A comparison of solar and conventional pavements via Life Cycle Assessment

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Highlights:

1. Conducted life-cycle assessment of solar pavement.

2. PV system is the largest contributor to the environmental impacts of solar pavement.

3. Without considering power generation benefits, solar pavement has high emissions.

4. In long-term, the development of solar pavement is environmentally beneficial.

Abstract: The sustainable and green development of roads is lately receiving significant attention. As a multi-functional road capable of both accommodating traffic loads and generating clean energy, solar pavements exhibit a strategic opportunity for the future path of development in the road engineering. Although solar pavements have significant environmental benefits during their operation, they can lead to increased carbon emissions during the process of material preparation, construction, maintenance, etc. Therefore, it is essential to implement the framework of Life Cycle Assessment (LCA) to investigate their potential environmental impacts and/or benefits. Hence, this paper systematically analyzes the

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energy consumption and emissions of solar pavements based on LCA. The results show that the total energy consumption and gas emissions of the solar pavement are far greater than those of the traditional asphalt pavement. Nevertheless, in long-term the power generation function of the solar pavement has significant energy and environmental benefits.

Keywords: Solar pavement; Life cycle assessment; Energy consumption; Energy payback time; Environmental impacts; PV-system

Nomenclature

AC:	Asphalt Concrete
BOS:	Balance of System
CLCD:	Chinese Reference Life Cycle Database
ECC:	Engineered Cementitious Composite
EFA:	Emission Factor Approach
EIO-LCA:	Economic Input-Output Life Cycle Analysis
EP:	Eutrophication Potential
EPBT:	Energy Payback Time
GHGs:	Greenhouse Gas Emissions
GWP:	Global Warming Potential
LCA:	Life Cycle Assessment
LCI:	Life Cycle Inventory
LCIA:	Life Cycle Impact Assessment
LCOE:	Levelized Cost of Electricity
NPV:	Net Present Value
PMMA:	Polymethyl Methacrylate
POCP:	Photochemical Ozone Creation Potential
PV:	Photovoltaic

RAP:	Reclaimed Asphalt Pavement
SMA:	Stone Mastic Asphalt
SVF:	Sky View Factor
WMA:	Warm Mix Asphalt

1. Introduction

Since the popularization of electrified transportation, the intense energy consumption by transportation and the negative effects of energy use have led to irreconcilable conflicts between the two. Facing the severe challenges brought by resource constraints, climate change, and environmental pollution, promoting the revolution of energy and transportation supply and promoting industrial transformation, are fundamental ways to cope with each challenge (Jia et al., 2020; Mantalovas and Di Mino, 2019; Barakat et al., 2022; Mantalovas et al., 2020.a; Praticò et al., 2020). Meanwhile, building a green, resilient, self-sustained and sustainable transportation energy integration system is an important future development path for the road engineering sector, and exploring renewable energy and transportation integration development technology is of great significance to improve the energy efficiency of transportation. Moreover, optimizing the energy structure of transportation, has become a current research hotspot and developed a variety of clean energy harvesting pavements (Vizzari et al., 2021), mainly including: solar collectors (Pan et al, 2015), thermoelectric pavements (Zhu et al, 2019), magnetoelectric pavements (Gholikhani et al., 2021) piezoelectric pavements (Wang et al, 2020) and solar pavements (Northmore and Tighe, 2016) etc.

Under the existing and expected future conditions of technology and traffic space resources, solar energy conversion to electrical energy is the most convenient way to utilize (Hu et al, 2022.b). The solar pavement is an emerging technology for the exploitation of the solar radiation and the production of electricity. The typical solar pavement is composed of three layers: i) a semi-transparent surface able to support the passage of the vehicles, guarantee the friction in the interface road/tire and allow the passage of the sunlight; ii) an electrical layer containing the photovoltaic cells and iii) a base layer for the load distribution in the subgrade (Hu et al., 2020). In general, the semi-transparent layer consists of 0.5 – 1 cm of tempered glass, PMMA (polymethyl methacrylate) or glass aggregates bonded together through a polymer resin; the solar cells are usually polycrystalline silicon, and the base is concrete or dense-graded asphalt mixture.

The first prototype of solar pavement dates to 2012, when the American company Solar Roadways designed hexagonal prefabricated panels, having area of 0.37m^2 and power output of 36 W. Each panel incorporated LEDs for illuminating road edge striping and heating elements to prevent the snow accumulation during winter (Brusaw, 2022). At the same time, TNO built a solar road of 70 meter, which generated 78 kWh/m^2 per year (SolaRoad, 2022). France and China were shown to be even more ambitious by building 1 km of solar pavement, which generated 280 MWh and 1000 MWh per year, respectively (Jiang et al., 2018; Colas., 2022).

In academia, the research focuses on four main aspects: the material design and the characterization of the semi-transparent layer, the structural design, the energy production, and the economic feasibility. Hu et al. (Hu et al. 2022) designed 50 mm thickness of semi-transparent layer, in which the solar cell is immerged into a mixture of unsaturated polyester resin and glass aggregates. Based on their result, the optimum mixture is given by 38.6% of resin and 61.4 of aggregates, while the target gradation for the glass aggregates is 6.9% of 13.2/16 mm; 44.5% of 9.5/13.2 mm and 48.6 of 4.75/9.5 mm. Vizzari et al. (Vizzari et al., 2018; Vizzari et al., 2019; Vizzari et al., 2020) evaluated the effect of grading curve, glue content and thickness on the optical and mechanical performance of the semi-transparent layer. In general, the fine particles have a severe impact on the transparency due to the interaction with the sunlight wavelength, while the increase of glue content has a positive impact on both optical and mechanical performances. Zha et al (Zha et al., 2021) designed a light-guided concrete solar pavement with light convergence through light-guiding optical fibers and finally determined that the power generation could reach 90 kWh/m^2 per year when the number of light guides was 81. Dezfooli et al. (Dezfooli et al., 2017) prepared two solar pavement panel models using rubber and plexiglass and investigated their structural performance. Ma et al. (Ma et al., 2019) for the Hong Kong regional environment, developed a square solar PV floor tile with pedestrian walking load capabilities and evaluated the mechanical and slip resistance of the structure and the electrical and thermal properties of the system, which showed promising results in terms of energy conversion, slip resistance, heat resistance and compressive strength. Yuan et al. (Yuan et al., 2022) used the finite element software ABAQUS to study the mechanical response of the solar pavement under vehicle and temperature loads, and the results showed that the photovoltaic panels were most significantly affected by the elastic modulus. Zha et al. (Zha et al., 2022) proposed a hollow panel solar pavement with micro photovoltaic array, optimized its structure size by finite element numerical simulation, and analyzed its power generation effect through PVsyst.

Finn et al. (Finn et al., 2021) proposed a methodological approach to analyze the efficiency of photovoltaic roads in dependence of topographic features like slope gradient, slope exposure and sky view factor (SVF) for the city of Bensheim in German. Their model is a decision-making tool for rating the potential efficiency of a solar road through a qualitative scale ranging from “ideal” to “not suitable”. Liu et al. (Liu et al., 2021) estimated the road photovoltaic capacity of cities with urban features obtained from remote sensing images. They calculated that the average electric production of sample cities could be around 5×10^9 kWh, equivalent to the electric demand of 1.4 million household electric vehicles.

Notwithstanding the production of green electric power, solar roads remain an expensive technology. Hu et al. (Hu et al., 2021) evaluated the net present value (NPV) and the levelized cost of electricity (LCOE) of four existing industrial products and they set the bar of 0.2 $/kW to make the solar pavement economically attractive. Although the economic cost of solar pavements is found to be higher than that of conventional asphalt or concrete pavements, their environmental benefits can be significant in terms of road temperature reduction, urban heat island mitigation and carbon dioxide (CO_2) reduction. Solar pavements based on photovoltaic technology have significantly less impact on air quality and climate change during operation than any other conventional power generation system and could help eliminate numerous environmental issues associated with the use of fossil fuels (Vizzari et al., 2022).

However, only few studies have initially evaluated the economic and environmental benefits of solar pavements. While the benefits resulting from the energy production during the operational phase are undoubtedly significant, carbon emissions increase due to the use of perceivably unsustainable materials (concrete, asphalt mixes, polymeric resins, crystalline silica, etc.) in the materials, construction, operation and maintenance process. In particular, the potential impact of this type of infrastructure on the environment is still unknown. Therefore, it is necessary to conduct life cycle assessment (LCA) for all stages in order to fill this research gap.

