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Life cycle assessment of power generation systems in Spain: Exploring a broader view from a consequential perspective

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ABSTRACT

Developing new clean power generation systems is a research priority for the energy sector, and selection should be based on environmental performance over the entire lifetime. Consequential Life Cycle Assessment evaluates the consequences of this selection and provides environmental data to support decision-making. This research uses a consequential approach to assess the environmental impacts of two medium power generation systems. The selected environmental impact assessment methods are IPCC 2013 GWP 100y and ReCiPe 2016. Moreover, the work describes a methodology for finding the marginal mix technologies for electricity and cooling energy production depending on the time horizon. The positive environmental consequences associated with short-term marginal energy mixes (electricity and cooling) progressively disappear when the marginal energy mix varies throughout time. The environmental results strongly depend on the marginal mix of technologies and evidence the necessity to develop methodologies and standards to improve the robustness of environmental assessments. A new line of discussion is opened concerning the temporal variation of environmental impacts of an energy production system, which could also be considered in Attributional Life Cycle Assessments.

1. Introduction

Substantial efforts are being made to develop and implement new renewable energy-based generation systems to protect the environment and the limited resources of the planet (IRENA et al., 2020). Reaching the critical goal of net zero emissions by 2050 will require significant efforts from society but will create opportunities that come with clean energy transitions. Clean electrification is essential in the early stages of transforming the global energy economy and the search for efficiency improvements (IEA (International Energy Agency), 2021).

The development and selection of new power generation systems must be accompanied by environmental assessments that evaluate their environmental performance in a clear, detailed, and understandable manner. Life Cycle Assessment (LCA) is a holistic approach that evaluates the environmental impacts caused by a product or service during its lifetime, from the extraction of raw materials until the disposal or recycling (cradle to grave) (International Organization for Standardization, 2006). Within the family of LCA, there are two approaches: Attributional Life Cycle Assessment (ALCA) and Consequential Life Cycle Assessment (CLCA).

ALCA attempts to describe the physical flows through the entire cycle of a product or service, and it attributes a portion of the potential environmental impact to a product life cycle. This approach is the most widely used and extended among scientists and technicians. Usually, when environmental results are presented, these are attributional (the approach used is rarely specified, as the default approach is attributional). In turn, CLCA aims to describe how these physical flows will change due to an action/decision, and it evaluates the environmental consequences of this decision. A CLCA estimates how global environmental burdens are affected by the production and use of the product (Ekvall, 2019).

This difference was formally adopted in 2001, and the modeling choice (attributional vs. consequential) and input data choice (average vs. marginal) have been and continue to be one of the most discussed and controversial aspects of the life cycle inventory (LCI) analysis.

The “most appropriate LCA approach” has been widely discussed. Weidema (2003) examined both methodological choices and pointed out that ALCA (retrospective) is applied for hot-spot identification, product declarations, and generic consumer information. In contrast, CLCA (prospective) studies environmental consequences and is typically used in product development and public policy-making. Ekvall et al. (2005) focus their discussion on the LCI, mainly on the choice between average and marginal data. However, they also recognize that

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Nomenclature

ALCA	Attributional Life Cycle Assessment
CLCA	Consequential Life Cycle Assessment
CSP	Concentrated Solar Power
GHG	Greenhouse gas
HTF	Heat Transfer Fluid
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
O&M	Operation and Maintenance
ORC	Organic Rankine Cycle
PTC	Parabolic Trough Collector
TES	Thermal Energy Storage
TTES	Tank Thermal Energy Storage

ALCA and CLCA have methodological limitations, and both can be used for learning purposes. Some authors, such as Plevin et al. (2014), recommend that consequential be used for decision support.

Ekvall et al. (2016) mention that the ILCD handbook (Commission, 2010) should be revised due to its inconsistent recommendations for choosing between attributional and consequential modeling and between average and marginal data in the LCI. Ekvall (2019) discusses the pros and cons of the two methodological options concluding that the CLCA is more accurate. Still, ALCA has other advantages, and the LCA expert should decide on the methodology. Brander et al. (2019) agree that decision support should be based on the consequential approach but argue that a review of the current situation, goal setting, and assessment of progress over time should use the attributional approach. More recently, Fauzi et al. (2021) reported that both methodologies could be employed due to their complementarity. Brander et al. (2019) had already suggested coupling ALCA and CLCA in a two-step assessment, firstly using ALCA to identify key impact categories and specify reduction targets and then using CLCA to check the environmental consequences of meeting these targets at a larger scale.

Porcelli et al. (2019) presented a review with a brief history of the consequential approach and its interpretation in the literature, also analyzing the case studies to clarify its applicability. A recent review of definitions and model restrictions for ALCA and CLCA also claimed the vagueness and open issues in literature (Schaubroeck et al., 2021).

Various methods have been used to build models to assess the environmental consequences of actions in CLCA (Palazzo et al., 2020). Kätelhön et al. (2015) presented an approach to model environmental impacts within the framework of LCA when introducing a new technology that changes the industry cost curve (replacing the highest-cost producer and changing the environmental profile of the product). However, the model focuses on short-term effects and does not consider the impact on future decisions. Zhao and You (2021) developed an optimization to determine the most appropriate technology for the chemical recycling of HDPE from economic and environmental viewpoints, adopting a consequential approach. However, the authors focus on the optimization superstructure rather than on the analysis of CLCA data.

There are different points of view and discussions on which approach to adopt. However, few studies compare ALCA and CLCA with examples (Thomassen et al., 2008). Limited studies have referred to power generation systems, such as photovoltaic technologies (Tian and You, 2021), air source heat pump and condensing gas boiler (Naumann et al., 2022), and biogas (Rehl et al., 2012). Despite the scarcity of studies, the existing scientific literature is instrumental in advancing the interpretation of the results.

Focusing on LCA and energy systems, electricity is crucial for energy generation systems because these produce and consume electricity. The long-term modeling of electricity systems is a complex and underexplored task. There can be considerable yearly changes in the electricity mix, evidencing the necessity of updated data for LCA evaluation. Nordenstam (2021) analyses the implications of method choices (ALCA, CLCA, and electricity mix) for the greenhouse gas (GHG) assessment of a district system producing heating and electricity. However, the author emphasizes that more research and advances are needed to cover other activities and to standardize the execution of consequential GHG inventories. Tian and You (2021) conducted ALCA and CLCA for two photovoltaic technologies. They concluded that CLCA provided complementary information that could not be obtained in ALCA, despite the difficulty in obtaining data and its relatively low quality. However, the work is focused on the LCA of the PV construction phase rather than on the assessment of the use phase of the panels and the impact on electrical grids.

There are few publications regarding case studies and consequential life cycle assessment interpretation. Luu et al. (2020) reviewed CLCA studies in the power sector, finding 31 papers on the CLCA for the power sector, including case studies and reviews: most applied economics models and CLCA to identify links between environmental impacts and socio-economic indicators.

The case studies are mainly in three fields, the first referring to the consequences of the large deployment of photovoltaic systems and their implication on the local power generation systems. Jones and Gilbert (2018) assessed the greenhouse gas emissions (GHG) of PV electricity generation deployment, considering future changes in manufacturing PV modules from a consequential LCA perspective. The second research field analyses the charging of electric vehicles and its consequences on the associated power grid (Jochem et al., 2015; Garcia and Freire, 2016). The third research field is related to the use of energy generation from biogas (Rehl et al., 2012), bioenergy (Brander, 2017), and biomass (Tonini et al., 2017).

This study aims to perform a CLCA to evaluate two medium size power systems located in Spain, which provide electricity and cooling to a shopping center. To this end, a deep analysis of available data and procedures is presented to establish the mix of marginal technologies for electricity and cooling generation.

The article is structured as follows: Section 2 presents a literature review on estimating marginal technologies for electricity generation as one of the critical aspects of the environmental assessment of power generation systems from a consequential point of view. Section 3 presents the Spanish case study and then focuses on the definition and scope of CLCA for energy systems. Within the latter and based on the literature review, the marginal mix technologies for electricity generation and cooling energy production has been estimated. The particularities of the Spanish market have been included in determining the mixes depending on the time horizon. Section 4 presents and discusses the results obtained from a consequential perspective and compares them with the ALCA results, and finally, Section 5 concludes the paper and prospects for future studies.

