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ORIGINAL PAPER

Rethinking environmental payback: its declining relevance in the decarbonization of the electricity mix

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Abstract

This study identifies, discusses and analyzes the most commonly used parameters for the evaluation of energy systems from an environmental perspective. This work provides a critical assessment of the applicability of environmental payback time as a metric for evaluating energy systems, particularly in the context of ongoing decarbonization efforts. A new environmental indicator is proposed, the dynamic payback time, which incorporates the evolution of the emission factor for the electricity grid throughout the operational lifetime of the energy system. The results of two case studies in two countries with dissimilar energy structures and diverse development of electricity generation systems (Brazil and Spain) are presented. A new parameter is presented, the EME parameter (Embodied emissions divided by the electricity Mix Emissions), which can help determine the potential impact of an energy system in the overall energy mix of a country. The results confirm that temporal evolution is a crucial parameter in the environmental assessment of energy systems, concluding that new dynamic parameters are essential for consolidating the findings from environmental studies.

Keywords Life cycle assessment · Carbon footprint · Lifetime avoided emissions · Environmental payback time · Emission factor · Renewable energy

Introduction

Energy systems are commonly evaluated from technical and economic viewpoints before any environmental criteria are applied. Environmental information should be progressively used as additional criteria for the evaluation of energy systems, and in recent years, there have been significant advancements in the tools used for analyzing and designing energy systems (Saini et al. 2025). The pursuit of sustainable energy solutions has driven the development of technologies aimed at tackling climate change (Silva et al. 2024).

The importance of integrating environmental considerations into system design is not recent, driven by increasing global environmental awareness and the implementation of stricter regulations to minimize the impacts of energy systems (Carvalho et al. 2012). For example, exergoenvironmental assessments can be carried out in addition to exergoeconomic analyses to help improve energy systems, leading to a more cost-efficient, environmentally sustainable, and competitive energy industry (Cavalcanti et al. 2024).

Due to very different decarbonization strategies throughout the world, there are significant impacts on the power generation systems, which should progressively rely on renewables to decrease emissions. This evolution should be reflected in the indicators and parameters that measure the environmental impacts of energy systems.

Life Cycle Assessment (LCA) can provide useful information regarding the environmental loads associated with energy systems (International Organization for Standardization, 2006). LCA is one of the most widely used environmental assessment tools (Blanco et al. 2020), and is highly regarded for its comprehensive approach, as it can encompass a product's entire life cycle (raw material extraction, manufacturing, transportation, use and maintenance, and final disposal).

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LCA highlights the specific stages where improvements can reduce environmental impacts (Hellweg et al. 2023) and can be applied at the design stage (Li and Zhao 2023) or after installation of an energy system (Bodziacki et al. 2024). There are two main perspectives of LCA: attributional (ALCA, which evaluates the global impact share of a product) and consequential (CLCA, which addresses the consequential impact of a decision) (Schaubroeck 2023; Guillén-Lambea et al. 2023). By modeling hypothetical scenarios, CLCA provides insight into the indirect and often less visible consequences of decisions, which are not captured in attributional studies.

Integrating LCA into energy system planning can support more sustainable transitions by revealing trade-offs between environmental impacts and performance outcomes (Gibon et al. 2017; Hauschild et al. 2022). As energy systems become increasingly complex—incorporating renewables, storage, and digital technologies—LCA offers a structured framework to assess their sustainability across temporal and spatial scales.

Despite the growing adoption of LCA in evaluating the environmental performance of energy systems, most current assessments rely on static parameters—which can lead to misleading conclusions, particularly in contexts where national grids are undergoing significant decarbonization. Without integrating the temporal variability of grid emissions, assessments may overestimate or underestimate the environmental benefits of a given system throughout its lifetime (Reinert et al. 2021). This methodological gap is especially relevant when comparing energy systems deployed in countries with distinct decarbonization trajectories, such as Spain and Brazil. Addressing this limitation is crucial to improving the accuracy, comparability, and policy relevance of environmental evaluations of energy systems.

The objective of the work presented herein is to confirm and demonstrate the need to implement the temporal variable in the evaluation of energy generation systems. The study begins by presenting and discussing the parameters most frequently employed to evaluate energy systems from an environmental perspective. The drawbacks of the parameters are identified, followed by the proposal of a new parameter: the environmental dynamic payback time (EDPT). This new parameter uses different yearly values throughout the lifetime of the energy system (instead of considering a fixed emission factor for the electric grid).

In addition, this work applies the EDPT to two energy systems, considering two very different geographical environments, Spain and Brazil. Both countries have their own decarbonization plans and strategies As a result of the EDPT analyses, an additional criterion has been identified, which is the ratio between the generation system embodied emissions and the electricity mix emissions (EME), throughout time. This new criterion can easily identify the benefits realized by an energy system, in comparison to the overall country electricity mix.

The contribution of this work is the presentation of two new parameters, EDPT and EME. Together, these novel parameters advance the field by bridging the gap between static LCA methods and the realities of evolving energy systems, offering a more robust framework for policymakers, planners, and researchers to guide sustainable energy transitions.

This research was carried out in Zaragoza (Spain) and in João Pessoa (Brazil), over a ten-month period from October 2024 to July 2025.

Materials and methods

Parameters used in the environmental evaluation of energy systems

This section covers the most employed parameters that are used to evaluate energy systems from an environmental point of view.

Emission factor or emission intensity

The emission intensity is calculated as the ratio of emissions from electricity generation and gross electricity generation, expressed in kg CO_2-eq/kWh. Emission intensity can also be referred as GHGe-rate (Lima et al. 2021). Depending on the environmental impact assessment method employed, the results can be expressed in terms of other indicators (e.g., CO_2/kWh or mPts/kWh using the Ecoindicator-99 method, for example) (Goedkoop and Spriensma 2001).