LCA is a decision-making tool to that can help with assessing the environmental impacts of road pavements from the material extraction to the end of life of the asset (Al-Sharafi et al., 2017; Herrando et al., 2022; Safei et al., 2015). It provides the eco-profile of the road, considering the interaction with human and natural systems. So far, many researchers have used LCA to quantify, analyze and compare the environmental impacts of different types of structures and road pavements (Santero et al., 2011; Wang et al. 2021; Zhou et al., 2022; Mantalovas and Di Mino, 2020; Mantalovas et al., 2019;

Mantalovas et al., 2020.b; Mantalovas et al., 2020.c; Lachat et al., 2021). Pranav et al. (Pranav et al., 2022) analyzed the life cycle of precast corundum mixed ECC (Engineered Cementitious Composite) covered pavement by using EIO-LCA (Economic Input-Output Life Cycle Analysis). The authors concluded that compared with a conventional concrete pavement, the precast corundum mixed ECC pavement could save 12,488.64 kt of emissions over its whole life cycle. Gulotta et al. (Gullotta et al., 2019) conducted an LCA on different pavement technologies of urban roads, and the results showed that the product stage accounted for more than 50% of the overall impacts, and the combination of WMA technology and use of RAP can improve the energy and environmental performance of this type of pavements. Chen et al. (Chen et al., 2022) studied the full life cycle of fly ash pervious concrete pavement and concluded that the impact of pervious concrete pavement system on the environment, mainly comes from the product stage, with greenhouse gas emission accounting for 81% to 92% and energy consumption accounting for 70% to 83%. Its impact on the environment depends predominantly on the mechanical properties of pervious concrete and the surface thickness required to achieve the same structural properties. In addition, climate change and time factors were considered in the overall impact study of pavement sustainability (Chen et al., 2021).

In this work, the purpose of this paper is to quantitatively assess the energy and environmental impacts of solar pavements through LCA to fully exploit the energy saving potential of solar pavements. The functional unit, system boundaries, and life cycle inventory of the solar pavement life cycle are proposed. The life cycle is divided into the following phases: product stage, construction process stage, and use stage. The energy consumption of a solar pavement and a conventional asphalt pavement are compared and evaluated, and the impacts of the solar pavement's life cycle stages are studied, and the key stages with high energy consumption and emissions are analyzed and discussed, which are conducive to promoting carbon neutrality goals.

2. Materials and methodology

2.1. The goal and scope definition

Solar pavement is a complex product system involving materials, transportation, energy, electronics, and other aspects. The main objective of this paper is to quantify the potential environmental impacts of a solar pavement in its entire life cycle using the framework of LCA, taking into account the ISO14040/44 series of international standards while focusing on five indicators using CML2001 methodology: total energy demand, global warming potential (GWP), eutrophication potential (EP), photochemical ozone creation potential (POCP), and acidification potential (AP). In this way, comparing the LCA results of a solar pavement with those of a traditional asphalt concrete pavement, in an attempt to improve the sustainability of the road engineering industry based on environmental benefits.

At present, the application of solar pavements in heavy traffic conditions is not given priority due to its lack of durability, making its service life comparably short. Thus, this study only considers the application of a solar pavement in the shoulder of low traffic volume highway in China. The functional unit used in the analysis was 3.5 m wide, 1 km single shoulder with a service life of 20 years. Since the solar pavement is a combination of a pavement and a photovoltaic system, it is necessary to convert the photovoltaic system into a unified functional unit. The characteristics of polysilicon photovoltaic modules used in solar pavement are shown in Table 1 (Fu et al., 2015), and the geometric layout of the solar pavement installed within the scope of the pavement functional unit is shown in Fig. 1. A total of 2022 photovoltaic modules (674 × 3) are required, and the capacity of the photovoltaic system is 404400 W_p.

Table 1

Main features of photovoltaic modules.

Item	Size (mm)	Weight (kg)	Generating efficiency (%)	Number of cells per module	Cell area (mm^2)	Maximum power at STC (Pmax) (Wp)	Lifetime (year)
Description	1482 × 992 × 35	16.8	16	54 (6×9)	156 × 156	200	25

The solar pavement also involves the balance of the system (BOS), which usually includes inverters, cables, and connectors, etc. However, BOS is mainly affected by mounting structures and has little influence on environmental impacts (Fu et al., 2015). But in the solar pavement, photovoltaic system does not need to carry out additional mounting structures, so BOS is not considered. The pavement structure mainly includes surface layer (solar pavement or asphalt concrete), modified asphalt binder course, subbase, and roadbed, as shown in Table 2. Asphalt mixture and solar pavement surface are considered in this calculation, but cement stabilized macadam, road structures and traffic ancillary unites are not taken into account.

Table 2

Pavement structures.

Structure layer	Typical asphalt pavement	Transparent resin concrete solar pavement
Upper layer	4 cm SMA-13 (Modified asphalt)	1 cm polyurethane resin and glass aggregates 3.5 cm electric layer (Modified asphalt)
Middle layer	5 cm AC-16	5 cm AC-16
Lower layer	7 cm AC-20	7 cm AC-20
Base	20 cm cement stabilized macadam	
Sub-base	20 cm cement stabilized macadam	

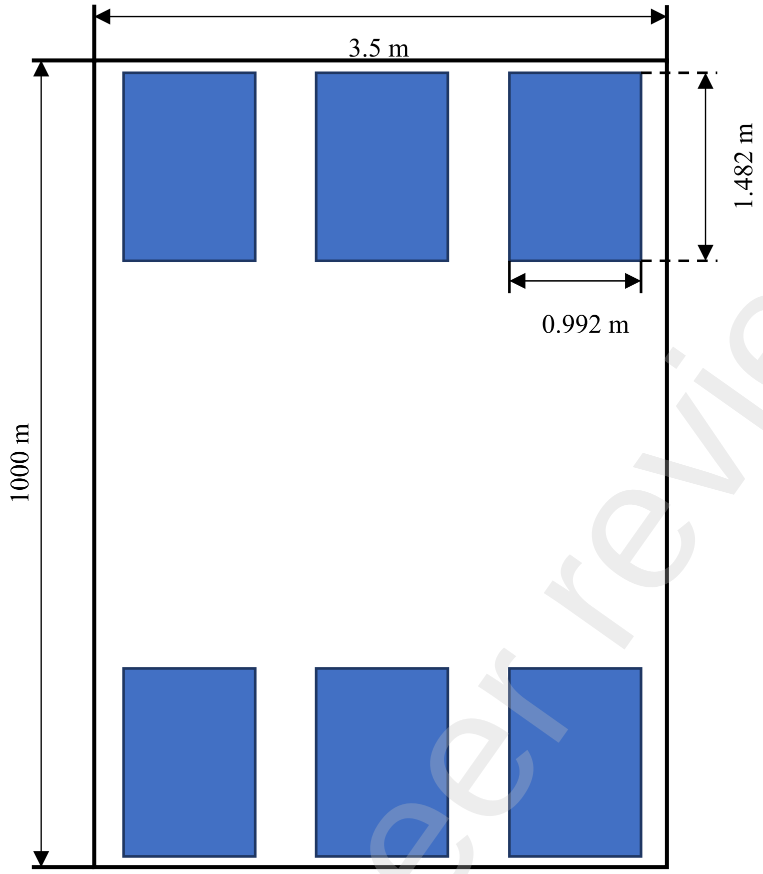

Fig. 1. Geometrical layout of the installed solar pavement.

The system boundary of the solar pavement's product system is presented in Fig. 2, which mainly consists of four parts: i) the product stage, which includes the acquisition, transport, and processing of raw materials, and the production of the asphalt mixture or solar pavement in the mixing plant; ii) the transportation, which refers to moving the road materials to the construction site; iii) the construction process stage, regarding all the processes and the equipment related to the road construction; iv) the use stage, which refers to the service life of the road and it takes into account all the interaction between road, vehicles and the environment. A complete LCA analysis should also include maintenance, recovery, and end-of life phases. The former activity takes into account the fuel and electricity consumption of materials and mechanical equipment caused by off-site and in-site activities, transportation, as well as the carbon emissions due to the vehicles operations.

