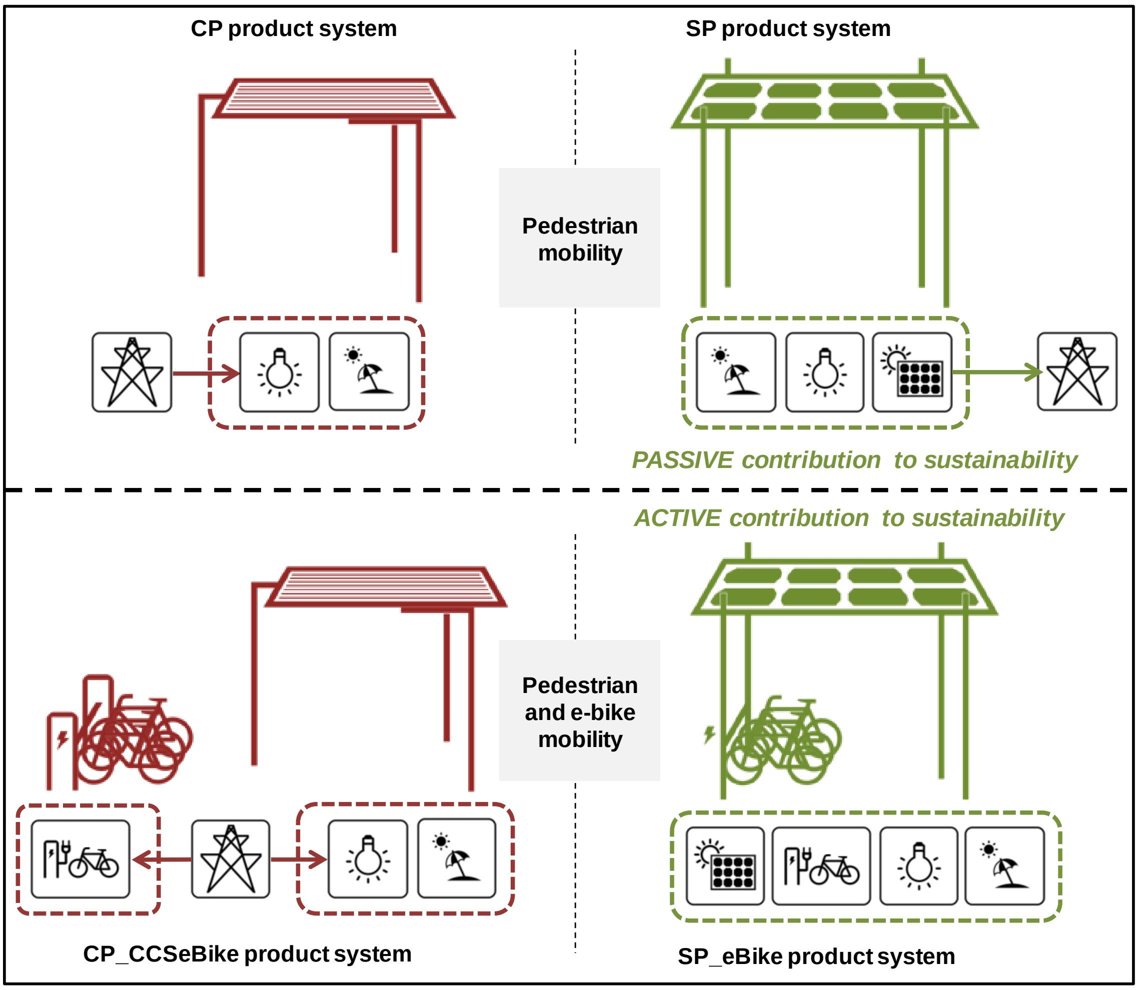


Fig. 4. Conceptual diagram of the functional equivalence of CP and SP designs.