2. Literature review

The energy systems under study (Section 3) provide electricity and cooling to meet the energy demands of a shopping center. Consequently, it is necessary to determine the marginal technology that will be affected by electricity production (and therefore displaced in the market). In addition, the cooling technologies that would cover the cooling demands in the absence of the proposed cogeneration systems will also be displaced.

The marginal technology is the one capable of responding to small changes in demand on the market - it is defined as the mix of technologies that will supply the possible increase in demand in a designated space of time (Weidema et al., 1999).

An exhaustive review has been accomplished on estimating the marginal technologies for electricity generation. The particularities of the Spanish market have been included in determining the mixes depending on the time horizon, the calculations and assumptions are detailed in Section 3.

Data on the evolution of the market share enables the estimation of average mix technologies. Nevertheless, pinpointing the marginal mix technology is a difficult task. There are several discrepancies and challenges to its determination and the need to define the time horizon. Olkkonen and Syri (2016) presented a method for estimating marginal electricity generation using Finnish, Nordic, and European energy systems, for the short term (2009–2010) and long term (until 2030). The authors recommended considering the variation of the marginal electricity for LCA.

Frequently, and according to Weidema et al. (1999), the marginal long-term technology is fossil fuels (cogeneration); natural gas power was found to be the marginal long-term technology in the Nordic power system.

Mathiesen et al. (2007) reviewed ten studies and concluded that coal and natural gas combined heat power (cogeneration) was the most common marginal long-term technology. They revealed that the studies did not apply the methodology consistently and referred to different arguments for choosing mainly coal power plants or natural gas cogeneration as the marginal technology. Mathiesen et al. (2009) published a study proving that identifying marginal technologies is more challenging than described in the theoretical recommendations of consequential LCA.

Some European countries have established short-term marginal mixes, mainly oriented to electric vehicle charging. Garcia and Freire (2016) estimated the marginal mix for Portugal using 2012–2014 data and identified coal and natural gas as the marginal energy sources, while Jochem et al. (2015) found the short-term marginal mix for Germany (0.38 $kgCO_{2eq}/kWh$) for controlled charging strategy. Arvesen et al. (2021) computed short-term marginal electricity mixes for European countries and verified that short-term marginal electricity predominantly comes from natural gas, with variable smaller contributions from nuclear. However, the authors note that short-term marginal electricity estimates present high uncertainty.

Vélez-Henao and Garcia-Mazo (2019) identified hydropower as the long-term marginal technology for electricity power generation in Colombia until 2030. For China, Zhao et al. (2016) concluded that the marginal generation technology will be fossil fuel-based until 2030. In Spain, there are substantial discrepancies between the marginal electricity mixes estimated, depending on the application. The Spanish electricity market has a liberalized marginal system, where energy offers and demands are expressed correspondingly for each hour of the following day. The hourly price of electricity is determined by the cost of the most expensive technology that has entered to meet demand (the last unit incorporated into the market). In this context, the lower-price technologies always sell their electricity, while the most expensive ones only do so when demand is high. The latter are, by definition, marginal technologies. However, the dynamics are not straightforward, as political and economic strategies usually govern the offers in the Spanish electricity market. Arcos-Vargas et al. (2020) explained the economic operation of the Spanish market and performed an environmental analysis to determine the impact of new PV generation electricity within the Spanish market in 2017. The authors provide a detailed hourly study, concluding that PV electricity will displace combined cycle technologies (during sunny hours).

García Redondo and Román Collado (2014) identified thermal and combined cycle power plants as the marginal technologies for Spain. The argument is that production is easily adjusted to market demand variations and considered unconstrained. Moreover, thermal and combined cycle power plants are the least competitive and the first to stop production.

Peters et al. (2022) quantified the environmental behavior of PV installations using marginal electricity mixes for Spain. Short-term marginal emission factors were evaluated for Spain, yielding hourly, seasonal, and average data. Hourly marginal electricity mixes are presented along with the average for each month of 2020. The marginal mix does not include solar or wind energy and rarely includes nuclear and cogeneration. Hydropower and imports are the most used technologies for balancing energy demands. Natural gas and coal show similar shares as for the average mix. Peters et al. (2022) concluded that electricity imports are essential to balance out the Spanish grid. However, this viewpoint is not shared by other authors, such as Arcos-Vargas et al. (2020), who noted the weak connection of the Spanish electricity system with France, Portugal, and Morocco. The authors highlight that this makes the Spanish system response to possible supply shocks more idiosyncratic.

The generation technologies that usually set the market price (marginal) are the most expensive at any given time, offering the highest opportunity cost: fuel oil and adjustable hydroelectric plants. Therefore, low and intermediate-price power plants will cover a considerable share of the demand. In other words, peak-price power plants are only enabled when high-energy demands occur. The lowest operation costs are associated with nuclear and run-of-river hydro (Agosti et al., 2007). The latter has a very low variable cost, but it must always be offered at its opportunity cost, given by the highest price at which it can be sold in a specific time horizon. Coal has intermediate production costs, slightly lower than combined cycles. Finally, fuel-gas thermal generation is the most expensive.

Generally, the power plants that set the price in a competitive market are the coal-fired plants when demand is low, combined cycle plants when demand reaches medium or high levels, and then fuel-gas plants during the hours of highest demand.

3. Methods

3.1. Case study: description of the two solar cogeneration systems

Two solar cogeneration systems have been defined in a previous study that conducted technical, environmental, and economic feasibility assessments to cover the cooling and electrical demands of a shopping center in Zaragoza (Spain) (Pina et al., 2020). Both solar cogeneration systems (System A and System B) contained a parabolic trough collector (PTC) field coupled with thermal energy storage (TES) tanks, mechanical chillers, and Organic Rankine Cycle (ORC). System A is hybridized with a biomass boiler, while System B is not. The systems produce electricity to cover the electrical demands and to supply power to the mechanical chillers for air-conditioning purposes. The annual thermal cooling demand is 6412 $MWh_{t,}$ and the yearly electricity demand (lighting, services, etc.) is 1370 MWh_e. A detailed description and the technical data of the equipment for the two solar cogeneration systems can be found in Pina et al. (2018). Fig. 1 and Fig. 2 show the annual energy balance of Systems A and B.

An attributional life cycle assessment was performed in a previous study, and detailed inventory data of all equipment was presented (Guillén-Lambea et al., 2022). The attributional method indicated that System B was more suitable from the environmental point of view than System A, considering System B as a remarkable design for future projects.

3.2. Consequential Life Cycle Assessment (CLCA)

A CLCA aims to assess the environmental impacts of all activities affected by a product or service's production, consumption, and disposal. According to Ekvall (2019), a CLCA estimates how global environmental burdens are affected by the production and use of a product. Its conclusions can support decision-making. This implies that the consequences are traced forward in time, so using data on marginal suppliers and substitution of displaced activities is relevant.

Ecoinvent (Swiss Center for Life Cycle Inventories, 2018) is the most widely used database and has processes and datasheets that are

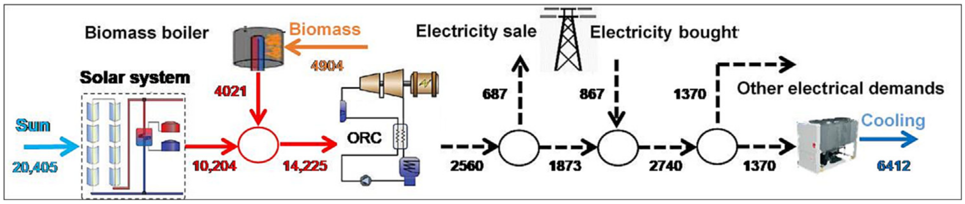

Fig. 1. System A, annual energy balance in MWh (ORC: Organic Rankine Cycle).