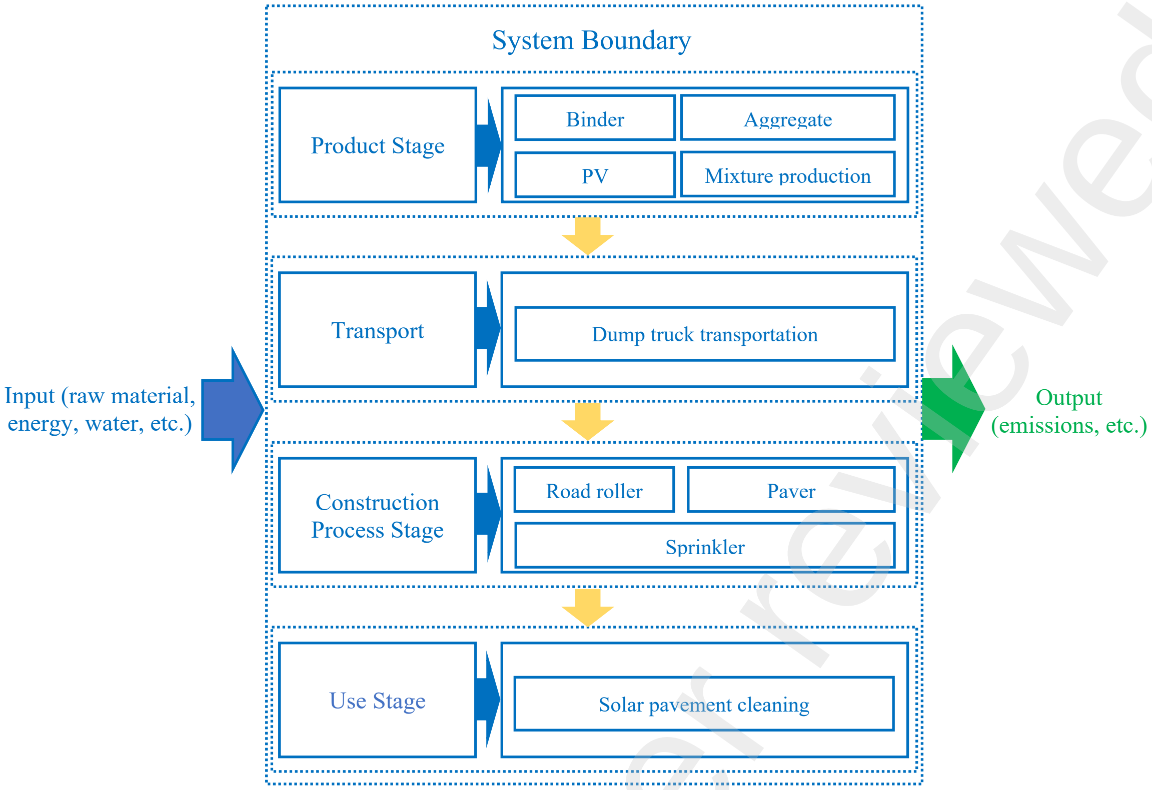

Fig. 2. LCA system boundary of solar pavement.

Regarding the end-of-life phase, it requires the identification of the final destination for the waste material or the re-allocation for recycling. This phase is usually simplified under the assumption of full disposal of the material. However, the earliest application of solar pavements was in France in 2016, and as so far there is no mature maintenance and scrap management approaches and/or protocols. Therefore, data related to the usability and scrappage phases of solar pavement systems are not available. For this paper, the end-of-life is omitted because it is considered as invariant in all the scenarios. Furthermore, national polices usually don't allow the full disposal of the road (Celauro et al., 2015). Although this may slightly underestimate primary energy demand and environmental impact, photovoltaic systems consume very few resources and have a weak impact on the environment during these phases (Cong et al., 2015). This LCA study follows a cradle-to-door approach. It includes all phases of material acquisition, production of the required mixtures, material transport to site, pavement construction and use.

In addition, within the traffic environment, the vehicles driving on the main road will accelerate the deposition of soil and dust on the surface of the solar pavement, which will adversely affect the power generation efficiency of the solar pavement. Therefore, differently from the traditional asphalt pavement, to maintain the efficient power generation level of the solar pavement, the solar pavement needs to be cleaned regularly during operation. Therefore, this paper incorporates the energy consumption and gas emissions generated by cleaning the solar pavement during operation stage into the research system.

2.2. Life cycle inventory

An important step in LCA is the life-cycle inventory (LCI), which considers the data of energy consumption and greenhouses gas emissions through all the processes from cradle to grave. Extended highway project can have severe impacts on the natural environment.

There are four different emission estimation tools (Sukhija et al., 2021): i) sampling or direct measurement; ii) mass balance principle; iii) analysis of fuel consumption; iv) emission factor approach (EFA). As it is difficult to control the boundary of gas emission test in raw material production, mixture production and construction during solar pavement/asphalt pavement construction, and the on-site collection and detection method is complex, this study uses the emission factor approach.

2.2.1. LCI of raw material acquisition and mixture production

2.2.1.1 Raw material acquisition

The object of this study is the newly built highway, and its materials are mainly newly produced materials, focusing on the energy consumption (fuel and electricity) and emissions (CO_2, CH_4, N_2O, CO, SO_2 and NO_X) of crushed stone, asphalt, polyurethane, gasoline, diesel oil, heavy oil and electricity.

The data are from Table 2 of Cong et al. (Cong et al., 2020) and from the Chinese Reference Life Cycle Database (CLCD).

Data on polysilicon solar cells are collected from literature (Fu et al., 2015), the Report on Clean Solar Photovoltaic Production in China (Li and Chang, 2012), and the Ecoinvent database. Table 3 presents a list of emissions to air per W_p solar module during production.

Table 3

Energy consumption and emissions per W_p solar photovoltaic system during production.

Material (W_p)	Energy (MJ)	Emission (kg)				
		CO_2	CH_4	CO	SO_2	NO_X
Solar PV system	1.26E+01	1.04E+00	5.56E-03	3.32E-05	7.63E-03	3.39E-04

The transparent resin concrete surface of the solar pavement is made of a polyurethane and glass particles mixture, and the clean transparent glass particles are derived from waste recycled photovoltaic glass, which can replace natural aggregates for building materials. It was assumed that the raw materials (E-o-L glass particles) are collected at no cost, as producers pay for the waste to be treated, or offset by governmental recycling incentives (Lim et al., 2022). Therefore, its energy consumption and emissions are not calculated at the raw material acquisition stage. The density of transparent resin concrete is 2.492 g/cm^3, of which polyurethane mass accounts for 21% (Hu et al., 2022.a). According to equation (1) and (2), the energy consumption and emissions in the raw material production stage are obtained respectively.

$$E_p = \sum_{i=1}^{N} E_i \times RM_i \tag{1}$$

$$Q_{p,k} = \sum_{i=1}^{N} Q_{i,k} \times RM_{i,k} \tag{2}$$

Where E_p is the total energy required in the production of raw material i, MJ; $Q_{p,k}$ is the total emission of gas k produced from raw material i, kg; N is the number of all raw materials; E_i is the quantity of primary energy for the unit production of raw material *i*, MJ; RM_i is the amount of raw material *i* needed for the construction of pavement, kg. The LCI of the raw materials in the production stage of the two kinds of pavement is calculated as shown in Table 4.

Table 4

Energy consumption and emissions of raw material extraction.

Pavement type	Material	Energy (MJ)	Emission (kg)					
			CO_2	CH_4	N_2O	CO	SO_2	NO_X
Asphalt pavement	Crushed stone	4.61E+04	5.16E+03	1.54E+01	3.02E-02	2.82E+01	1.21E+01	4.05E+01
	Asphalt	9.70E+04	2.78E+04	3.67E+02	2.33E-01	1.11E+03	3.12E+02	2.27E+02
	Total	1.43E+05	3.30E+04	3.82E+02	2.63E-01	1.14E+03	3.24E+02	2.68E+02
Solar pavement	Crushed stone	3.46E+04	3.87E+03	1.16E+01	2.27E-02	2.11E+01	9.06E+00	3.04E+01
	Asphalt	6.75E+04	1.94E+04	2.55E+02	1.62E-01	7.72E+02	2.17E+02	1.58E+02
	Polyurethane	9.45E+05	4.12E+04	1.25E+02	3.59E+00	8.02E+01	9.49E+01	7.31E+01
	Solar PV system	5.10E+06	4.19E+05	2.25E+03	0.00E+00	1.34E+01	3.09E+03	1.37E+02
	Total	6.15E+06	4.84E+05	2.64E+03	3.77E+00	8.87E+02	3.41E+03	3.99E+02

2.2.1.2 Mixture production

In the production stage of mixtures, aggregates, asphalt, glass, polyurethane, and binders are included. In this paper, according to the quota method of energy consumption calculation, according to JTGT 3832-2018 "Highway Engineering Budget Quota" and JTGT 3833-2018 "Highway Construction Machinery Shift Cost Quota", we calculated the number of shifts of each mechanical equipment required for mixing mixture and the amount of various energy consumed. The equation is presented as follows:

$$E_{mp} = \sum M_i \times e_i \tag{3}$$

Where E_{mp} is the total energy required in the mixture production, MJ; M_i is the number of machine shifts of type *i* construction machinery; e_i is the energy consumption per unit shift of type *i* construction machinery.