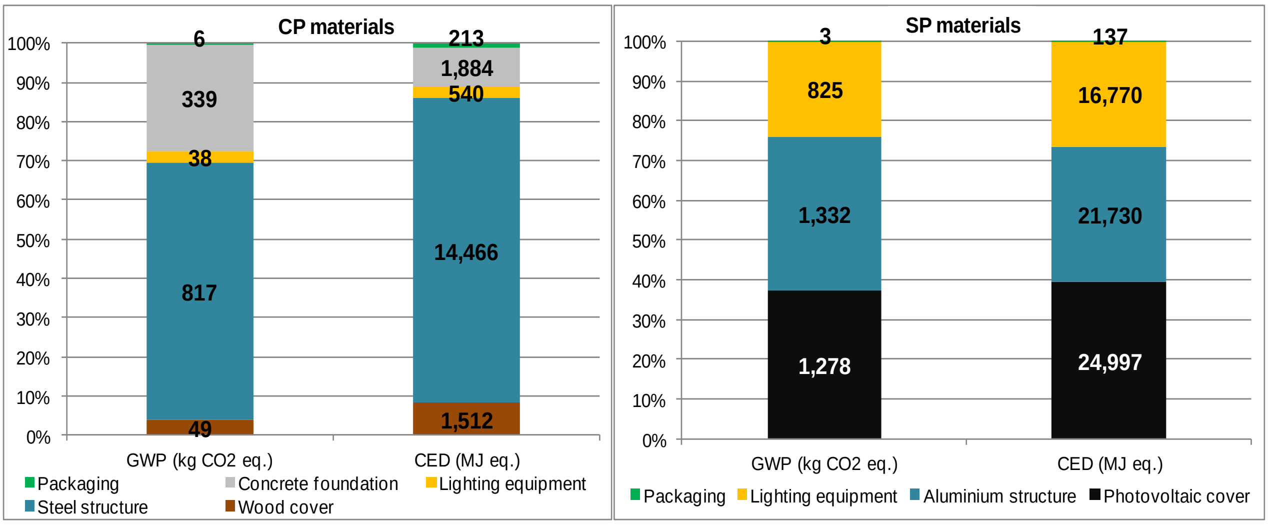


Fig. 5. Relative contribution to GWP and CED by the materials used in the CP and SP design.