Kim et al. (2023) applied LCA to a 30 MW photovoltaic energy system, obtaining the emission intensity of the electricity produced throughout its lifetime (30 years). The authors then proposed actions to reduce emissions from manufacturing and deployment, such as the decarbonization of aluminum and concrete production. Li et al. (2021) carried out a LCA for a 40 MW wind farm in China and obtained an emission intensity higher than nuclear and hydropower. The authors also presented strategies to improve the environmental performance of wind power.

Usually, the emission intensities from renewables and nuclear energy are much lower (and generally less variable–NREL, 2013) than those from fossil fuels. Nevertheless, emission intensities alone are not sufficient to evaluate or determine the installation of an alternative energy system; instead, they are considered alongside other parameters for a more comprehensive analysis.

Recent emission intensity values for electricity production have been published by Scarlat et al. (2022), who considered emissions from the construction and decommissioning of power plants and upstream emissions, leading to the determination of the emission intensity of electricity produced and used in Europe. However, as mentioned by Carvalho and Delgado (2017), the most critical aspects that affect coherence and transparence of the LCA results were definition of the functional unit, the LCA method applied, and the impact allocation method. There is a wide variation in emission intensity results due to a lack of standardization when using the same methodology to model each inventory, such as conceptual divergences (Delgado and Carvalho, 2017).

There is an extensive list of boundaries that affect the intensity factor of a country. Usually the values published by public institutions in different countries, those calculated using databases and software for LCA, and those available from public platforms cannot be compared. It is important to understand how the factor has been calculated, and how the scope and boundaries have been specified. At least the following considerations must be taken into account:

(1) There is a significant gap between electricity generation and consumption, including upstream emissions, operational emissions, and use-related emissions. Moreover, only a limited number of studies consider emissions associated with the construction and decommissioning of electricity generation facilities (Scarlat et al. 2022).

For example, in the case of Spain, the emissions factors published by *Red Electrica Española* (REE) (REE, 2025) only consider direct emissions associated with electricity production. This means that indirect emissions associated with the construction of power plants, fuel transportation, maintenance, etc., are not included.

(2) The greenhouse gases (GHG) considered within the calculation of the emission factor can vary, as well as the characterization factors employed.

For example, in Spain, the GHG included are CO_2 and N_2O, with CH_4 being excluded (REE, 2021). In addition, N_2O emissions from coal-fired thermal power plants, natural gas combined cycle plants and fuel gas thermal power plants are not considered in the calculation of CO_2 emissions for these technologies in Spain (REE, 2021).

Calculation of the greenhouse effect potential of N_2O uses its Global Warming Potential (GWP), which is 265 in the Fifth Assessment Report (AR5) of the Intergovernmental panel on Climate Change (IPCC, 2014). However, the 2023 AR6 report (IPCC, 2023) presents the GWP of N_2O as 273. Country reports are not updated as quickly as those of intergovernmental organizations.

(3) In the calculation of the CO_2-eq emissions of the electricity mix of some countries, a null value is assigned to nuclear and renewables (solar, wind, hydropower, geothermal, and ocean) in official published reports. In these cases, renewable operational emissions are considered either zero or negligible, and consequently, emissions from construction and decommissioning account for the largest share of the total life cycle emissions of renewable electricity generation; however, they are not included in the emission factor calculations. In contrast, for fossil-based electricity production, operational emissions are the dominant contributor, while construction-related emissions have a minimal impact due to the large-scale production capacity of such plants over their lifetime. For consistency, emissions associated with the construction of energy facilities should be accounted for regardless of the type of energy source.

(4) International interconnections. Usually, the electricity mixes published are associated with the generation of each country only. For this reason, emissions associated with energy imports from other countries are not added, and the energy exports are not discounted either.

(5) LCA databases. The LCA databases include different electric mixes in countries around the world. For example, the Ecoinvent database (Ecoinvent 2023), one of the most widely used databases in the world, includes regularly updated electricity data. Electricity generating datasets cover a wide range of fossil and renewable resources, production technologies, and includes secondary electricity production datasets from various industrial processes. There are several generation technologies for renewables, and various electricity generation and infrastructure datasets for the most common fossil electricity generation schemes. Considering that electricity is typically generated, transmitted, and consumed at different voltage levels, the Ecoinvent database categorizes electricity-related data based on these levels: high voltage (above 24 kV), medium voltage (between 1 and 24 kV), and low voltage (below 1 kV).

In the Ecoinvent database, high-voltage electricity is primarily fed by large power plants and transmitted over long distances via AC or DC lines, with losses occurring during transmission and transformation. Medium-voltage electricity is produced by some power plants, such as waste incineration facilities, and is used by large industries such as paper mills. Low-voltage electricity is primarily consumed by households and is supplied through transformer stations that step down medium-voltage electricity. Photovoltaic modules typically feed into the low-voltage grid. Transmission, transformation, and distribution losses are accounted for in the respective Ecoinvent datasets (Ecoinvent 2023). The intensity factors of the Spanish electricity mix in 2020 in the Ecoinvent database are 0.183 $kgCO_{2\text{-eq}}$/kWh for high voltage, 0.203 $kgCO_{2\text{-eq}}$/kWh for medium voltage and 0.211 $kgCO_{2\text{-eq}}$/kWh for low voltage. For Brazil, the respective values are 0.199, 0.225 and 0.244 $kgCO_{2\text{-eq}}$/kWh for 2020. Therefore, depending on the voltage level selected, the intensity factor also varies considerably.

Summarizing, significant variations in GHG emission for electricity generation and consumption estimates can arise from differences in LCA methodologies, assumptions, and system boundaries. The US National Renewable Energy Laboratory (NREL) conducted the LCA Harmonization Project (NREL, n.d.) to standardize and refine GHG emission estimates for electricity production from various sources. By aligning key LCA assumptions—such as system boundaries, operating lifetime, and performance parameters (e.g., capacity factor, thermal efficiency)—(NREL, n.d.) reduced inconsistencies and helped improve estimate reliability.