To produce the conventional asphalt mixture it is considered that the loose paving coefficient is

1.2, according to the road structure in Table 2, SMA-13 is 168 m^3, and AC-16 and AC-20 are both medium-grained asphalt mixture, 504 m^3 in total. The calculation results are shown in Table 5.

Table 5

Energy consumption and emissions to produce the asphalt mixture.

Asphalt mixture	Equipment	Machinery (shift)	Consumption (kg/one-shift)	Total consumption (kg)
168 m^3 SMA	Asphalt mixing plant (120 t/h)	0.72	Heavy oil: 5170.18 Electricity: 1618.42	Heavy oil: 3722.53 Electricity: 1165.26
	Wheeled loader (2m^3)	1.53	Diesel oil: 92.86	Diesel oil: 142.08
	Dump truck (5t)	0.74	Gasoline: 41.91	Gasoline: 31.01
504 m^3 middle-grained asphalt mixture	Asphalt mixing plant (120 t/h)	1.73	Heavy oil: 5170.18 Electricity: 1618.42	Heavy oil: 8944.41 Electricity: 2799.87
	Wheeled loader (2m^3)	3.70	Diesel oil: 92.86	Diesel oil: 343.58
	Dump truck (5t)	1.98	Gasoline: 41.91	Gasoline: 82.98

For the production of the solar pavement's mixture, in the preparation process of the transparent resin concrete solar pavement, the first is the transparent resin concrete on its surface, which needs to be evenly mixed with glass and polyurethane. According to the size of glass aggregate, it is treated as fine-grained asphalt mixture. The transparent resin concrete is 35 m^3, and the medium asphalt mixture is 504 m^3. The use of asphalt mixing equipment is usually considered, but because the transparent resin concrete is prepared without heating, it can be mixed at room temperature and thus, only electricity consumption is considered. For the surface and the integration of the photovoltaic cells, generally stamp molding and static pressure (Hu et al., 2022.a) is required. The energy consumption and emissions of this part are negligible and are not considered in this study. The final values are shown in Table 6.

Table 6

Energy consumption and emissions to produce the solar pavement.

Mixture	Equipment	Machinery (shift)	Consumption (kg/one-shift)	Total consumption (kg)
35 m^3 transparent resin concrete	Asphalt mixing plant (30 t/h)	0.53	Electricity: 624.02	Electricity: 330.73
	Wheeled loader (1 m^3)	0.56	Diesel oil: 49.03	Diesel oil: 27.46
	Dump truck (5 t)	0.27	Gasoline: 41.91	Gasoline: 11.32
504 m^3 middle-grained asphalt mixture	Asphalt mixing plant (120 t/h)	1.73	Heavy oil: 5170.18 Electricity: 1618.42	Heavy oil: 8944.41 Electricity: 2799.87
	Wheeled loader (2 m^3)	3.70	Diesel oil: 92.86	Diesel oil: 343.58
	Dump truck (5 t)	1.98	Gasoline: 41.91	Gasoline: 82.98

After calculation, the energy consumption and emissions of the conventional asphalt pavement and the solar pavement in the final mixture production stage are shown in Table 7.

Table 7

Energy consumption and emissions of production.

Pavement types	Material	Energy (MJ)	Emission (kg)					
			CO_2	CH_4	N_2O	CO	SO_2	NO_X
Asphalt pavement	Heavy oil	5.29E+05	3.79E+04	1.52E+00	2.53E+00	5.32E+02	8.87E+02	3.26E+01
	Diesel oil	2.07E+04	1.55E+03	6.31E-02	1.46E-01	1.70E+01	3.40E-01	1.19E+00
	Gasoline	4.91E+03	3.50E+02	1.48E-02	3.42E-02	3.99E+00	3.42E-02	1.82E-01
	Electricity	1.43E+04	3.69E+03	1.04E+01	5.63E-02	6.90E-01	1.26E+01	1.02E+01
	Total	5.69E+05	4.35E+04	1.20E+01	2.77E+00	5.54E+02	9.00E+02	4.42E+01
Solar pavement	Heavy oil	3.74E+05	2.67E+04	1.07E+00	1.79E+00	3.76E+02	6.26E+02	2.30E+01
	Diesel oil	1.58E+04	1.18E+03	4.82E-02	1.11E-01	1.30E+01	2.60E-01	9.05E-01
	Gasoline	4.06E+03	2.89E+02	1.23E-02	2.83E-02	3.30E+00	2.83E-02	1.51E-01
	Electricity	1.13E+04	2.91E+03	8.23E+00	4.45E-02	5.45E-01	9.92E+00	8.08E+00
	Total	4.05E+05	3.11E+04	9.37E+00	1.97E+00	3.92E+02	6.36E+02	3.21E+01

2.2.2. LCI of transportation stage

Carbon emissions related to transport vehicles is mainly from the production and use of fuel, energy, and electricity. Including road material transported to the construction site. Commonly used transport vehicles mainly have different specifications of truck, dump truck, transport vehicle fuel mainly diesel and gasoline.

It was assumed that 30 t dump trucks were used as a means of transport, in the transport process. Dump trucks are usually considered to be fully loaded to the site and no-load when returning to the storage point, and no-load energy consumption to full load energy consumption ratio is 70/100 (Liu et al., 2022). To reflect the energy consumption attribute of engineering technology itself, eliminate the energy consumption difference caused by different transport distances to the greatest extent, and at the same time, make the energy consumption carbon emissions have certain engineering reference, a unified 50km transport distance is set up as the calculation transport distance. The densities of SMA-13, AC-16, AC-20 asphalt mixture and transparent resin concrete are 2.46 t/m^3, 2.43 t/m^3, 2.44 t/m^3 and 2.49 t/m^3, respectively. The energy consumption is calculated according to literature (Cong et al., 2020). The final energy consumption and emissions during the transport stage are shown in Table 8.

Table 8

Energy consumption and emissions of transport stage.

Pavement types	Structural layer	Energy (MJ)	Emission (kg)					
			CO_2	CH_4	N_2O	CO	SO_2	NO_X
Asphalt pavement	4 cm SMA-13	2.88E+04	2.19E+03	7.78E+04	1.09E-01	1.65E+01	1.96E+00	7.10E+01
	5 cm AC-16	3.70E+04	2.82E+03	1.00E+05	1.40E-01	2.13E+01	2.52E+00	9.13E+01
	7 cm AC-20	4.94E+04	3.75E+03	1.33E+05	1.86E-01	2.84E+01	3.37E+00	1.22E+02
	Total	1.15E+05	8.76E+03	3.11E+05	4.34E-01	6.62E+01	7.85E+00	2.84E+02
Solar pavement	1 cm transparent resin concrete	6.17E+03	4.69E+02	1.67E+04	2.33E-02	3.54E+00	4.21E-01	1.52E+01
	3.5 cm electric layer	4.11E+03	3.13E+02	1.11E+04	1.55E-02	2.36E+00	2.81E-01	1.01E+01
	5 cm AC-16	3.70E+04	2.82E+03	1.00E+05	1.40E-01	2.13E+01	2.52E+00	9.13E+01
	7 cm AC-20	4.94E+04	3.75E+03	1.33E+05	1.86E-01	2.84E+01	3.37E+00	1.22E+02
	Total	9.67E+04	7.35E+03	2.61E+05	3.64E-01	5.55E+01	6.59E+00	2.39E+02

2.2.3. LCI of construction process stage

The emissions from the construction site mainly refer to the emissions from the mechanical equipment of the construction site and the operation process of the transport vehicles in the field. Asphalt mixture in the construction stage mainly includes two construction processes: paving and compaction (Chang et al., 2022). Compaction includes initial compaction, re-compaction, and final compaction. The construction of solar pavement adopts assembled construction technology, which is prepared and shaped by prefabricated slabs and transported to the construction site for installation. Common equipment consumes energy, gasoline, diesel, heavy oil, coal, and electricity. Using the quota method to calculate the energy consumption and emissions of this part, the results are shown in Table 9.

Table 9

Energy consumption and emissions of construction process stage.