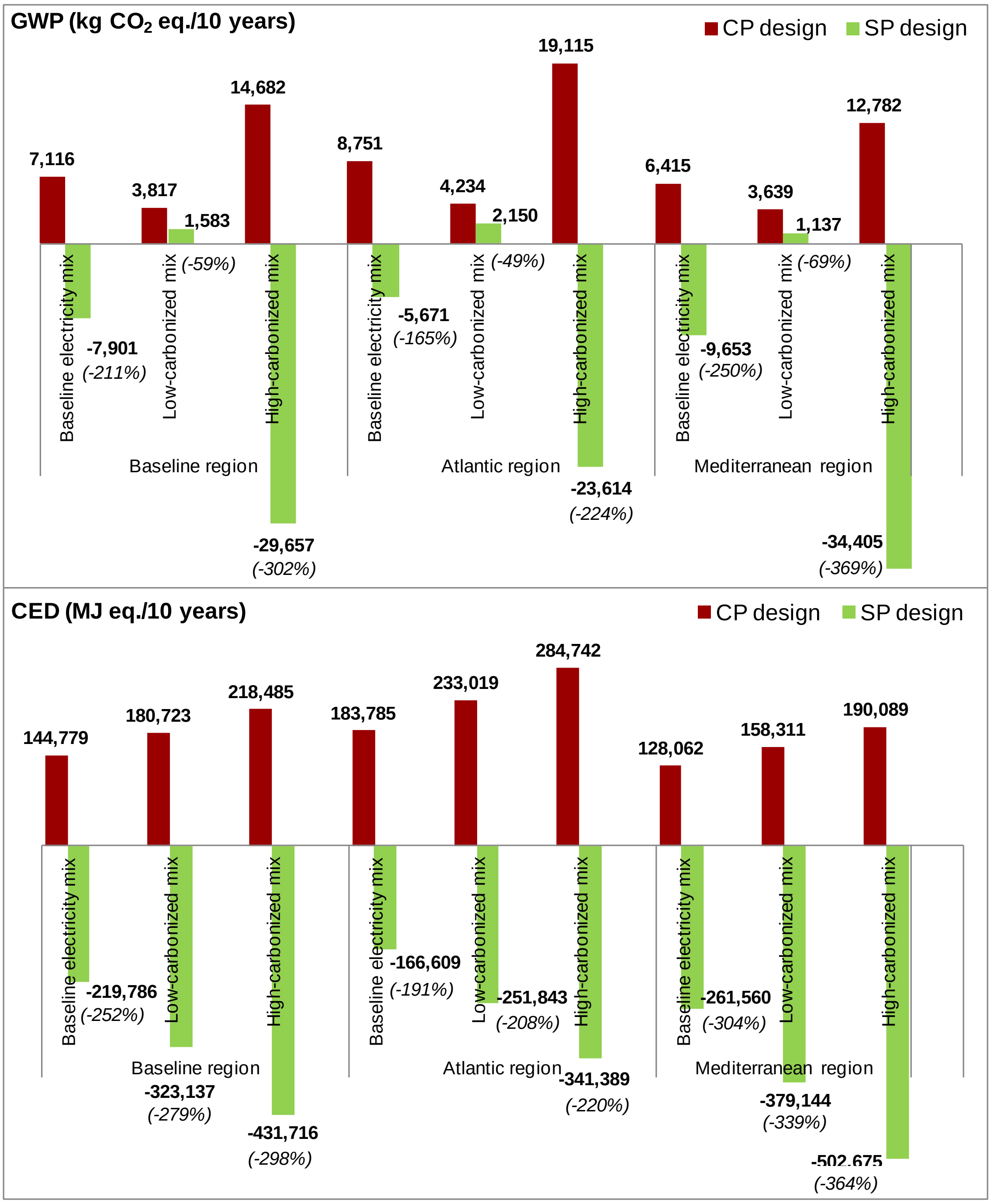


Fig. 6. Comparison of the life cycle environmental performance of CP and SP product systems according to the geographical emplacement and carbon-intensity of the electricity grid mix.