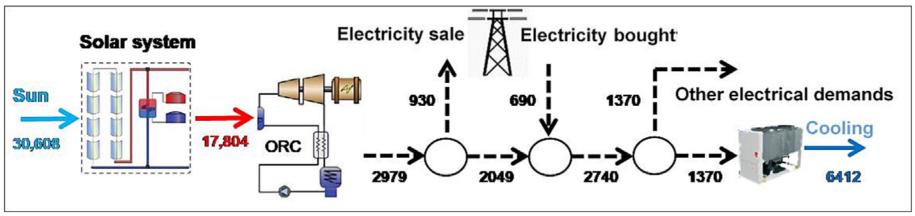

Fig. 2. System B, annual energy balance in MWh (ORC: Organic Rankine Cycle).

constantly updated. Ecoinvent contains three system models: allocation at the point of substitution, cut-off by classification, and consequential. The latter manages two methodological choices, the first using an unconstrained supply of products and the second using substitution[1] to convert multi-product activities to single-product activities. The CLCA avoids allocation, while ALCA is based on average data and allocation by dividing environmental burdens throughout the life cycle of one process. The choice of input data and the modeling of the process are vital aspects and probably the most complicated task when performing an accurate LCA.

Ekvall and Weidema (2004) clearly defined the competing product, and Weidema et al. (1999) proposed a five-step procedure to identify the competing products. Substitution occurs when a product, material, or service is replaced by another. In the ecoinvent database, supplies are categorized according to technological levels (outdated, old, current, modern, and new technologies) – in which the two first are constrained.

3.3. Definition of system boundaries

Electricity production is critical data, as its reliability will condition the quality and robustness of consequential LCA results. Marginal cooling technologies must also be considered, and therefore it is crucial to identify marginal cooling technologies for the accuracy and validity of the consequential assessment.

Herein surplus electricity produced by the energy systems can be considered a by-product. When considering the substitution method, the electricity exported into the grid should be moved to the input side with a negative sign (maintaining the mass balance). The self-generated electricity can substitute electricity generation elsewhere, obtaining credits for the producing unit as this displaces other sources of electricity generation (as a reference product).

For the remainder of components and materials, the same Ecoinvent processes selected by Guillén-Lambea et al. (2022) for their ALCA were adopted, but considering the consequential approach. The most copious materials by weight are: reinforcing steel, flat glass (for mirrors), concrete (for TES tank), chromium steel, and HTF fluid. All stages of the system lifecycle are included, from resource extraction to end of life for all equipment (including waste management scenarios for raw materials). The construction of buildings, roads, and system dismantling is not included. Detailed LCIs for each piece of equipment can be found in Guillén-Lambea et al. (2022). The lifetimes considered are 30 years for the solar system, 50 years for the TES, and 20 years for the ORC, mechanical chillers, and biomass boiler. Fig. 3 represents the system boundaries depending on the LCA model: attributional or consequential.

3.4. Marginal electricity production mix. The case of Spain

The short-term marginal mix is the mix that responds to a momentaneous demand change within an existing operational generation scheme. The long-term marginal mix includes transforming the generation scheme over time (Vandepaer et al., 2019). Depending on the time horizon, three considerations could be made regarding the use of marginal electricity mix data, and the three approaches are presented below:

1) Approach 1. Calculation of the marginal mix technologies based on the increases in electricity generated from a reference year to a horizon year. A long-term approach, result based on published data. Data until 2050.

2) Approach 2. Calculation based on the incremental approach (approach 1), but using Spanish updated data for electricity generation. Mid-term approach, as the Spanish published data contains estimations until 2030.

3) Approach 3. Estimation based on marginal electricity mixes published, available from 2019 to 2021. Short-term approach.

3.4.1. Approach 1. Long-term estimations

The marginal mix technologies can be estimated by considering the increases in electricity generated by each source from a reference year to a time horizon year. Eq. (1) was proposed by Schmidt et al. (2011), who define the long-term marginal electricity suppliers in a country as the national mix of planned/predicted new installations during a specified period of time.

$$S_{i,T} = 100\frac{P_{i,T} - P_{i,r}}{\sum_{i}^{n}(P_{i,T} - P_{i,r})} \quad (1)$$

In Eq. (1), i refers to an electricity-producing technology, T is the year chosen as the time horizon that corresponds to the year when the installation of new capacity caused by a change in electricity demand is expected to become operational, r is the reference year that corresponds to the year in which the decision producing an alteration in electricity demand is taken, P is the electricity generated at time T or r by technology I, n includes all unconstrained electricity producing technologies

[1] By-products are moved to the input side with a negative sign, while the by-products that can substitute other productions provide credits to the producing activity.

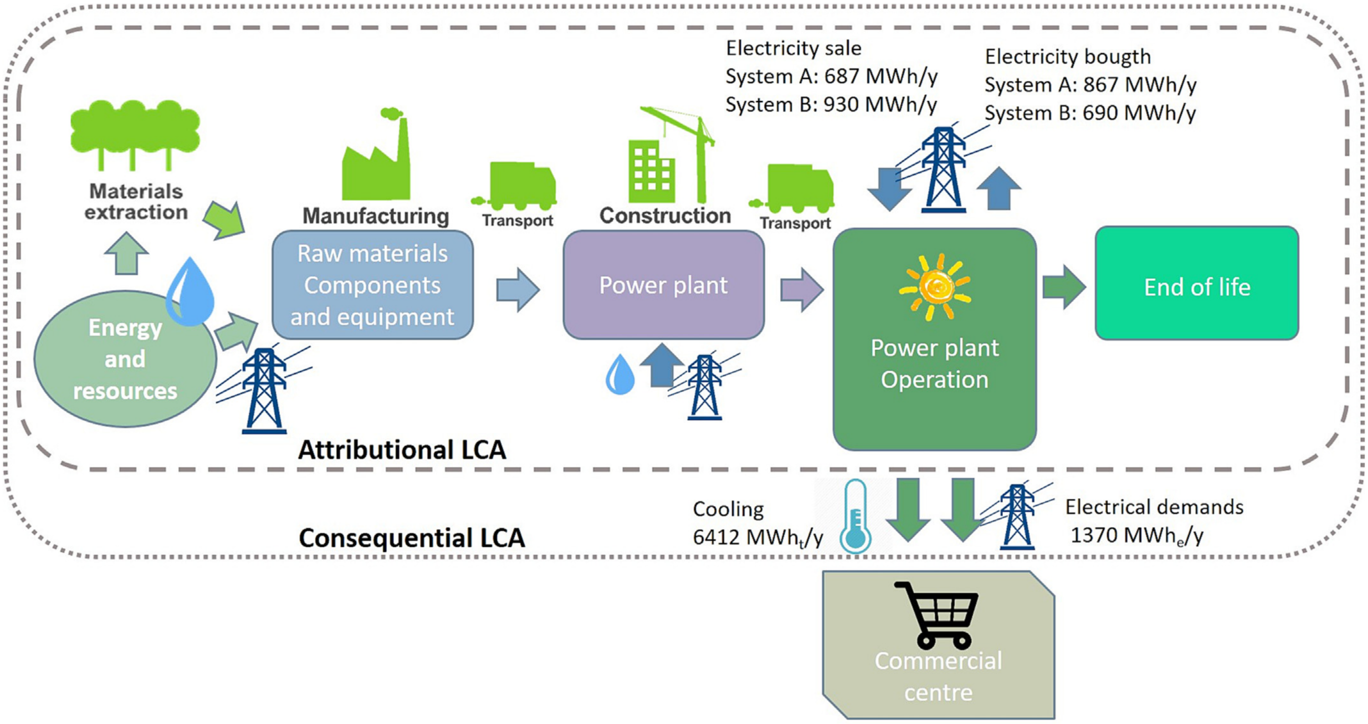

Fig. 3. LCA system boundaries.

with a growing production at T concerning r, and S is the share that supplier i contributes to the marginal mix given a time horizon T.

With Eq. (1), Schmidt et al. (2011) consider that there are no constrained suppliers; however, this is not representative of reality. For example, sources or technologies decreasing in the studied period are assumed to be uncompetitive, and the possibility of natural resources unavailability is not considered. A constrained technology such as cogeneration is assumed to be unconstrained.