Pavement types	Equipment	Energy (MJ)	Emission (kg)					
			CO_2	CH_4	N_2O	CO	SO_2	NO_X
Asphalt pavement	Asphalt mixture paver (6 m)	5.46E+03	4.08E+02	1.66E-02	3.83E-02	4.47E+00	8.94E-02	3.12E-01
	double-drum vibratory roller (10 t)	1.80E+04	1.34E+03	5.47E-02	1.26E-01	1.47E+01	2.95E-01	1.03E+00
	pneumatic tired roller (16-20 t)	6.67E+03	4.99E+02	2.03E-02	4.69E-02	5.47E+00	1.09E-01	3.81E-01
	double-drum vibratory roller (15 t)	1.21E+04	9.05E+02	3.69E-02	8.51E-02	9.93E+00	1.99E-01	6.92E-01
	Sprinkler truck (10000 L)	6.06E+02	4.53E+01	1.85E-03	4.26E-03	4.97E-01	9.93E-03	3.46E-02
	Total	4.28E+04	3.20E+03	1.30E-01	3.01E-01	3.51E+01	7.02E-01	2.45E+00
Solar pavement	Asphalt mixture paver (6 m)	4.08E+03	3.05E+02	1.24E-02	2.87E-02	3.35E+00	6.70E-02	2.33E-01
	double-drum vibratory roller (10 t)	1.35E+04	1.01E+03	4.11E-02	9.48E-02	1.11E+01	2.21E-01	7.71E-01
	pneumatic tired roller (16-20 t)	5.00E+03	3.74E+02	1.52E-02	3.51E-02	4.10E+00	8.20E-02	2.86E-01
	double-drum vibratory roller (15 t)	9.04E+03	6.76E+02	2.75E-02	6.35E-02	7.41E+00	1.48E-01	5.17E-01
	Sprinkler truck (10000 L)	4.55E+02	3.40E+01	1.38E-03	3.19E-03	3.73E-01	7.45E-03	2.60E-02
	Total	3.21E+04	2.40E+03	9.76E-02	2.25E-01	2.63E+01	5.26E-01	1.83E+00

2.3.4. LCI of Use stage

The emission during the use stage mainly comes from the fuel/energy consumed by the vehicles in the process of traffic loading and the emission related to the physicochemical and combustion process of the vehicle fuel/energy used. This stage is the longest stage in the life cycle of a road. The emissions related to the surface characteristics of the road, such as the direct interaction of road wear and vehicle carbon emissions, and roughness, also contribute to the long-term cumulative emissions of the road life cycle. Since the investigated asset is the shoulder of the highway, the traffic flow is significantly less, and there is also uncertainty and lack of relevant data, these factors are not considered. In this stage, only solar pavement cleaning is considered, and a 4000 L sprinkler car was used for cleaning. 6.5 L water was used for every 1 kW installed capacity of solar pavement (Yang et al., 2022). The amount of water required for one full cleaning cycle is 2628.6 L, and the cycle was once a month. Within the service life of 20 years, the energy consumption and emissions required for cleaning are shown in Table 10.

Table 10

Energy consumption and emissions required for cleaning.

Type	Consumption (kg)	Energy (MJ)	Emission (kg)					
			CO_2	CH_4	N_2O	CO	SO_2	NO_X
Sprinkler shall	279.83	1.21E+04	8.59E+02	3.64E-02	8.39E-02	9.79E+00	8.39E-02	4.48E-01

3. Results and discussions

3.1. Energy demand and payback time

3.1.1 LCA energy consumption evaluation

The energy consumption at each stage of the life cycle of the two pavements are shown in Fig. 3.

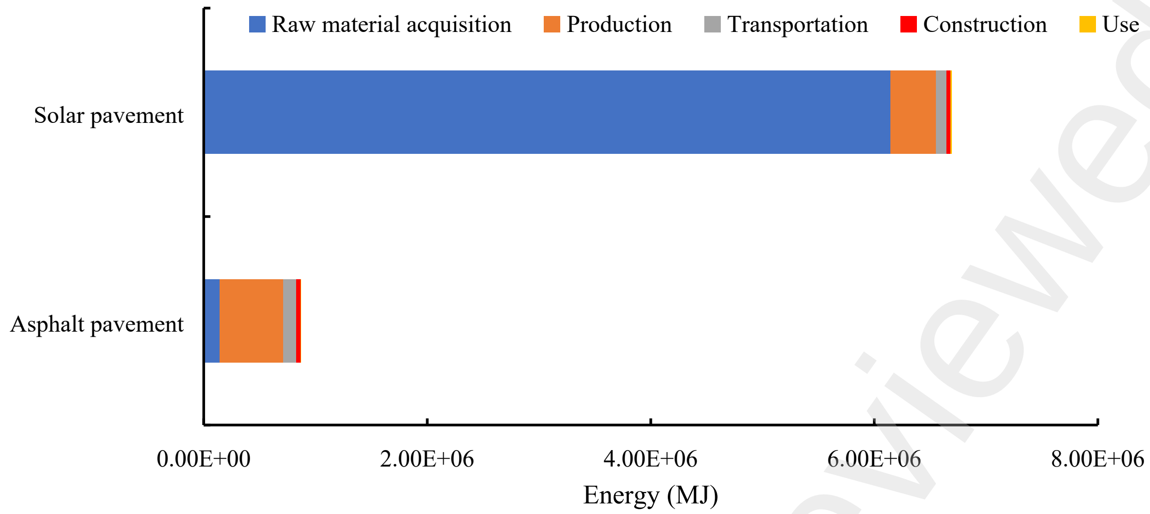

Fig. 3. Energy consumption for each life cycle stage.

According to the analysis of the total energy consumption in the life cycle of the pavements (Fig. 3), the total energy consumption of the solar pavement is 6.69E+06 MJ, which is 7.69 times higher than that of the asphalt pavement. The main contributor is the product stage and more specifically the raw material acquisition for the solar pavement, which contributes 6.15E+06 MJ, accounting for 91.8%, while the contribution of the other stages is not more than 7%. Most of the energy consumption comes from producing solar PV modules and polyurethane, accounting for 76.2% and 14.1% of the total energy consumption, respectively. This is mainly because the production of PV modules requires a large amount of electricity, while most of the electricity in China is currently obtained by burning coal. At the same time, this result also highlights the importance of energy-oriented process optimization in the photovoltaic industry in solar pavements. Special photovoltaic cells that meet the technical requirements of photovoltaic pavements should be developed, and low-energy cost technologies for photovoltaic cells should be improved to effectively reduce their energy contribution. In addition, efforts should be made to reduce the proportion of coal-fired power generation in power supply.

The energy consumption of the solar pavement is far higher than that of the asphalt pavement in the product stage, while the energy consumption of the stages is the opposite. For the asphalt pavement, the largest contributor to energy consumption is the mixture production process, accounting for 65.4%. The comprehensive energy consumption ratio in the production phase of the mixture and raw materials exceeds 80% of the entire life cycle of the asphalt pavement, followed by 13.2% in the transport phase. This indicates that the material production phase is the main energy consumer in the life cycle of the asphalt pavement, which consumes a lot of heavy oil and diesel.

3.1.2 Energy payback time

Solar pavement is an emerging multi-functional pavement that integrates the ability to produce renewable energy and accommodate traffic loads thus, providing the function of transport as well. To evaluate the sustainability and environmental performance of a solar pavement, it is necessary to analyze the relationship between the energy used to manufacture it and the energy generated by the system during its life cycle. Energy Payback Time (EPBT) is the most widely used energy evaluation index, which is defined as the time required for renewable energy systems to generate the same energy (terms of primary energy equivalent) that was used to produce the system itself (Xie et al., 2018). The calculation method of EPBT is as follows:

$$EPBT = \frac{Total\,primary\,energy\,demand[\mathrm{MJ}]}{Annual\,power\,generation[\mathrm{MJ/year}]} \tag{4}$$

Due to the low traffic flow and without considering the influence of vehicle shadow occlusion, the electricity production of a solar pavement in the first year can be obtained by the following equation:

$$E_0 = \eta_m \cdot A \cdot G\ (1 - \varepsilon) \tag{5}$$

Where E_0 is the first-year power generation, kWh; η_m is the power generation efficiency of photovoltaic modules, %; A is the photovoltaic laying area, m^2; G for annual radiation, kWh/m^2; ε is the transmittance barrier coefficient of transparent resin concrete, %.