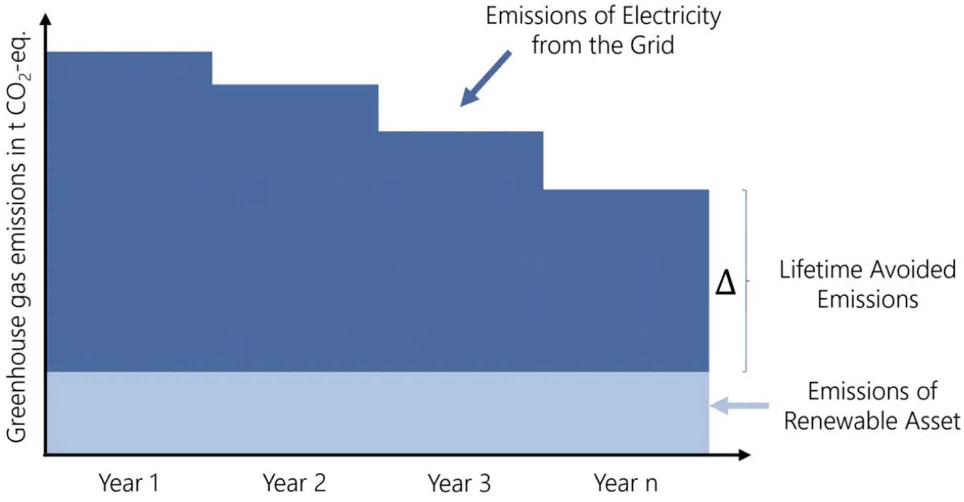

Fig. 1 Approach to calculating lifetime avoided emissions from renewables (Schimidt-Achert et al. 2022)

Calculation of the environmental indicators related to energy generation can benefit from research efforts directed to the harmonization of assumptions and should consider the dynamics of electricity mixes in the coming years (transcendental to achieve decarbonization by 2050) (European Climate Law, Regulation (EU) 2021/1119, 2021).

Lifetime avoided emissions

Avoided emissions refer to the decrease in emissions that can be attributed to the implementation of sustainable practices or technologies. The lifetime avoided emissions is the difference between the emissions from a project activity and a reference scenario, over a defined period (European Commission 2020). In other words, the lifetime avoided emissions are calculated as the sum of the emissions from the displaced grid purchase minus the emissions from the installation of an energy system, throughout the lifetime of the energy system. This parameter can be also expressed in terms of emissions/kW_p.

Lamnatou et al. (2024) presented lifetime avoided emissions, based on the electricity mixes of Spain and France, for façade-integrated solar systems with Organic Photovoltaic cells and Ethylene Tetrafluoroethylene components. The authors also applied other environmental impact assessment methods, and presented annual avoided energy-demand impacts, avoided ReCiPe impacts, avoided USEtox impacts, and avoided ecological-footprint results. Considering a 10-year lifetime, the proposed solar energy system presented lifetime avoided emissions of 1 t $CO_{2\text{-eq}}/kW_p$ in Paris, whereas, in the case of Barcelona, the lifetime avoided emissions were 5 t $CO_{2\text{-eq}}/kW_p$. The lower amount of avoided emissions for Paris is due to the low carbon content of the electric grid.

Figure 1 shows the emission balance from Schimidt-Achert et al. (2022), which focuses on the comparison between a renewable energy system and the electric grid, but the former can be any proposed energy system with a lower emission intensity than the electric grid. A similar balance of emissions is also carried out for the calculation of payback times.

Due to their forward-looking nature, lifetime avoided emissions are the result of a comparative exercise (i.e., emission balance throughout the lifetime of the energy system), comparing the emissions associated with a reference scenario and emissions associated with a proposed energy system.

Environmental payback time (EPBT) and greenhouse gas payback time

(GPBT)

A popular indicator is the environmental payback period or time (EPBP) that is used to measure the sustainability of energy systems (Grant et al. 2020). EPBT can be also referred to as Greenhouse Gas Payback Time (GPBT), quantified as a measure of the embedded emissions of an energy system divided by the emissions from the electricity mix where the system is installed.

Although different equations have been found for the EPBT or GPBT, the concept is the same. For example, Pinto et al. (2020) uses Eq. (1) to compute the years of system operation necessary to compensate emissions.

$$\text{GPBT} = \frac{\text{Total emissions}}{\text{Emissions avoided during lifetime}} \tag{1}$$

Schultz and Carvalho (2022) calculated the GPBT with Eqs. (2) and (3).

$$GPBT_n = GPBT_{n-1} - E_{y,n-1} \cdot \left(EF_{mix} - EF_{ES}\right) \tag{2}$$

$$\text{EF}_{ES} = \frac{\text{Emissions}_{ES}}{E_{\text{plant,tot}}} \tag{3}$$

In which GPBT is the GHG payback time in years; E_y is the annual electricity generated by the energy system (kWh, which decreases annually due to degradation). EF_{mix} is the emission intensity of the electric grid (kg CO_2-eq/kWh), EF_{ES} is the emission intensity of the energy system analyzed (kg CO_2-eq/kWh. The index "n" is the current year analyzed, which varies from 2 to the lifetime of the energy system, $E_{plant,tot}$ is the sum of the electricity generated by the energy system over its lifetime, considering its annual degradation; and $Emissions_{ES}$ value is obtained from the LCA result, considering the installation's emissions and emissions during the operation and maintenance (O&M) phases.

EPBT is affected by technology type, efficiency, irradiation levels, and by the electricity mix. The emissions associated with the electricity mix are usually based on the most recent data on energy generation technologies (i.e., previous year average values).

Grant et al. (2020) mentioned that avoiding environmental impacts by selecting locations with lower payback times raises a question regarding the most appropriate impact category or categories to consider. Although there are several environmental impact categories, not all are relevant in the context of renewables, for example. Global Warming Potential (GHG emissions) can be selected if only one category is considered in the context of climate change (Grant et al. 2020).

Environmental dynamic payback time (EDPT)

Based on the idea that the EPBT quantifies the time it takes to recoup the environmental impact from an energy system compared to the environmental impacts of the electricity grid, sometimes the results can be misleading if there are considerable yearly changes in the electricity mix.