Eq. (1) is also used by Vandepaer et al. (2019) to calculate the long-term marginal electricity supply mixes of 40 countries, which were integrated into Ecoinvent's v.3.4 consequential database. The estimated mixes are calculated for the 2015 reference year and 2030 horizon year. Reference data are taken from European Commission (2016) and predicted data from IEA (IEA (International Energy Agency), 2016). According to Vandepaer et al. (2019), the consequential method defined in the Ecoinvent database reflects long-term consequences of small-scale, defining small-scale choices as decisions that do not influence the market parameters (e.g., production, volumes, cost) and can be supposed to be linearly related to the size of the change (Weidema et al., 2013). Data on the long-term marginal electricity supply was published by Vandepaer et al. (2019) for the case of Spain. From those data, the percentages of marginal electricity mixes depending on the reference and the horizon time are calculated and presented in Table 1 (using Eq. (1)).

Other time scenarios are completed with data available from Buyle et al. (2019), who also published detailed electricity marginal data for additional reference and horizon years. They calculated the marginal electricity mixes by considering only competitiveness, and the proportions of each source/technology were estimated by calculating the slope of the increment (instead of the increment between the reference and horizon years). These estimations are presented in Table 1. Table 1 also contains data for some relevant environmental indicators published by (Vandepaer et al., 2019) for the obtained marginal electricity mixes.

Table 1
Estimation of the marginal electricity mixes for Spain (long term).

		(Vandepaer et al., 2019) Reference year_Horizon year				(Buyle et al., 2019) Reference year_Horizon year	
Source/technology	Ecoinvent process for electricity	**2015_2030**[c]	**2015–2020**	**2020–2030**	**2030-2040**	**2020–2040**	**2020–2050**
Hydro	Hydro, reservoir, non-alpine region		0.25 %	0.15 %	0.01 %	0.80 %	1.00 %
Hydro_pump	Hydro, run-of-river		0.49 %	0.28 %	0.02 %		
Natural gas	Natural gas, combined cycle		23.57 %	0.00 %	18.67 %	3.50 %	
Diesel	oil		0.00 %	2.01 %	2.43 %	1.80 %	0.90 %
Wind onshore	Wind, >3 MW turbine, onshore	30.78 %	34.96 %	30.04 %	21.68 %	27.10 %	41.1 %
Biomass	Wood, future	6.71 %	10.95 %	5.71 %	3.98 %	4.90 %	4.30 %
Solar photovoltaic	Photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted	62.02 %	29.77 %	61.81 %	53.22 %	61.90 %	52.70 %
Fossil fuels		0.00 %	23.57 %	2.01 %	21.10 %	5.30 %	0.90 %
Renewables		100.00 %	76.43 %	97.99 %	78.90 %	94.70 %	99.10 %
Environmental impacts	kg CO_2-eq/MWh[a]	**65.90**	**156.43**	**NA**	**125.79**	**67.00**[d]	**64.50**[d]
	ReCiPe Pt/MWh[b]	**14.42**	**24.72**	**NA**	**17.23**	**4.84**[d]	**4.89**[d]

[a] IPCC 2013 GWP 100y.
[b] ReCiPe Endpoint (H/A).
[c] Data in Ecoinvent (v 3.4).
[d] Calculated by the authors with the data published by Buyle et al. (2019).

Long-term changes in electricity production technologies are not included in the consequential processes herein studied. Therefore, the environmental impacts are expected to be minor as long as the technologies evolve towards more environmentally-friendly systems.

The lowest proportion of electricity generation by renewable energies (highlighted row, 76.43 %) is obtained for the 2015–2020 scenario, which is logical due to a more moderate implementation of renewable sources in those years than in the years to come. In addition, 2015–2020 cannot be defined as a long-term estimate (only five years), which might influence the validity of Eq. (1) (tiny increments are produced, which could mask the results when transformed into percentages).

There is a drop in the percentage of renewable energy for the 2030–2040 scenario for (Vandepaer et al., 2019) data (78.90 %) as well as for (Buyle et al., 2018) (79.22 %), which destabilizes the trend. This is because the marginal data of electricity production with natural gas has a pronounced drop in 2030. Consequently, if 2030 is taken as the reference year, natural gas appears in the marginal energy mix with a consequent increase in the environmental impacts associated with the marginal electricity mix. From these estimates, it can be concluded that it is not advisable to take a reference year for which there is no actual data (i.e., before the current date). The fragility of Eq. (1) is evident. Because of the variations detected in this analysis, it is risky to base the results of a consequential life cycle analysis on estimates of marginal technology mixes for electricity production.

3.4.2. Approach 2. Mid-term estimations

In Spain, the evolution of the Spanish energy market and its prediction up to 2030 was published in the National Integrated Energy and Climate Plan (PNIEC) (MITERD, 2020). The report presents two scenarios: one that includes the estimates of electricity generation based on market trends (trend scenario), while the other presents estimates according to the country decarbonization objectives (target scenario), from 2015 (real) to 2030 (estimated) in five-year steps. The marginal energy mix data shown in Table 2 are obtained with these data and by applying the incremental approach.

Neither nuclear nor carbon and its derivatives appear in the marginal electricity mix when the target values for power generation production are applied. However, these resources remain in the market trend scenario. The high percentage (14.7 %) of natural gas in the 2015–2030 trend scenario is noteworthy, although not reflected in the Ecoinvent v3.5 marginal mix. Data for Ecoinvent v3.5 was included in the table for comparison purposes, the GHG emissions are similar to version 3.4 (Table 1), but Recipe impacts have been considerably reduced. The v3.5 includes new data on concentrated solar power from parabolic trough and solar towers.

The definition of horizon year considers that it is the year in which new production, or in this case, a new power generation system is launched. The question is, as the variation of the marginal mix will considerably affect the environmental results, would it be appropriate to include the variation of this marginal mix throughout the lifetime of the power generation system?

3.4.3. Approach 3. Short-term estimations

Another method for calculating the marginal technology mix, perhaps the most appropriate to reduce uncertainties, would be to use current marginal technologies as the basis. It is certainly closer to reality, but it has two drawbacks: the difficulty in finding published data on actual marginal mixes and the lack of short- or long-term estimates.

However, the most significant advantage of using actual data is that it reflects the characteristics, trends, and singularities of the electricity market for a specific country. Many parameters govern the distribution of electricity generation; undoubtedly, the economic factor is currently the most important for Spain.

OMIE is the electricity market operator that manages the Iberian Peninsula day-ahead and intraday electricity markets (OMIE, n.d.). Table 3 shows the 2019–2022 values.

2022 data were estimated maintaining the variation of each technology from 2020 to 2021. Coal practically disappears, and hydropower is the most relevant marginal technology, with combined cycle maintaining a non-negligible percentage due to its competitiveness during intermediate-level demands. The environmental impacts for the 2022 marginal technology mix were calculated with SimaPro software (PRe Consultants, 2019) as 151 kg CO_{2eq}/MWh (IPCC 2013 GWP 100y) and 7.09 pts./MWh (Recipe 2016 Endpoint H/A). The environmental impacts of the estimated short-term marginal electricity mix are lower than the mid-term impacts (trend data) marginal electricity mix for the 2030 horizon. However, these values are higher than those obtained with target data (Table 2). The environmental results of the marginal mix at longer time horizons (2040 and 2050) improve considerably for the short term, with reductions of 55.6 % for GHG emissions in 2040 and 57.3 % in 2050. When considering the ReCiPe method, the impact decreases by 32.3 % for 2040 and 2050.

As these variations are significant and will have a considerable impact on the environmental results of the study case, it is proposed to adjust the marginal mixes of electricity production throughout the lifetime of the system (Section 4.3).

Table 2
Estimation of the marginal electricity mixes for Spain (mid-term).