The total solar radiation resources in China are abundant, but there are regional differences. G is the average annual radiation amount 1110 kWh/m^2 in Hunan (920-1300 kWh/m^2) (Pu et al., 2021), while ε is 10% (Hu et al., 2022.a). In fact, due to the influence of dust and dirt and the gradual decline of surface transparency over time, the theoretical power generation in the first year calculated by the above formula can be utterly optimistic, and needs to be calibrated. By comparing the actual and theoretical power generation in the first year of several typical solar road test projects, the ratio between the actual energy output and the theoretically possible energy output can be calculated. The correction coefficient η_{pr} is in the range of 52%-64%. The life cycle power generation of solar pavement can be calculated from equation (6):

$$E_{TOT} = \sum_{t=1}^{T} E_0 \cdot \eta_{pr} \cdot (1-d)^{t-1} \tag{6}$$

Where E_{TOT} is the total power generation, kWh; t is years 1, 2, 3... T; d is decline factor for solar modules, 0.01.

In this paper, an average of 58% as input for η_{pr}, was implemented and the energy consumption and environmental benefits offset during the use stage of the life cycle for the solar pavement are shown in Table 11.

Table 11

Energy saving and environmental benefits of solar pavement during the use stage.

Type	Electricity（kWh）	Energy (MJ)	Emission (kg)					
			CO_2	CH_4	N_2O	CO	SO_2	NO_X
Solar PV system	4485707.72	1.61E+07	4.17E+06	1.18E+04	6.37E+01	7.81E+02	1.42E+04	1.16E+04

The total energy production for the solar pavement over the assumed service life of 20 years is 1.61E+07 MJ. Considering the annual degradation rate of the solar pavement, its annual power generation is not a fixed value, so it is necessary to calculate the annual cumulative energy production to make it equal to the total energy demand, and then determine the EPBT. The relationship between the annual cumulative energy production and the total energy demand for the solar pavement is shown in Fig 4.

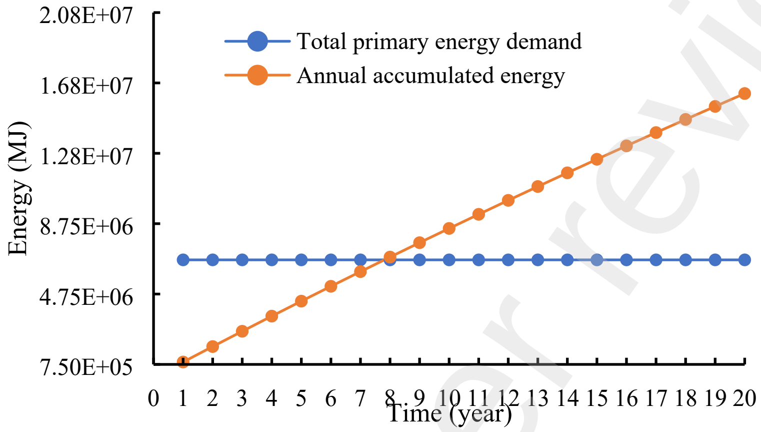

Fig. 4. Relationship between the annual cumulative energy production and the total energy demand of the solar pavement.

The EPBT of the solar pavement is 7.83 years, far less than its service life. In terms of energy consumption throughout the life cycle, the power generation of the solar pavement during the use stage can deliver significant energy and environmental benefits, reducing energy demand by about 241.3%. Generally, if a place with high solar radiation is chosen, this value can be even higher.

3.2. Life cycle impact assessment

The life-cycle impact assessment (LCIA) is a tool for the translation of the life-cycle inventory results into measures of human and environmental impacts. LCIA provides additional information for better understanding the environmental significance of the LCI.

3.2.1 Results of LCI

The emission of both pavement types at each stage in the life cycle are shown in Table 12. The total emissions (CO_2, CH_4, N_2O, CO, SO_2, and NO_x) of the solar pavement are around 5.78 times higher than the asphalt pavement. However, due to photovoltaic power generation, the operation phase has huge environmental benefits, reducing the total emissions by 788.2%. For each life cycle stage, the gas emissions in the product stage are the most relevant. The main reason for this phenomenon is that the production process of photovoltaic modules is an energy and emission intensive process. At the same time, the main contributor for both the asphalt and the solar pavement is carbon dioxide, accounting for 95.7% and 98.4% of the total emissions.

Table 12

The emissions of both pavement types at each stage in the life cycle.

Pavement Type	Stage	Gas (kg)						
		CO_2	CH_4	N_2O	CO	SO_2	NO_x	Total
Asphalt pavement	Raw material acquisition	3.30E+04	3.82E+02	2.63E-01	1.14E+03	3.24E+02	2.68E+02	3.51E+04
	Production	4.35E+04	1.20E+01	2.77E+00	5.54E+02	9.00E+02	4.42E+01	4.49E+04
	Transport	8.76E+03	3.11E+05	4.34E-01	6.62E+01	7.85E+00	2.84E+02	9.15E+03
	Construction	3.20E+03	1.30E-01	3.01E-01	3.51E+01	7.02E-01	2.45E+00	3.24E+03
	Total	8.84E+04	3.12E+05	3.77E+00	1.79E+03	1.23E+03	5.98E+02	9.24E+04
Solar pavement	Raw material acquisition	4.84E+05	2.64E+03	3.77E+00	8.87E+02	3.41E+03	3.99E+02	4.91E+05
	Production	3.11E+04	9.37E+00	1.97E+00	3.92E+02	6.36E+02	3.21E+01	3.22E+04
	Transport	7.35E+03	2.61E+05	3.64E-01	5.55E+01	6.59E+00	2.39E+02	7.68E+03
	Construction	2.40E+03	9.76E-02	2.25E-01	2.63E+01	5.26E-01	1.83E+00	2.42E+03
	Use	8.59E+02	3.64E-02	8.39E-02	9.79E+00	8.39E-02	4.48E-01	8.70E+02
	Toal	5.25E+05	2.64E+05	6.42E+00	1.37E+03	4.05E+03	6.72E+02	5.34E+05

3.2.2 Characterization and impact assessment

The key to interpreting environmental damages is to allocate different types of emissions into the same environmental impact category indicators and determine their magnitude. For this study, the selected impact category indicators are GWP, EP, POCP, and AP (Harvey et al., 2016). The gases involved in GWP, AP, EP and POCP are grouped as Fig. 5.

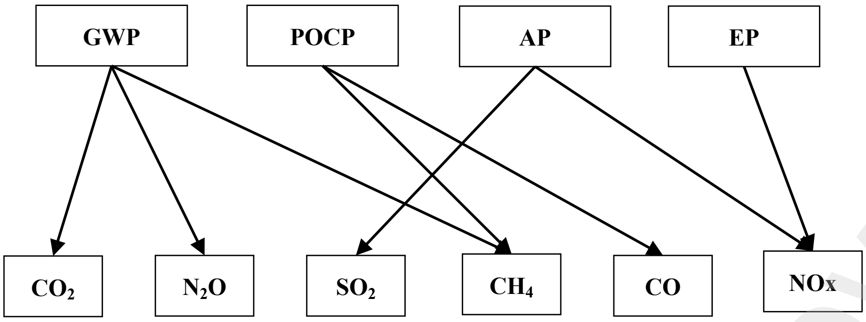

Fig. 5. Environmental impact category indicators and their corresponding emissions.

Once the LCI results are assigned to the impact categories, the following step is the characterization, which is the sum of the LCI results under the same impact category. The product between the LCI results of the *i*-th impact category and the conversion factor (CF) is called impact category indicator (CI):

$$CI = \sum_{i=1}^{n} LCI\_results_i \cdot CF_i \tag{7}$$

In particular, the CF is used to uniform the LCI results at a common unit. The CF values are given in Table 13 (Cong et al., 2020). The environmental pollution impact results of each stage of the two pavements are shown in Fig. 6.

Table 13

The conversion factors of gas pollution.

Type	GWP (100 years)			EP	POCP		AP	
Gas	CO_2	CH_4	N_2O	NOx	CH_4	CO	SO_2	NO_x
CF	1	25	298	1.35	0.007	0.03	1	0.7

3.2.2.1 Global warming potential (GWP) impacts

The GWP describes the rise of the average temperature near Earth's surface, due to the greenhouse gas emissions (GHGs). GHGs have a direct impact on the sea level rise, the occurrence of extreme weather events, the environmental and human health (Harvey et al., 2016). They are usually produced by fuel combustion during raw material extraction, production, and transportation. CO_2, N_2O and CH_4

are the main contributors to the greenhouse effect.