Delgado and Carvalho (2017) presented electricity mix dynamics for Brazil for years 2001, 2006-2015, and a forecast for 2024. LCA-based emissions varied widely according to the electric mix, from 0.194 kg CO_2-eq/kWh in 2001 to 0.308 kg CO_2-eq/kWh in 2014. More recently, Oliveira et al. (2024) presented data on the electric grid for the period 2017-2023 and verified decreasing trends for natural gas and coal in 2019 and 2022, due to seasonal demands and electricity offsets. Also, the share of solar photovoltaic electricity increased gradually since 2017, whereas fuel oil and diesel presented steep changes.

The Spanish electricity mix has been progressively increasing the participation of renewables in the last decade, with a more intense contribution in the last five years. European Union policies to mitigate climate change (European Green Deal, 2019) and the commitments made by Spain (National Energy and Climate Plan (NECP) Spain, 2024) have boosted the penetration of renewable sources in Spanish electricity generation. In 2018, fossil fuels accounted for 32% of the Spanish electricity mix, nuclear energy for 24% of production and renewables accounted for 28%. Renewable production in the Spanish electricity system increased by 15.1% in 2023 compared to 2022, registering an all-time record for renewable production (reaching 50.3%) (REE, 2024). Consequently, the emission factor of electricity production has shifted from 0,290 kg CO_2-eq/kWh in 2015 to 0,190 kg CO_2-eq/kWh in 2019, reaching 0,100 kg CO_2-eq/kWh in 2024 (REE, 2024).

There can be considerable yearly changes in the electricity mix supplied by a country's electric grid, which highlights the need for constant updating of LCA data.

Calculating a 25 or 30-year EPBT based on a fixed, static value can provide very different results if there is a steep change in the composition of the electricity mix. For example, if the Brazilian 2022 electric mix data is used (63.35% hydro, 11.97% wind, 11.49% natural gas, 4.37% biomass, 2.77% coal, 2.17% oil and 1.29% solar), the associated emissions are 0.268 kg CO_2-eq/kWh. However, if the 2023 electric mix is used (67.13% hydro, 14.44% wind, 3.00% natural gas, 3.69% biomass, 1.18% coal, 0.12% oil, and 8.23% solar), the associated emissions drop to 0.140 kg CO_2-eq/kWh. These data were obtained using Simapro 9.6.0.1 (2024), Ecoinvent 3.8 (2021) and IPCC 2021 GWP 100y (IPCC, 2021), based on the yearly figures published by the Brazilian National System Operator (2023, 2024). The emission intensities presented can lead to almost doubling the EPBT of an energy system, when using 2022 and 2023 electric grid data for Brazil.

Due to these highly divergent EPBT obtained because of changes in the electricity mix, and considering the perspective of Guillén-Lambea et al. (2023) of looking into future changes in energy generation technologies, it is proposed to consider different electricity mixes throughout the lifetime of the energy system. This is suggested for a more adequate representation, year by year, of the operation of the energy system and its electric grid scenario.

Herein the parameters that define the environmental behavior of energy systems have been calculated for two scenarios in Spain and Brazil: i) constant grid intensity factor (as usual), which is usually the most recent available data (previous year), and ii) dynamic grid intensity factor, considering predictions for the next years.

In the case of Brazil, reference documents utilized for energy projections include the statistical annual reports of the Energy Research Company (2024a) and the Ten-Year Plan for Electricity Expansion 2034 (published by the Energy and Mines Ministry in 2024) (Energy Research Company 2024b). The constant grid intensity factor has been calculated with SimaPro (PréSustainability, 2024), following the method of Carvalho and Delgado (2017) using the Ecoinvent database (2021) and IPCC 2021 GWP 100 y method (IPCC, 2021). The most recent electricity mix is introduced (2024), considering low voltage. Government data were available for 2024 (ONS, 2025) and the Ten-Year Plan Electricity Expansion Plan 2034 (Energy Research Company 2024b) was followed to establish the 2034 electricity mix (with 86% participation of renewables). Due to the lack of 2050 data or predictions, these were obtained via extrapolation, following the trend established by the Ten-Year Plan for Electricity Expansion 2034, reaching 84,6% of renewables in the mix. The projection assumes continuous linear increase, which could not reflect political or technological changes. It must be highlighted that actual data could diverge due to crises, innovation, or acceleration of energy transition.

In the case of Spain, the constant grid intensity factor has also been calculated with SimaPro (PréSustainability, 2024) for the 2024 electricity mix. For the dynamic grid intensity factor, Simapro (PréSustainability, 2024) includes the prediction of the Spanish PNIEC for 2030, which predicts more than 80% of electricity generation from renewables. For 2050 and in accordance with the European decarbonization objectives (NECP, Spain, 2023), production by renewables could reach 94% of the electricity mix. Table 1 shows the breakdown of electricity mixes.

Study cases

This section covers two study cases, focusing on two energy generation systems, one in Spain and one in Brazil.

Spanish case

The Spanish case is based on Pina et al. (2020) who carried out technical, environmental, and economic feasibility assessments for an energy system covering the cooling and electrical demands of a shopping center in Zaragoza (Spain). A solar plant was designed, including a parabolic trough collector (PTC) field coupled with thermal energy storage (TES) tanks and an Organic Rankine Cycle (ORC). The system produces electricity to cover the shopping center's electrical demands and to supply power to the mechanical chillers for cooling production. The annual electricity production is 2979MWh$_e$.

The solar field has an aperture area of 19,620 m^2 and four TES tanks (two for cold and two for hot storage) with a total volume of 1392 m^3 each, with total storage capacity of 32.6 MWh$_t$. The ORC has nominal electrical power of 978 kW$_e$.

An attributional life cycle assessment was performed in a previous study and detailed inventory data of all equipment (Guillén-Lambea et al. 2022). A lifetime of 20 years was considered for the ORC, 30 years for the solar system (Burkhardt et al. 2011), and 50 years for the TES tanks (Raluy et al. 2021).