			Ref. year 2015-Horizon year 2030		Ref. year 2015-Horizon year 2020		Ref. year 2020-Horizon year 2030	
Source/technology	Ecoinvent process	Ecoinvent v3.5 (2015–2030)	Trend scenario	Target scenario	Trend scenario	Target scenario	Trend scenario	Target scenario
Hydro and hydro pump	Hydro, reservoir, non-alpine region	0.32 %	0.90 %	4.99 %	6.68 %	6.56 %	0.00 %	5.18 %
Natural gas	Natural gas, combined cycle power plant		14.75 %		3.78 %	0.00 %	16.01 %	0.00 %
Nuclear	Nuclear, pressure water reactor		1.04 %	0.00 %	3.61 %	3.65 %	0.00 %	0.00 %
Wind onshore	Wind, >3 MW turbine, onshore	20.27 %	46.13 %	43.06 %	45.78 %	49.15 %	47.12 %	41.01 %
Biomass	Wood, future	4.43 %	1.80 %	3.86 %	6.84 %	6.93 %	0.00 %	3.62 %
Solar photovoltaic	Photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted	60.35 %	35.38 %	48.08 %	33.31 %	33.72 %	36.87 %	50.19 %
Solar concentrated		14.60 %						
Fossil fuels		0.00 %	14.75 %	0.00 %	7.39 %	3.65 %	16.01 %	0.00 %
Renewables		100.0 %	84.25 %	100.0 %	92.61 %	96.36 %	83.99 %	100.00 %
Environmental impacts	kg CO_2-eq/MWh[a]	**68.20**	**195.47**	**112.16**	**139.86**	**118.00**	**195.94**	**117.62**
	ReCiPe Pt/MWh[b]	**4.66**	**7.84**	**6.30**	**7.03**	**6.62**	**7.62**	**6.56**

[a] IPCC 2013 GWP 100y.
[b] ReCiPe Endpoint (H/A).

Table 3
Mix of electricity marginal technologies in Spain (short-term).

	2019	2020	2021	2022 (estimated)
Coal	9.5 %	2.6 %	1.5 %	0.38 %
Combined cycle	27.3 %	20.7 %	15.9 %	10.59 %
Hydraulic	40.9 %	45.8 %	54.9 %	61.07 %
Hydraulic pumping	6.0 %	8.8 %	10.2 %	11.07 %
Nuclear	0.0 %	0.4 %	0.1 %	0.00 %
Renewables[a]	30.1 %	29.5 %	23.6 %	16.89 %
Imp Portugal	0.0 %	0.1 %	0.0 %	0.00 %

[a] Renewables include cogeneration, waste, biomass.

3.5. Marginal cooling production mix. The case of Spain

In systems A and B, three mechanical chillers consume 1370 kWh_e/y to produce 6412 kWh_t/y cooling. Therefore, it is necessary to find the marginal cooling technology and estimate the environmental impacts caused by producing 6412 kWh/y. The results will determine whether the selected technology is up to market expectations from an environmental perspective and the environmental consequence of making this choice.

The cooling mix marginal technology for Spanish commercial applications must be determined: the short term marginal mix that responds to changes in cooling demand within a given cooling technology pool, plus the long-term marginal cooling mix that considers a change of cooling technologies over time.

In Ecoinvent v3.5 (Swiss Center for Life Cycle Inventories, 2018), there is a defined process 'Cooling energy {GLO}| market for | Conseq, U', which redirects to the process 'Cooling energy {RoW}| from natural gas, at cogen unit with absorption chiller 100kW | Conseq, U'. The process includes a single-effect absorption chiller that operates with heat from a natural gas-operated cogeneration unit (allocation exergy) with 100 kW cooling capacity connected to a 250 kW hybrid air cooler. The process includes heat input from a 160kW_{el} cogeneration unit, electricity and water for operation, and its infrastructure (absorption chiller, air cooler, piping). The environmental impacts (consequential approach) associated with the production of 1kWh cooling are 0.481 $kgCO_2eq$ (IPCC GWP 100y) and 12.6 mPt (ReCiPe Endpoint (H/A), mainly due to gas consumption.

Although the heating energy consumption in the EU market has been extensively investigated, the space cooling sector remains under-explored. Uncertainties are present, and most limited research and data are based on estimations (Pezzutto et al., 2022). Cooling accounted for 18.5 % of total electricity use in buildings, up from 13 % in 1990 (IEA, 2018), and should continue to increase because cooling degree days are expected to grow up to 50 % by 2050 (depending on the region) (NCEI, 2022). For the Spanish market, the air conditioning market experienced an increase of 12.91 % between 2021 and 2021 (AFEC, 2022).

Evaluating marginal cooling technologies in the short- and long-term terms requires consideration of technology growth data and cooling technology roadmaps. Solar energy could be essential due to decarbonization trends and because space cooling demands align with sun hours. AIE presents detailed information about the current and market trends for space cooling (IEA, 2018). For district cooling networks, residential and commercial buildings, chillers are the most widespread technology: in 2017, the IEA estimated 41 million operating chillers worldwide, of which more than 85 % are electric-powered and water- or air- cooled. The installed capacity amounted to 3350 GW, with thermally driven chillers (natural gas) responsible for 470 GW. Considering these data represent the current market, it seems reasonable to consider that the cooling production technologies are represented by 85 % electric-powered chillers and 15 % absorption chillers running with natural gas.

A new process was created within SimaPro (PRe Consultants, 2019) for the mix of marginal cooling technologies: a cooling energy unit (1 kWh) that considers 15 % of the production by the consequential process already defined in Ecoinvent v3.5 (natural gas) and 85 % of a newly defined consequential process with electric chillers (with marginal electricity production estimated for the 2022 Spanish market). The environmental impacts obtained for the current and short-term cooling mix technology are 101.92 $kgCO_{2eq}$/MWh_t and 3.20 pt./MWht (Table 4).

Following the procedure of electricity generation technologies, it is vital to establish the dynamics of space cooling technologies, focusing on the Spanish market. Following the rules of the ecoinvent database, only modern and new technologies are considered unconstrained.

The energy efficiency of cooling equipment worldwide has increased considerably in recent years because of advances in air-conditioning technology and shifting demands. The average seasonal energy efficiency ratio (SEER) of space cooling systems in the residential and commercial sector, weighted by sales, reached 4.2 in 2016, about 50 % higher than in 1990 (IEA, 2018). The performance of cooling systems will continue improving, although at a slow rate because the energy performance of vapor compression refrigeration cycles is limited by the laws of thermodynamics (IEA, 2018). Recent research has been focused on novel refrigerants to find an optimum combination of performance, safety, ease of use, total lifecycle cost, and lower environmental impact (AFEC, 2022).

There are currently wide variations in the efficiency of cooling systems. Improved and new regulations and more efficient production systems could reduce cooling energy consumption by as much as three to five times (IEA, 2018). In Spain, the individual cooling demand is supplied using primarily (small) split units, large split units, and chillers.

The selected mechanical chiller for systems A and B is model Cobalt W 153.3 from Swegon (Chillers with heat pump: Cobalt W, n.d.), with EER = 4.68 and SEER = 5.6. These values are considered at the high end of the range for current technologies but will remain at the low end in future decades. With a lifetime of 20 years, it is assumed that existing technologies will be more efficient in the future, with better environmental performance. Therefore, the environmental impacts of future technologies have been calculated considering the aforementioned efficiency values. These future technologies are considered the marginal technology for cooling production.

The estimated values for cooling marginal technology in the short-term and mid-term horizons have been modeled with SimaPro (Table 4). The mix of electricity marginal technologies used to power the chillers corresponds to those estimated in Tables 1 and 2.

The considerable drop in the environmental impacts of the technologies in the midterm is mainly due to the expected disappearance of natural gas-fired equipment. In the long term, it is foreseeable that the technical characteristics of the equipment will continue to improve, and technologies with EER = 8 are considered.

Table 4
Cooling marginal mix environmental results.

Time horizon	Chillers EER	Cooling marginal mix environmental results		Marginal electricity mix
		IPCC 2013 GWP 100y ($kgCO_2$ eq/MWht)	Recipe 2016 Endpoint (H/A) (pt/MWht)	
Short-term (current)	4.68	101.92	3.26	Current 2022
Mid-term (2030)	6.00	20.16	1.09	Target scenario 2020–2030
Long-term (2040)	8.00	9.59	0.67	Long-term 2020–2050 (Buyle et al., 2019)

Table 5
GHG emissions (IPCC 2013 GWP 100y), consequential perspective, short-term.