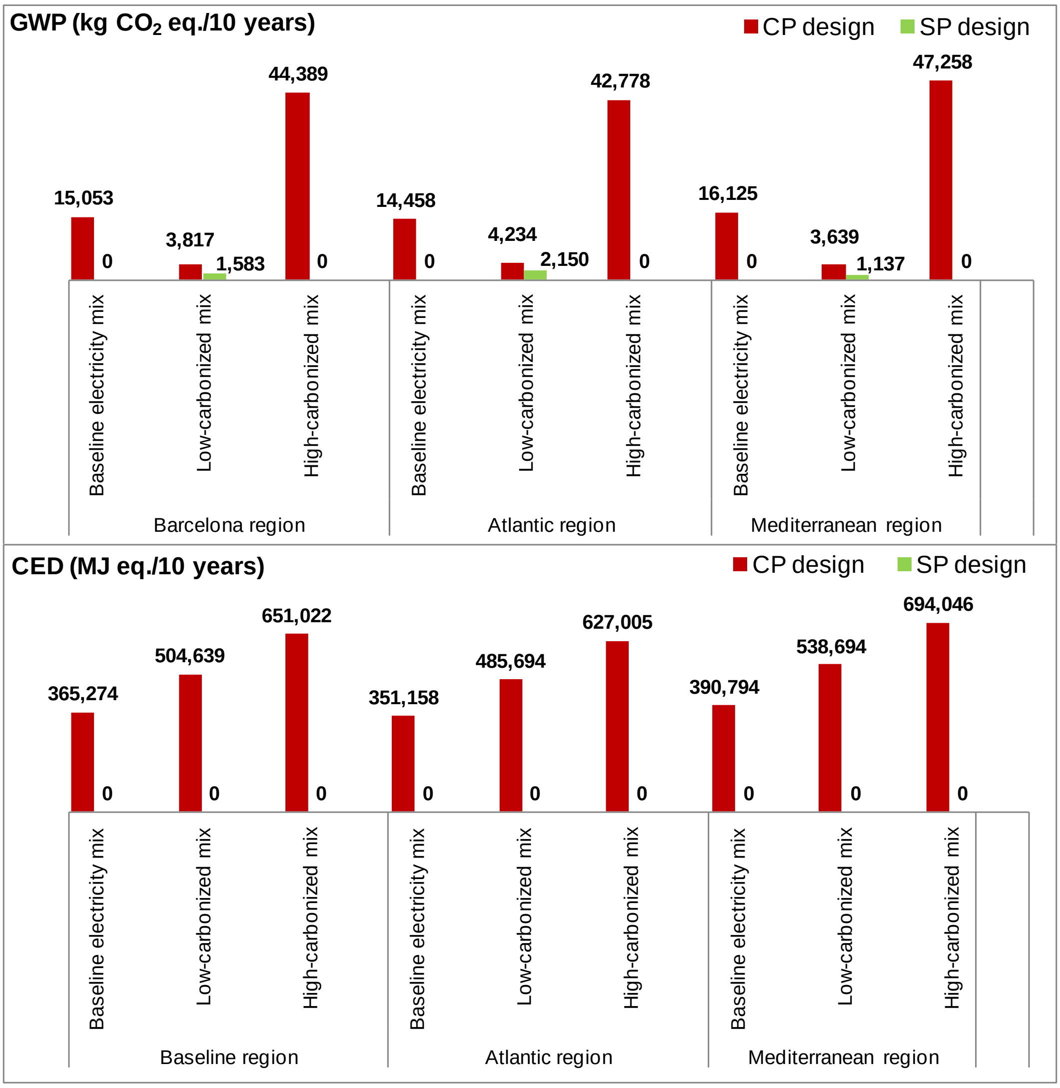


Fig. 7. Comparison of the life cycle environmental performance of CP_CCSeBike and SP_eBike product systems according to the geographical emplacement and carbon-intensity of the electricity grid mix.

TABLES

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

Table 1. Data used for sensitivity analysis of the environmental performance of the pergolas. Acronyms: CP – conventional pergola; SP – solar pergola; spE – surplus photovoltaic electricity.

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**
CED (MJ eq.)	**CP**	18,614	18,721	1,941	105,503	**144,779**
	SP	63,634	18,375	1,562	0	**83,571**

Table 2. Life cycle environmental performance of CP and SP product systems. Note that the environmental benefits related to the end-use of the spE generation by the SP design (operation stage) are cut-off.

Environmental indicator	**Geographic emplacement**	**Electricity grid mix**	**Annual savings**	**Payback time (years)**	**Clean lifetime spE (kWh)**	**Total lifetime savings (*)**
GWP (kg CO_2 eq.)	Baseline region	Baseline electricity	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 region	Baseline electricity	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 region	Baseline electricity	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
CED (MJ eq.)	Barcelona region	Baseline electricity	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 region	Baseline electricity	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 region	Baseline electricity	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

Table 3. Life-cycle environmental performance indicators of the SP product system operating in different geographic emplacements with variable carbonized electricity grid mixes. (*) compared with the implementation of the CP product system.

Geographic emplacement	**Electricity grid mix**	**Nº daily (100%) charged e-bikes**					
		GWP “free”			**CED “free”**		
		Min.	**Average**	**Max.**	**Min.**	**Average**	**Max.**
Baseline region	Baseline electricity mix	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 region	Baseline electricity mix	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 region	Baseline electricity mix	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

Table 4. Number of e-bikes fully charged by day (annual average) using clean spE generation by the SP_eBike concept. Note: Min. (battery pack: 36 V/10 Ah – charging time: 6 h), Max. (battery pack: 24 V/9 Ah – charging time: 4 h), average (battery pack: 36 V/9 Ah – charging time: 5 h).