Brazilian case

The Brazilian study case is based on Schultz and Carvalho (2022), who designed a 16.4 MW solar photovoltaic system in Northeast Brazil. The system is constituted of 59,248 PV panels and the supporting structure. The analysis also includes eight inverters, 108 junction boxes, eight medium voltage transformers, and two high voltage transformers. Installation area is also included, along with cables and grounding components, transportation, maintenance and operation throughout its lifetime (which includes necessary equipment replacement: 2 inverters and 938 PV panels). An administrative building,

Table 1 Electricity mixes for Spain and Brazil (2024, 2030, and 2050)

	Spain electricity mix (%)			Brazil electricity mix (%)		
	2024	2030	2050*	2024	2034	2050**
Biomass				7.7	6.2	5.6
Natural gas				4.9	13.5	12.7
Oil				0.6	0.4	0.3
Wind	22.9	33.6	40.0	15.2	16.1	19.8
Nuclear	19.6	9.7	6.0	2.0	2.5	2.3
Photovoltaic	16.7	33.1	40.0	9.8	15.5	22.1
Combined Cycle	13.2	5.2	0.0	–	–	–
Coal	1.1	–	–	1.3	0.6	0.4
Hydro	13.0	7.6	5.2	58.5	45.3	37.0
Hydro pumping	2.0	–	–			
Thermosolar	1.6	3.0	4.4			
Fuel-gas	1.6	–	–			
Cogeneration	6.2	4.7	0.0			
Other renewables	1.4	2.9	4.4			
Renewable waste	0.3	–	–			
Non-Renewable waste	0.5	–	–			

* Estimated values for scenario 2025 following the trend up to 2030 and the Spanish NECP targets (NECP, 2030)

** Estimated values for scenario 2050 following the trends established by the Ten-Year Plan for Electricity Expansion 2034 vegetation management (mowing) and washing of panels are also considered.

The LCA of Schultz and Carvalho (2022) was updated with the most recent version of SimaPro software 9.6.0.1(PréSustainability, 2024), using the Ecoinvent v3.8 database (2021). The environmental impact assessment method used is the IPCC 2021 GWP 100y (IPCC, 2021), which groups GHG emissions in terms of carbon dioxide-equivalents (CO_2-eq) throughout 100 years.

Following Schultz and Carvalho (2022), the electricity generation based on climate data for João Pessoa is 759,039.86 MWh_e over 25 years. This amount includes the degradation of PV panels, with a consequent annual decrease in electricity production. The performance degradation of technologies should be considered to avoid over-estimation of the energy produced (Colla et al. 2020).

Results and discussion

Dynamic intensity emission factors

According to the established variable mixes (Table 1), the intensity factors of the electricity grid have been calculated via LCA for the two countries. For the years in between, a linear interpolation provided the results of the electricity mixes. The intensity emission factors are represented in Table 2.

Different emission factor behaviors are observed for Brazil and Spain. For Brazil, the Ten-Year Electricity Expansion Plan 2034 (PDE 2034), developed by the Brazilian Energy Research Company, provided detailed projections for the Brazilian energy sector from 2025 to 2034, with a focus on the role of natural gas. Forecasts indicate a significant increase in domestic natural gas production, driven primarily by the ultra-deep water exploration of the pre-salt carbonate reservoirs in the Santos Basin (Southeast Brazil) (Cavalcanti et al. 2021). It is estimated that gross production will reach 217 Mm^3/day by 2027, representing a 97% growth compared to 2024 levels. The PDE 2034 further emphasizes that natural gas will play a crucial role in enhancing the flexibility of the Brazilian electricity matrix, ensuring system reliability and supporting the sustainable expansion of renewable energy in the country (PDE 2034, 2024). This is reflected by the emission factors presented in Table 2, as the installed capacity of natural gas-fired power plants is expected to increase in the coming years, playing a fundamental role in complementing intermittent renewable sources such as hydro, solar, and wind power. Natural gas will be prioritized for activation during periods of low renewable generation, reducing dependence on more polluting sources such as diesel oil and coal. It is expected that the Angra 3 nuclear facility begins operation in 2029, adding 1405 MW, and that carbon generation decreases its participation throughout time as facilities are deactivated. For 2050, generation expansion follows the continuous increasing trend. Although there are bottlenecks in the transmission that do not follow the increasing trend, the Brazilian electricity generation capacity has increased and will continue to.

In Spain, the new version of the National Integrated Energy and Climate Plan, approved in September 2024 (NECP, 2024) is followed, which sets more ambitious goals for sustainability and energy independence by 2030. According to the new NECP, Spain aims to achieve 50% energy autonomy by 2030, thus reducing its reliance on fossil fuels and enhancing renewable energy sources. The final goal is to reduce GHG emissions by 32% compared to 1990 levels. The gradual reduction of nuclear generation must be highlighted, with only three nuclear power plants in operation by the end of 2030 (of the seven currently available), and closure of all coal-fired power plants. Strong growth in solar photovoltaics is considered, along with the installation of new solar thermal generation and significant growth in self-consumption. Cogeneration is slightly reduced compared to 2024 values. In 2030, based on the assumptions considered, a penetration of 81% of total renewable energy generation will be achieved.

Table 2 Dynamic emission intensity factors for Spain and Brazil, from 2024 to 2050

	Electricity mix emissionskg CO_2-eq/kWh	
Year	**Spain**	**Brazil**
2024	**0.168**	**0.165**
2025	0.153	0.175
2026	0.138	0.185
2027	0.123	0.193
2028	0.108	0.201
2029	0.093	0.208
2030	**0.092**	0.206
2031	0.090	0.204
2032	0.088	0.202
2033	0.087	0.201
2034	0.085	**0.199**
2035	0.084	0.198
2036	0.082	0.197
2037	0.080	0.195
2038	0.079	0.194
2039	0.077	0.193
2040	0.075	0.192
2041	0.074	0.191
2042	0.072	0.190
2043	0.071	0.189
2044	0.069	0.188
2045	0.067	0.187
2046	0.066	0.187
2047	0.064	0.186
2048	0.063	0.185
2049	0.062	0.185
2050	**0.061**	**0.184**

Table 3 Embodied emissions of the solar power plant of the Spanish case study

Item		Emissions (kg CO_2-eq)
Equipment	Collector Field	2,068,197.5
	Heat Transfer Fluid	447,277.1
	Thermal energy storage	6,827,937.6
	ORC	172,699.7
Total		**9,516,111.9**

Environmental dynamic payback time

Spanish case

Table 3 shows the emissions for the Spanish study case, including raw material extraction, manufacture of components and assembly of equipment, transport and end-of-life with Spanish waste treatment scenarios (Guillén-Lambea et al. 2022). The method applied is the IPCC 2013 GWP 100y.