	SYSTEM A ($t\ CO_{2\ eq}/y$)	SYSTEM B ($t\ CO_{2\ eq}/y$)
Collector field	59.85	89.78
Heat transfer fluid	10.77	16.16
Thermal energy storage	73.10	142.92
Solar system	**143.73**	**248.86**
Biomass boiler	11.87	–
Chillers	16.70	16.70
Organic rankine cycle	7.62	12.54
Equipment	**179.91**	**278.10**
Pellets	46.41	–
Electricity (marginal)	−180.18	−243.77
Cooling (marginal)	−653.50	−653.50
Operation	**−787.27**	**−897.27**
Total system	**−607.37**	**−619.17**

Table 7
GHG emissions (IPCC 2013 GWP 100y), consequential perspective, mid-term.

	SYSTEM A ($t\ CO_{2\ eq}/y$)	SYSTEM B ($t\ CO_{2\ eq}/y$)
Equipment	**179.91**	**278.10**
Pellets	46.41	–
Electricity (marginal)	−139.97	−204.92
Cooling (marginal)	−129.29	−129.29
Operation	**−222.85**	**−334.21**
Total system	**−42.94**	**−56.11**

4. Results and discussion

4.1. Consequential perspective in the short term

The proposed power generation systems are expected to be built and commissioned within the next few years. For this purpose, the following inputs were required: i) mix of marginal electricity generation technologies estimated for 2022 (Table 3); ii) mix of marginal cooling generation technologies estimated for 2022 (short term, Table 4).

Table 5 presents the GHG emissions for systems A and B from a consequential perspective. Table 6 shows the consequential results for ReCipe 2016 EndPoint (H).

Although equipment causes significant environmental impacts, these are far outweighed by the effects avoided due to the system's operation. The consequences of building the energy system have, at least in its first years of operation, considerable environmental advantages. System A and System B present very similar results, with a slight edge for System B.

The results obtained for the ReCiPe indicator corroborate those obtained for the IPCC method, in which the results highly depend on the mix of cooling production technologies selected. In Table 6, System B has 27.3 % lower environmental impacts.

4.2. Consequential perspective in the mid-term

In this case, the proposed power generation systems are expected to be built and commissioned soon. For this purpose, the reference year is 2022 (when the decision is made), and the horizon year (when the product or system will reach the market) is 2030. The following inputs were required: i) mix of marginal electricity generation technologies estimated for 2030 (target scenario 2020–2030 for the Spanish market, Table 2), and ii) mix of marginal cooling generation technologies estimated for 2030 (Table 4). Table 7 presents the results for systems A and B considering the IPCC 2013 method.

The positive environmental consequences of building the proposed energy systems diminish over time due to the environmental impacts associated with electricity and the marginal cooling mixes. The annual impacts caused by the equipment have been practically neutralized, and the positive consequences of implementing the systems have almost disappeared.

Table 8 presents the results for the ReCipe 2016 EndPoint (H) method.

As with the IPCC method, the ReCiPe results show that the annual impacts caused by the equipment are nearly offset.

The results are strongly dependent on the selection of electric and cooling marginal technologies. Therefore, it seems much more realistic to consider a temporal variation of both parameters over the lifetime of the energy systems. Thus the environmental consequences of an energy system projected in 2022 will vary over its lifetime. This will require estimating the mix of marginal technologies over the next 20 years or lifetime of the system.

These results open a new line of discussion on the temporal variation of environmental impacts of an energy production system. This consideration can be applied to consequential LCAs but should also be considered for attributional LCAs.

4.3. Consequential perspective: variation of the mix of marginal technologies during the lifetime of the energy system

The lifetime of equipment varies from 20 years (biomass boiler, ORC, mechanical chillers) to 50 years (TES). An estimation of the annual environmental impacts has been made by varying the mix of marginal technologies for electricity and cooling production. It is assumed that the projected energy systems will come into operation in the current year, 2022, and will be in operation for 20 years, until 2042. The scenarios are shown in Table 9.

The yearly GHG emissions for each time scenario and each proposed power system are shown in Fig. 4. From the viewpoint of GHG emissions, the positive consequences are diluted over time.

Table 6
ReCiPe 2016 EndPoint (H) results, consequential perspective, short-term.

	SYSTEM A (kPt/y)				SYSTEM B (kPt/y)			
	Human health	Ecosystem	Resources	Total	Human health	Ecosystem	Resources	Total
Solar Field	2.300	0.279	0.027	2.605	3.450	0.418	0.040	3.908
Heat Transfer Fluid	0.570	0.038	0.008	0.616	0.855	0.057	0.011	0.923
Thermal energy storage	4.148	0.290	0.052	4.490	8.109	0.568	0.101	8.778
Solar system	**7.018**	**0.607**	**0.086**	**7.711**	**12.414**	**1.043**	**0.152**	**13.609**
Biomass boiler	0.491	0.028	0.007	0.526	–	–	–	–
Chillers	0.625	0.039	0.002	0.665	0.625	0.039	0.002	0.665
Organic Rankine Cycle	0.359	0.018	0.003	0.381	0.609	0.031	0.006	0.646
EQUIPMENT	**8.492**	**0.692**	**0.098**	**9.282**	**13.648**	**1.112**	**0.160**	**14.920**
Pellets	1.540	4.811	0.044	6.395	–	–	–	–
Electricity (marginal)	−7.776	−0.561	−0.100	−8.437	−10.521	−0.759	−0.135	−11.415
Cooling (marginal)	−18.973	−1.450	−0.517	−20.940	−18.973	−1.450	−0.517	−20.940
OPERATION	**−25.209**	**2.800**	**−0.573**	**−22.982**	**−29.494**	**−2.208**	**−0.652**	**−32.354**
TOTAL SYSTEM	**−16.717**	**3.493**	**−0.475**	**−13.699**	**−15.847**	**−1.096**	**−0.492**	**−17.434**

Table 8
ReCiPe 2016 EndPoint (H) results, consequential perspective, mid-term.

	SYSTEM A (kPt/y)				SYSTEM B (kPt/y)			
	Human health	Ecosystem	Resources	Total	Human health	Ecosystem	Resources	Total
EQUIPMENT	**8.492**	**0.692**	**0.098**	**9.282**	**13.648**	**1.112**	**0.160**	**14.920**
Pellets	1.540	4.811	0.044	6.395	–	–	–	–
Electricity (marginal)	−7.190	−0.516	−0.102	−7.808	−8.576	−0.834	−0.180	−9.590
Cooling (marginal)	−6.472	−0.460	−0.087	−7.018	−6.472	−0.460	−0.087	−7.018
OPERATION	**−12.122**	**3.835**	**−0.144**	**−8.431**	**−15.048**	**−1.294**	**−0.266**	**−16.608**
TOTAL SYSTEM	**−3.630**	**4.527**	**−0.046**	**0.852**	**−1.400**	**−0.181**	**−0.106**	**−1.688**

Table 9
Variation of electricity and cooling marginal mixes over time.

System operating time	Cooling marginal technology	Mix of marginal electricity production
2022–2026	Mix 85 % heat pump and 15 % absorption chiller at cogeneration unit Heat pump EER: 4.68	Mix of marginal technologies in Spain for current year 2022
2027–2031	100 % Heat pump, EER: 6	Mix of marginal technologies in Spain Target 2020–2030
2032–2036	100 % Heat pump, EER: 7	Mix of marginal technologies calculated with Buyle et al. (2019) data 2020–2040
2037–2042	100 % Heat pump, EER: 8	Mix of marginal technologies calculated with Buyle et al. (2019) data 2020–2050

Moreover, it could be the case that the proposed systems are not beneficial in the relatively near future (before the end of its lifetime).

The cumulative emissions over the entire lifetime of the systems are depicted in Fig. 5. It has been assumed that data do not vary over five-year periods.

The consequences of installing system A are highly favorable as avoided emissions of 2440.8 tCO_{2eq} are obtained, compared to 2323.9 tCO_{2eq} avoided by system B.