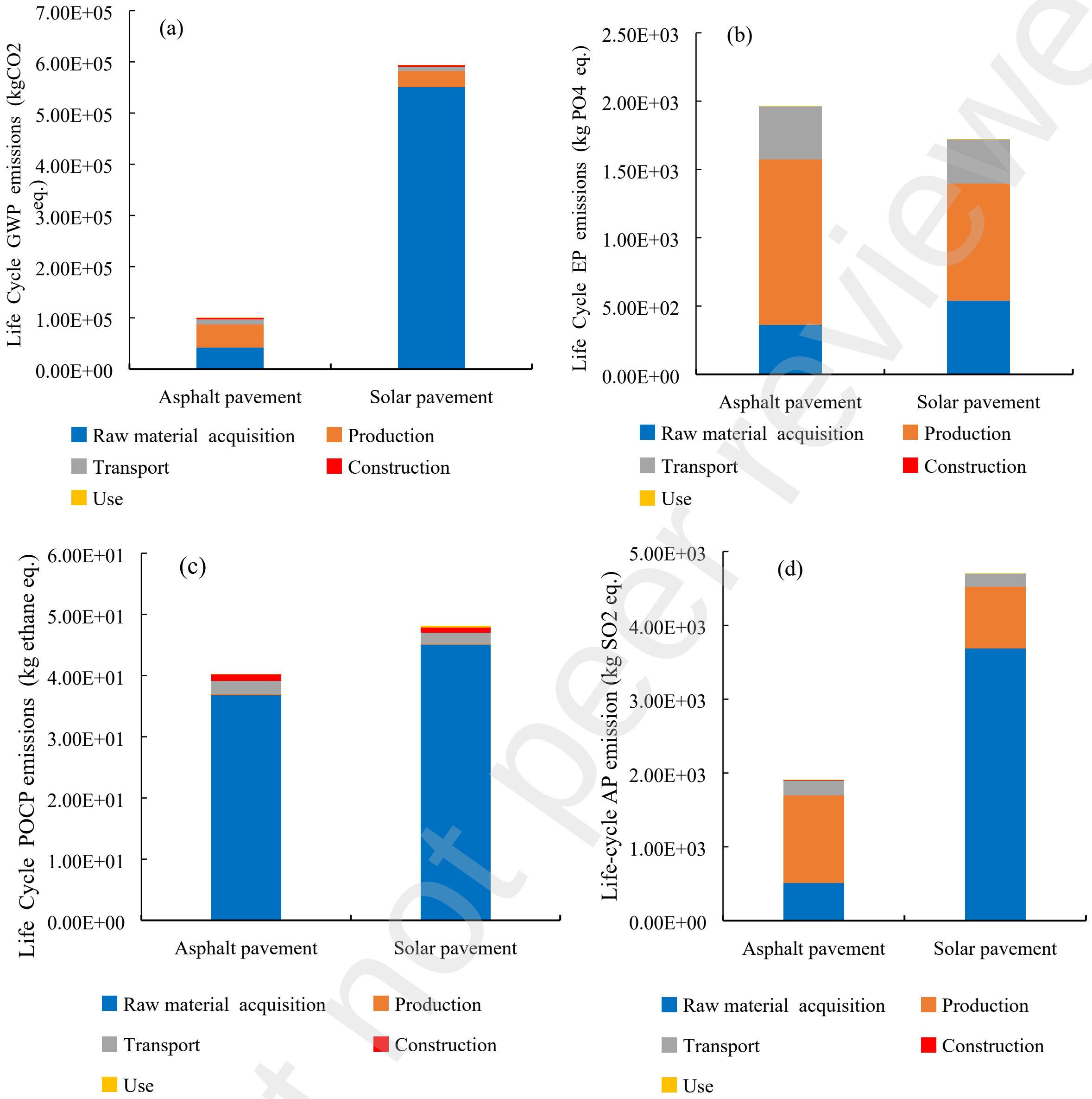

Fig. 6. Environmental pollution: (a) GWP; (b) EP; (c) POCP; (d) AP.

It can be seen from Fig. 6(a) that the global warming potential indicators for the solar pavement and the asphalt pavement are 1.00E+05 kgCO_2eq. and 5.94E+05 kgCO_2eq., respectively. Compared to the asphalt pavement, the solar pavement is detrimentally associated with more global warming potential. The CO_2 emissions in the product stage account for more than 92% of the total GWP emissions for the solar pavement, becoming the largest source of carbon emissions, an order of magnitude more than the CO_2 emissions in the second place (mixture production). The key to reducing CO_2 emissions is to reduce energy consumption in the production process of photovoltaic modules. For the asphalt pavement, the highest contributor is the production of the mixture accounting for GWP to 44.5%, followed by the raw material acquisition, accounting for 42.5%. As far as the emission amount is concerned, in addition to the product stage, the emissions for asphalt pavement corresponding to also all the other stages are greater than that of the solar pavement, mainly because the transparent resin concrete can be mixed and formed at room temperature, and the prefabricated pavement process is also conducive to reducing the use of construction machinery and equipment. Solar pavement can generate electricity cleanly during the use stage, which can partly offset the emission of air pollutants from China's coal-based power structure. The GWP result of the solar pavement shows that it is sufficient to repay the greenhouse gas pollution in the life cycle of the solar pavement, and the GWP recovery rate is as high as 755%.

3.2.2.3 Eutrophication potential (EP) impacts

EP refers to the increased growth of algae and plants in the aquatic ecosystem, due to nitrogen-based fertilizers. The result is a reduction of dissolved oxygen in water bodies. It can be seen from Fig. 6(b) that there is little difference in EP emissions between the solar pavement and asphalt pavement, even the total EP emissions of the solar pavement are 12.3% lower than that of asphalt pavement. The mixture production stage is the largest contributor to EP of the two pavements, and the second largest contributor is the process of raw material acquisition. Similarly, photovoltaic power generation in the operation stage can make the recovery rate of EP reach 907.2%.

3.2.2.3 Photochemical smog potential (POCP) impacts

POCP refers to the abilities of volatile organic compounds (VOCs) to produce secondary photochemical pollutants such as ozone at ground level. POCP has adverse effects on human health and ecosystems. It can be observed from Fig. 6(c) that the POCP impact of the solar and asphalt pavement is very similar and the raw material acquisition is the most relevant stage, accounting for more than 90%. The POCP emissions in each stage for the solar pavement is in the following order: raw material acquisition > transport > construction process > use > mixture production. The recovery rate of POCP is 220.3% due to photovoltaic power generation.

3.2.2.4 Acidification potential (AP) impacts

The AP deals with the increasing of hydrogen ion (H+) in the environment. The air pollutants responsible of the acidification are the sulfur dioxide (SO_x) and nitrogen oxides (NO_x), which are deposited through rain. For pavements, they occur because of the fuel combustion. According to Fig. 6(d), the AP of the solar pavement is 2.47 times that of the asphalt pavement. Among them, raw material acquisition accounted for 78.4% of the total, mixture production and transportation accounted for 17.8% and 3.7% respectively, while the contribution of the pavement cleaning within the use stage was less than 1%. Considering the environmental benefits brought by the energy production during the us stage, the AP recovery rate of the solar pavement reaches 474.8%.

3.3. Comprehensive environmental impact assessment

To quantitatively evaluate the impact of environmental load caused by different gas emissions, the standard human equivalent method (Yang, 2002) is used to normalize all impact types according to equation (8). The calculation results are shown in Fig. 7.

$$N_i = \frac{C_i}{S_i} \tag{8}$$

Where N_i is the environmental potential impact of Class i environmental impact type standardization; C_i is the characteristic result of Class i environmental impact type. S_i is a standardized reference value for Class *i* environmental impact type.

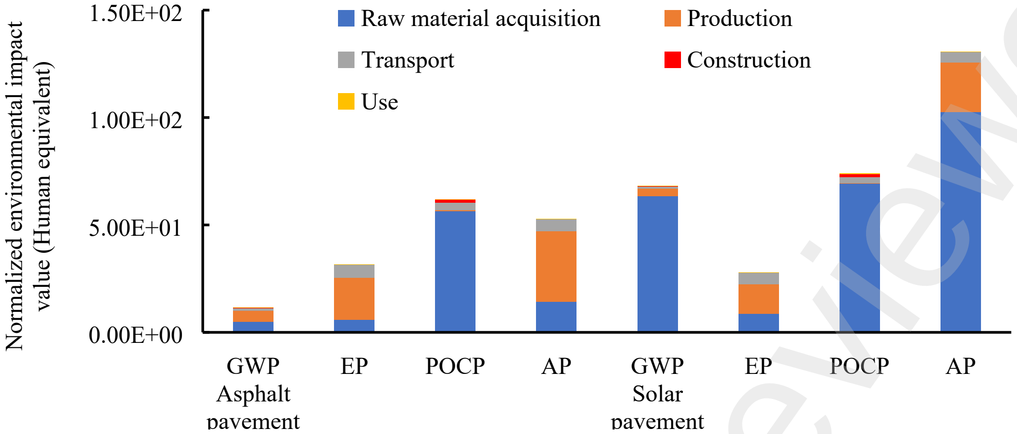

Fig. 7. The normalized environmental impact value of impact category (Human equivalent).