The annual electricity production is 2979 MWh, and degradation of electricity production has been considered:-3% in the first year, -0.7% in the following five years and -0.5% per year until 2050.

Figure 2 shows the greenhouse gas payback time for a fixed emission intensity factor (2024), and considering a variable emission intensity factor (following Table 2).

The GHG payback time obtained for the constant emission factor is 20 years and 9 months. Which, on the other hand, does not amortizes the emissions within the lifetime of the ORC (20 years). However, when the variable emission factors are applied throughout 30 years, the graph shows that the red line does not cross the x-axis.

It is observed that as the Spanish electricity mix is decarbonized (including more renewables), the GHG payback time increases. The decarbonization of the electricity grid worldwide has unleashed new challenges for energy systems.

The environmental behavior of energy systems should no longer be measured by the GHG payback time with static emissions, but rather consider the dynamics of the electricity mix. In addition, these results highlight the need to define new parameters for the environmental performance of electricity generation systems. The results point out the need to standardize the calculation of emissions from electricity grids, which should include emissions due to manufacture, maintenance, and power plants (equipment and buildings).

Brazilian case

Table 4 shows the emissions for the Brazilian study case, including raw material extraction; manufacture of components and assembly of equipment, transport and end-of-life with Brazilian waste treatment scenarios (Schultz and Carvalho 2022).

The annual electricity production is 33,512 MWh, and degradation of electricity production has been considered:—3% in the first year, -0.7% in the following five years and then -0.5% per year until 2050.

Figure 3 shows the greenhouse gas payback time for a fixed emission intensity factor (2024) and considering a variable emission intensity factor (following Table 2).

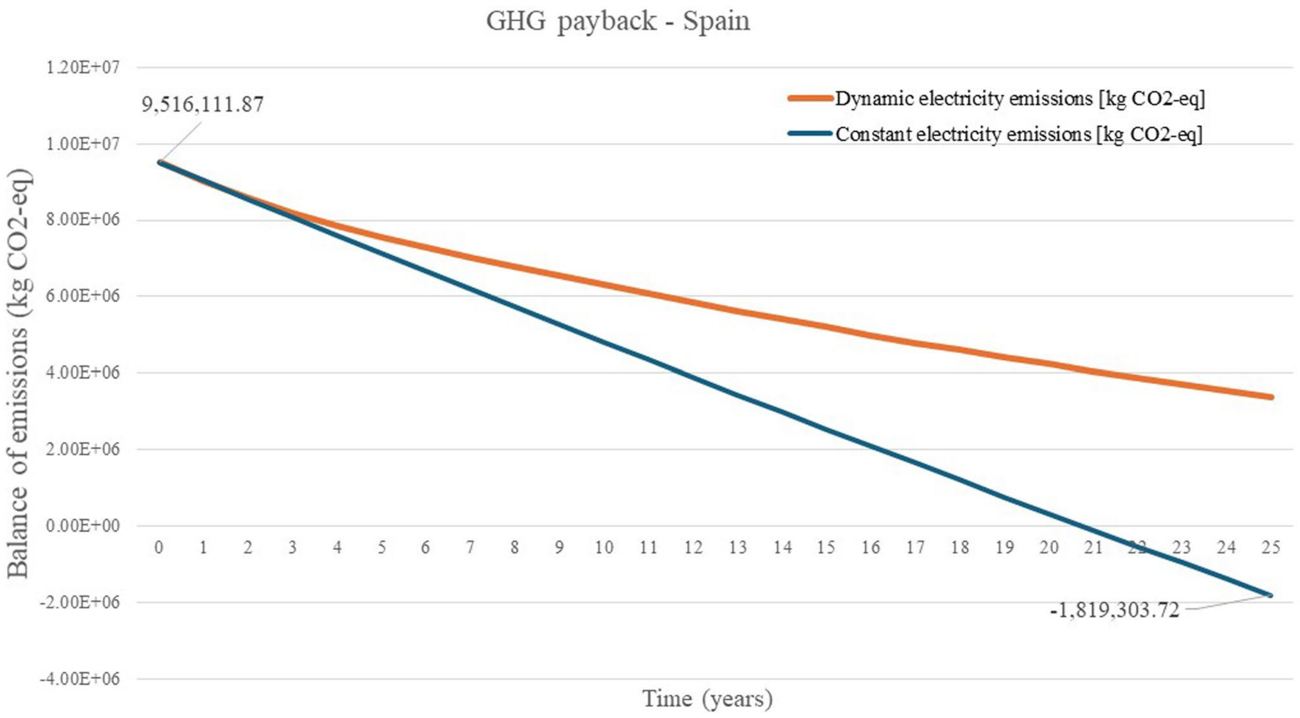

Fig. 2 GHG Payback: Spanish case

Table 4 Embodied emissions of solar PV system of the Brazilian case study

Item		Emissions (kg CO_2-eq)
Equipment	PV panels	20,053,608
	Cables, grounding	1,048,161
	Inverters	395,442
	Transformers	440,978
	Administration building	115,522
	Junction boxes	15,426
Operation and maintenance		
	PV panel replacement	250,343
	Inverter replacement	98,860
	PV panel washing	57,339
	Mowing	59,094
Total		**22,534,773**

Figure 3 shows a very different behavior from the Spanish case study (Fig. 2), but aligned with the Brazilian electricity mix dynamics. Reliance on natural gas due to the pre-salt reserves leads to a different behavior from the Spanish case. For the Brazilian case study, both curves cross the x-axis at around 4 years.