Figs. 6 and 7 show the impacts obtained by applying the ReCiPe method for systems A and B, respectively. The environmental impacts generated during the first years of the energy systems are negative, −13.7 kPt/y for system A and − 17.4 kPt/y for system B. After the first five years, system B presents good performance with negative impacts, but system A generates 0.9 kPt/y. After the third five-year period, both systems have positive impacts, with values of 5.5 kPt/y for system A and 2.7 kPt/y for system B. The human health category has the highest contribution, and the ecosystem category is fundamental in system A due to pellet consumption.

In this type of analysis, these results lead to another question: perhaps it would be more advisable to consider the impacts of the equipment in the first year of the system's lifetime only. This reflection can give a new interpretation of the results.

The cumulative impacts over the lifetime of the systems (20 years) are represented in Fig. 8, assuming that data do not vary over five-year periods. The consumption of pellets has a considerable negative impact on the results of system A, making this consumable responsible for the higher environmental impacts of this system.

The environmental impacts of both systems throughout their lifetimes are negative; therefore, the environmental consequences can be said to be favorable, system B with −70,7kPt and system A with −11.4kPt.

4.4. CLCA and ALCA

The results of the attributional LCA for systems A and B have been published and analyzed by Guillén-Lambea et al. (2022). The

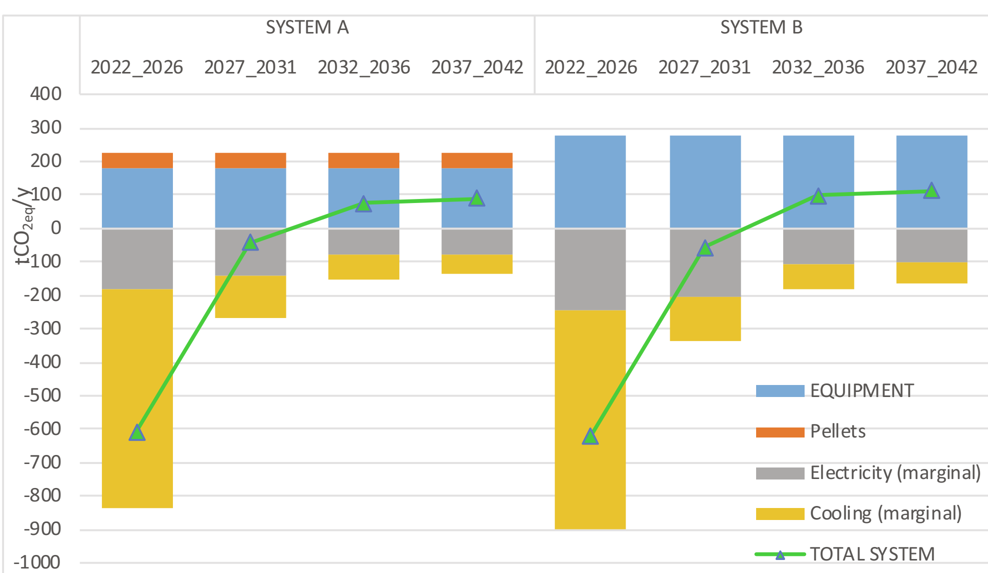

Fig. 4. GHG emissions (tCO_{2eq}/y) for each time scenario.

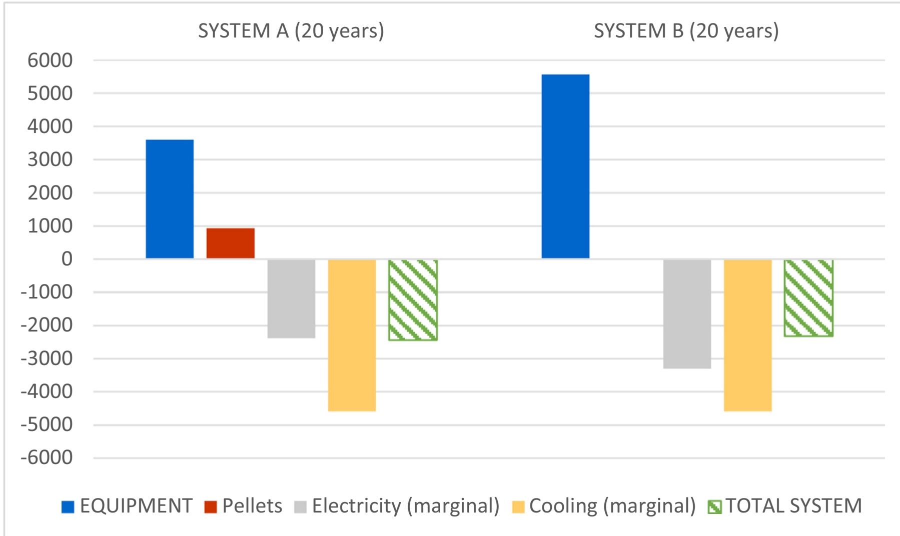

Fig. 5. Cumulative emissions (tCO_{2eq}) over the lifetime of the system, consequential perspective.

cumulative environmental impacts during the 20-year lifetime must be calculated to analyze the environmental results from a consequential perspective and relate them to those obtained from an attributional perspective. Table 10 (IPCC method) and Table 11 (ReCipe method) present the results for the two energy systems. It should be noted that the intention is not to compare the results directly but to interpret the results obtained from the two perspectives.

The IPCC results for the equipment from a consequential perspective are worse than the attributional perspective, with GHG emissions 15.8 % higher for system A and 13.2 % for system B. However, the impacts obtained with the Recipe method are lower from a consequential perspective, −8.8 % for system A and −6.4 % for system B.

The evolution of the Spanish electricity production system and the continuous improvements planned in the cooling production systems enable the conclusion that system B presents the best environmental performance from attributional and consequential perspectives. It is more advantageous to install systems with higher production of renewable electricity because although equipment has higher environmental impacts when considering the entire lifetime, the operation phase helps mitigate environmental results.

The results of ALCA show positive CO_2-eq emissions computed over 20 years of operation for both energy systems. However, CLCA yields negative emissions - indicating that the selection and implementation of both power systems has positive environmental consequences by accounting for emissions over the entire life cycle. It must be highlighted that the results obtained when applying the mix of marginal technologies in the short term are highly favorable and similar for both systems but might be too encouraging when compared to the emissions obtained by varying the mixes over time.

Finally, this study contributes to the ongoing discussion on the dynamics of energy systems and decarbonization targets. Once installed, an energy system should contribute to decarbonization and environmental objectives for as long as possible (ideally throughout its lifetime). However, there could be shifts in the energy technologies

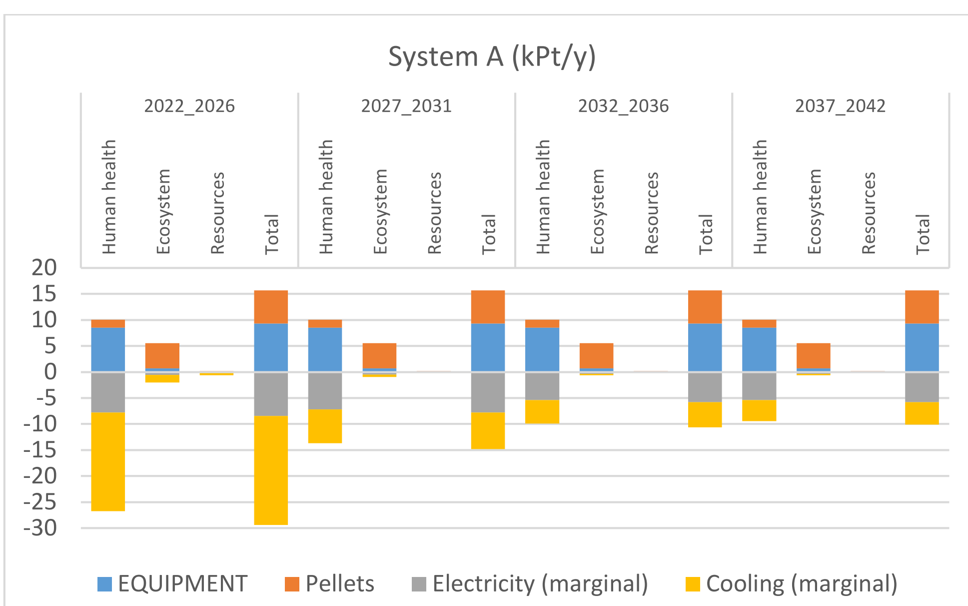

Fig. 6. ReCipe results (kPt/y) for each time scenario for System A.