Both solar and asphalt pavements have large GWP emissions, but after the normalization, POCP and AP are the key factors leading to regionalized environmental impacts. The scores of GWP, EP, POCP and AP of solar pavement are 5.93, 0.88, 1.20 and 2.47 times that of the asphalt pavement, respectively. The product stage is still the main contributor to most impacts after the normalization.

To further merge the indicators, the weight factor W_i is added for weighted evaluation (Yang, 2002). The weighted evaluation process is the judicial process of product value. The relative importance of each potential environmental impact index is determined by referring to the weight size. The specific environmental impact is weighted and integrated into the total environmental impact value of LCIA (Li, 2016). The calculation formula is as follows:

$$LCIA = \sum N_i \times W_i \tag{9}$$

Fig. 8 shows the weighted environmental impact values at each stage of the LCA for both pavements. The environmental impact potential of the asphalt pavement and the solar pavement, after weighting is 1.04E+02 and 2.12E+02 Human equivalent, respectively. The solar pavement has the greatest impact on AP, followed by GWP, accounting for 45.1% and 26.8% respectively, while POCP and EP account for 18.5% and 9.6% respectively.

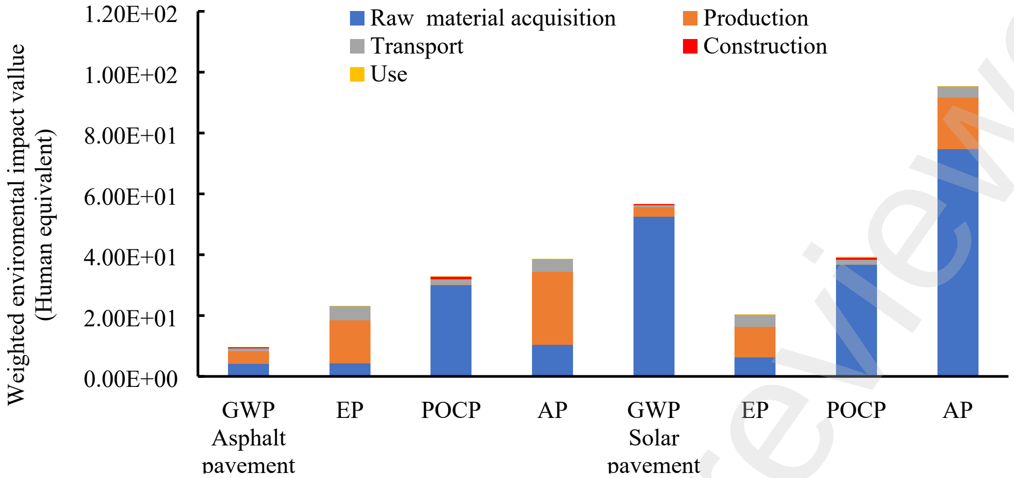

Fig. 8. The weighted environmental impact value of the impact category indicators (Human equivalent).

Overall, it can be seen that the product stage is the most relevant one with the raw material acquisition being the "protagonist", followed by the production of the mixtures. From the perspective of life cycle, targeted measures should be taken for the product stage, such as improving the level of the production efficiency and minimizing material consumption.

4. Discussion

It becomes evident from this case study that the environmental impacts of a solar pavement are initially severe, but they can be easily offset in a short time window. Thus, it can be perceived as a significant investment for greener transportation infrastructure since within a small-time window it is capable of offsetting the environmental impacts originating from its production and construction stages. However, it is worth noting that the environmental impacts of such a pavement are context and region sensitive. In other words, countries with higher hours of sunlight that utilize renewable energy sources can detect significantly improved environmental performances of their solar roads.

In order to further enhance the sustainability of solar pavements, it is necessary to utilize clean energy in their production process and reduce the proportion of coal-powered generation in the power supply to reduce the environmental impacts; actively encourage and support the development of redesigned photovoltaic cells that meet the technical requirements of a solar pavement; embrace the low energy cost technology of photovoltaic cells and enhance the contribution intensity of the solar pavement in achieving carbon peaking and carbon neutralization. However, this can be a complex shift that can be halted by limitations emerging from outdated policy related implications. In other words, a lot of countries lack specifically tailored and standardized procedures of utilizing renewable energy sources. Moreover, countries that experience significantly reduced annual hours of sunlight due to their geolocation would most likely not be able to easily compensate for the environmental impacts of their potential solar pavement in the same time window as countries with an elevated amount of sunlight hours, making again the process of offsetting the environmental impacts of a solar pavement region sensitive. Furthermore, policy implications may arise since standardized procedures for the most efficient maintenance and end of life reclamation and recycling of such materials, or even conventional construction materials that are predominantly used during road construction are not in place in most of the countries.

Hence, from the point of view of stakeholders and decision makers, the results of this study can support their attempt for the transition of the road engineering sector towards a more sustainable operational pattern by assisting them to connect the scientific facts with the industrial reality and needs. In detail, as deduced from the results analysis, the most relevant stage in the LCA of the solar pavement was the product stage, and within it, the raw material acquisition was the hotspot. From this fact they can understand the urgent need to enhance the efficiency of the material extraction processes and ultimately instead of using virgin materials, re-use, recycle and in a broader sense implement principles of the Circular Economy for truly greener transportation infrastructure that with minimized environmental impacts can be self-sustained, as similarly concluded by other studies. Understanding, and now, being able to interpret the outcomes of this and related studies, stakeholders and policy-makers can adopt recommendations and focus on improving the suggested aspects of their solar pavements by introducing practices and legislations or even nationwide policies that ultimately support the sustainable conceptualization and realization of solar pavements.

5. Conclusions

In this paper, a comparative life cycle assessment of a solar and an asphalt pavement has been conducted. Based on the research results, the following conclusions can be drawn:

(1) The total energy consumption for the solar pavement is much higher than that of the conventional asphalt pavement. The energy consumption of the former is 7.69 times than that of the latter. However, because the solar pavement has the function of clean power generation, it has the characteristics of energy recovery. Due to the energy benefits brought by power generation, the energy demand of the solar pavement is reduced by 241%, and the energy recovery period is 7.82 years. In all life cycle stages, the product stage is the main contributor to the energy demand of the solar pavement, accounting for 91.8%. Within that, the energy consumption in the production process of the photovoltaic modules and polyurethane is the most relevant due to the consumption of a large amounts of electricity.

(2) Without considering the power generation benefits, compared to the asphalt pavement, the solar pavement is not conducive to reducing the emission of pollutants. The total emissions from the solar pavement are about 5.78 times that of the asphalt pavement. The production of the photovoltaic modules is a significantly energy intensive process, which requires large amounts of electricity. On the other

hand, the environmental benefits brought by the power generation are sufficient to completely offset the gas emissions generated during the construction of the solar pavement. The recovery rates of GWP, EP, POCP and AP are 755%, 907.2%, 220.3% and 474.8% respectively.

(3) After normalization and weighting, the comprehensive environmental impact score of the solar pavement is 2.03 times that of asphalt pavement. The category with the greatest impact on the environmental load of gas emissions during the construction period of solar pavement is GWP, followed by AP, EP and POCP. The most critical environmental impact category indicator becomes AP, and GWP is the second. At the same time, the total score of the raw material acquisition is still the highest in the whole life cycle.

The authors propose that the key points for further research include:

1) At present, the project of solar pavement has not reached the age of recycling, and the maintenance mechanism is not clear, so the maintenance and the recycling process at the end of life of a solar pavement should be furtherly researched and established.

2) The combination design method of solar pavement structure and the impact of construction technology progress on the environment should be furtherly explored.

Acknowledgments

This work was supported by National Natural Science Funds of China [grant number 51878077]; Transportation Standard (quota) Program of the Ministry of Transport of China [grant number 2019-17-077]; Research and Innovation Project for Graduate Students in Hunan Province, China [grant number CX20190645]; SMARTI ETN project under the H2020-MSCA-ETN-2016 [grant number 721493]. Thanks to the anonymous reviewers for many comments that have notably helped us improve the manuscript.

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