Analysis of Fig. 2, which presents the Spanish study case, reveals the need for a new parameter, which can provide a more realistic view of the convenience of adopting an energy production system. This new parameter should relate component-related and operation emissions of the energy system with those of the electricity grid. This is required because the decarbonization trend of the Spanish electricity mix leads to a dynamic payback curve that does not cross the x-axis.

Table 5 shows the annual emissions produced by the Spanish and Brazilian study cases in 2024, 2030, and 2050, the emissions of the electric grid in a dynamic scenario, and the ratio between these values, called the EME parameter (Embodied emissions divided by the electricity Mix Emissions).

When EME in Table 5 exceeds the unit value, the energy system is no longer interesting from an environmental point of view. EME can be a useful indicator at the time of evaluating the benefits of an energy system in comparison with the current country scenario.

Figure 4 shows the overall emissions of the energy system (blue) and the emissions of the electric grid (orange), for both case studies. The embodied emissions are calculated per kWh of energy produced by the system. They therefore increase slightly over time as some decrease in energy production has been assumed due to losses and deterioration of equipment.

In 2035 for Spain, the annual emissions of the energy system are the same as those of the electricity grid, which is when it would no longer be interesting to exploit the energy system from an environmental perspective.

For Brazil, the behavior is different: the blue and orange curves do not touch throughout time because of the government expansion plan for electricity, which despite including renewables, still relies on natural gas. As such, the results from the Brazilian study case can be useful for policy to illustrate the

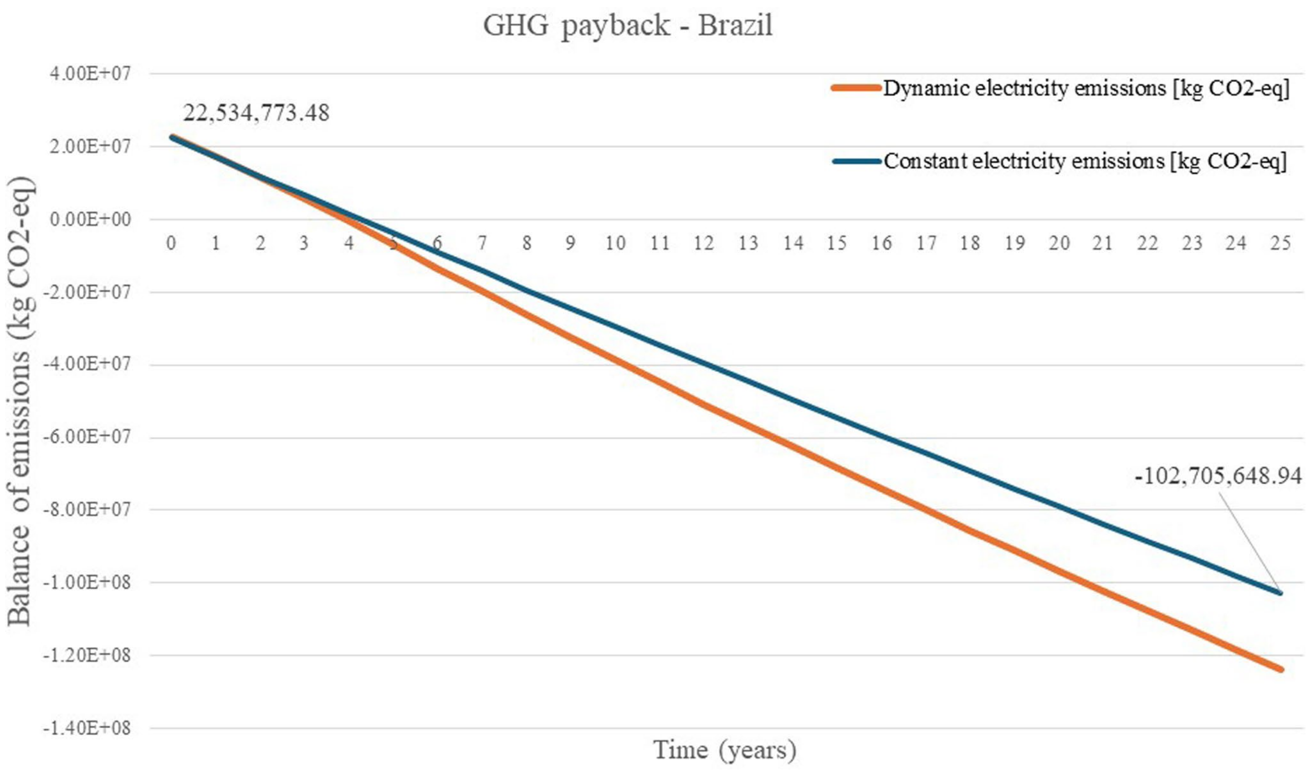

Fig. 3 GHG Payback: Brazilian case

Table 5 Emissions for the Spanish and Brazilian study cases (2024, 2030, and 2050), emissions of the electric grid, and the EME parameter

Year	Spain: embodied emissions [kg CO_2-eq/kWh]	Spain: electricity mix Emissions [kg CO_2-eq/kWh]	EME
2024	0.077	0.168	0.458
2030	0.082	0.092	0.891
2050	0.091	0.061	1.492

Year	Brazil: embodied emissions [kg CO_2-eq/kWh]	Brazil: electricity mix emissions [kg CO_2-eq/kWh]	EME
2024	0.028	0.165	0.168
2034	0.029	0.206	0.140
2050	0.032	0.184	0.174

benefits of renewables in mitigating climate change and how the global warming savings vary geographically.