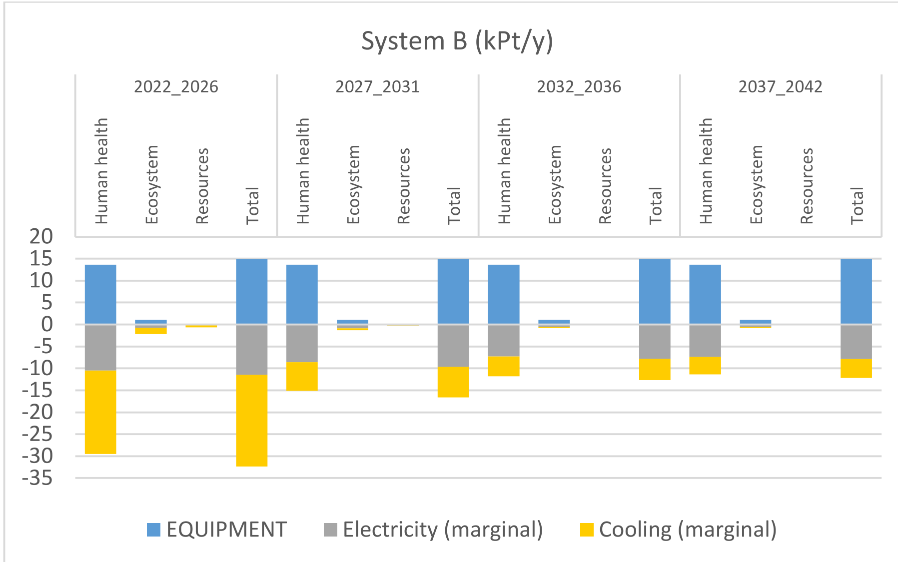

Fig. 7. ReCipe results (kPt/y) for each time scenario for System B.

displaced that could change the evolution of the avoided emissions. It was verified herein that this could occur around 2030–2035 (8–13 years after system installation), and the proposed system will cease to realize environmental benefits. A relevant contribution has been made herein by presenting a new way of evaluating power generation systems.

5. Conclusions

This work presents a CLCA and ALCA for power generation systems, accounting for environmental impacts throughout the lifetime of systems. The results strongly depend on the selection of marginal mix technologies for electric and cooling energy production.

This study highlighted the intricacies involved in the Life Cycle Assessment of electricity mixes, focusing on the consequential approach. Establishing a mix of marginal technologies for electricity generation was not straightforward, hindering the drawing of more general conclusions.

The marginal mixes of electricity and cooling were estimated using three different time horizons: short-term, mid-term, and long-term. The results obtained when varying the marginal energy mixes (electricity and cooling) over time are also presented. The CLCA results for the short-term horizon are very encouraging; however, these positive consequences are diluted over time when considering the variation of marginal mixes throughout the lifetime of the energy systems. When attempting to define the extension of the potential minimization of emissions throughout the lifetime of the energy system, the results indicate that soon (2030–2035), there will be a change in the emissions balance. This means that although the proposed energy systems start by making positive contributions, they stop contributing to minimizing emissions in the near future, hindering further decarbonization and environmental benefits.

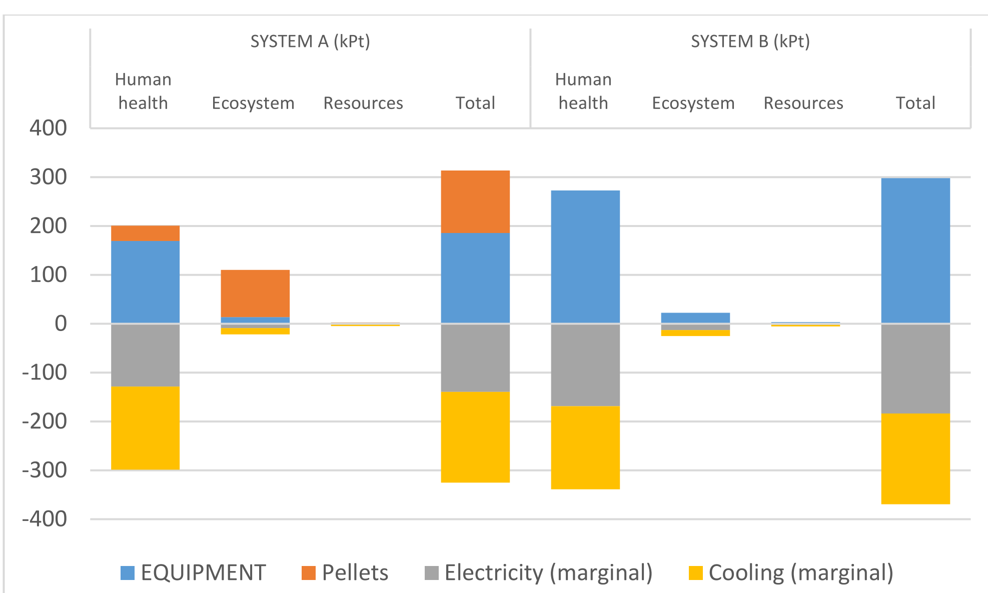

Fig. 8. ReCiPe cumulative impacts (kPt) over the system lifetime, consequential perspective.

Table 10
Cumulative emissions (IPCC).

		Equipment	Pellets	Electricity	Cooling	Operation	**Total system**
SYSTEM A (t CO_{2eq})	ALCA	3106.6	882.8	608.8	–	1491.6	**4598.4**
	CLCA short time	3598.2	928.2	−3603.6	−13,070.0	−15,745.4	**−12,147.4**
	CLCA mid-time	3598.1	928.1	−2799.4	−2585.7	−4457.0	**−858.9**
	CLCA variation	3598.1	928.1	−2383.2	−4583.9	−6039.0	**−2440.8**
SYSTEM B (t CO_{2eq})	ALCA	4915.0	–	−811.8	–	−811.8	**4103.0**
	CLCA short time	5562.0	–	−4875.4	−13,070.0	−17,945.4	**−12,383.4**
	CLCA mid-time	5562.0	–	−4098.5	−2585.7	−6684.2	**−1122.2**
	CLCA variation	5562.0	–	−3302.0	−4583.9	−7885.9	**−2324.0**

Table 11
Cumulative impacts (ReCiPe).

		Equipment	Pellets	Electricity	Cooling	Operation	**Total system**
SYSTEM A (kPt)	ALCA	203.6	28.8	28.8	–	153.2	**356.8**
	CLCA short time	185.6	128.0	−168.8	−418.8	−459.6	**−274.0**
	CLCA mid-time	185.6	128.0	−156.2	−140.4	−168.6	**17.0**
	CLCA variation	185.6	127.9	−139.2	−185.8	−197.0	**−11.4**
SYSTEM B (kPt)	ALCA	318.8	–	−38.4	–	−38.4	**280.4**
	CLCA short time	298.4	–	−228.2	−418.8	−647.0	**−348.6**
	CLCA mid-time	298.4	–	−191.8	−140.4	−332.2	**−33.8**
	CLCA variation	298.4	–	−183.4	−185.8	−369.2	**−70.7**

An important question raised as a consequence of this research, which must be addressed in more detail by future work, regards using a fixed energy mix throughout the lifetime of products (either average or marginal). This study demonstrated that the environmental performance of power generation systems was strongly affected when the energy mix varied with time.

It is relevant and perhaps indispensable to perform consequential LCAs of power generation systems, despite the lack of robustness in the definition of marginal technologies and straightforward procedure for estimating marginal energy mixes.

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Declaration of competing interest

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

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