In both cases, it is necessary to include the dynamics of the electricity mix for an appropriate evaluation of the energy systems. The new parameter proposed herein, EME, which is

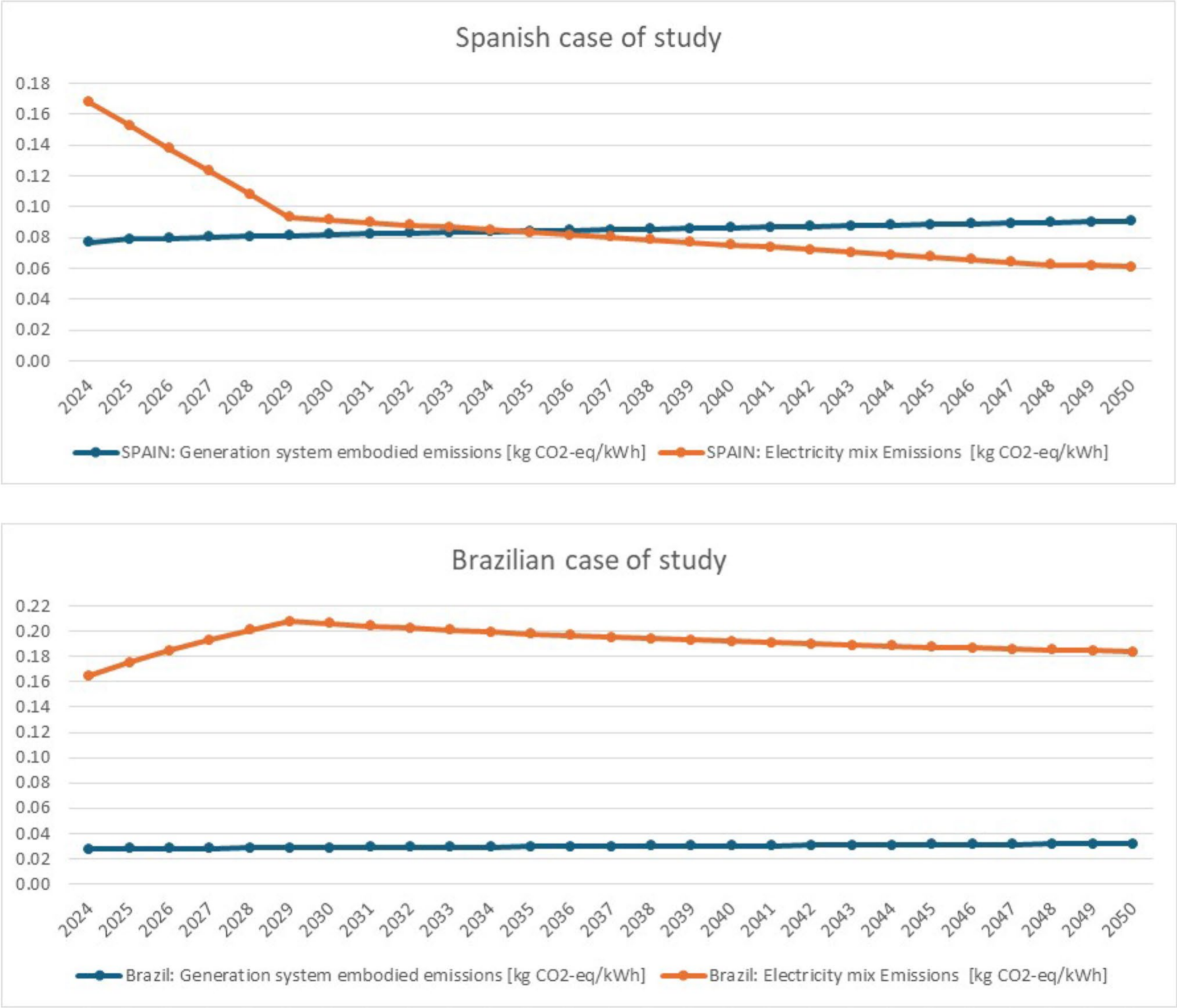

Fig. 4 Annual overall emissions of the energy system (blue) and emissions of the national electric grid (orange): **a** for the Spanish study case, and **b** for the Brazilian study case

the ratio between the generation system embodied emissions and the electricity mix emissions, can be an additional criterion employed in the assessment of energy systems and guide towards decarbonization efforts. It is necessary to assess the environmental impacts of electricity generation around the world with unified, precise and realistic criteria that guarantee the decarbonization of the planet by 2050.

Conclusion

This work highlights the varied limits and boundary conditions affecting the calculation of electricity generation intensity factors, emphasizing the need for standardized tools and public databases. It also stresses the importance of including embedded emissions from generation systems and equipment for an accurate evaluation of emission factors across energy technologies. This need is increasing, especially in Europe, as countries speed up efforts to decarbonize the electricity grid.

Two case studies have been analyzed herein, for Spain and Brazil, which have presented very different electricity mix dynamics over time. The Spanish trend follows heavy decarbonization, while the Brazilian trend relies on natural gas as established by governmental publications. The results confirm that temporal evolution is an essential parameter in the environmental evaluation of energy systems.

Finally, this work demonstrates the need to substitute the parameters currently used to measure the environmental performance of power generation systems. More specifically, the environmental payback should consider the evolution of power generation systems. A new dynamic payback is proposed, which reflects the environmental impact of energy generation systems throughout time, in a much more realistic way.

In addition, the EME parameter has been presented herein, which relates the embodied emissions of an energy system and the local electricity mix emissions. EME can be a useful tool to indicate the potential impact of an energy system in the overall energy mix of a country.

In conclusion, this study shows that measuring the environmental impact of electricity generation is complex and depends on many changing factors. The case studies of Spain and Brazil highlight how different electric mixes and trends can affect emissions. To better reflect these changes over time, this study proposes a new dynamic payback method and introduces the EME parameter, which connects the emissions from building energy systems to the local electricity mix. These tools can help make more accurate decisions when planning energy systems and support efforts to reduce emissions more effectively.

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Data availability We declare that all data supporting and generated in this study are available from the corresponding author on reasonable request.

Declarations

Conflict of interests The authors declare that they have no competing interests or personal relationships that could have appeared to influence the work reported in this paper.

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