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Review article

Environmental assessment of smart energy management systems at distribution level — A review

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ABSTRACT

The global transition from traditional electrical grids to smart grids is well underway: the primary objective of smart grids is to optimize energy flows, achieving improved energy efficiency through better integration of renewable sources, reduced reliance on environmentally harmful production methods, and enhanced utilization of emerging energy technologies. This aims to decrease unnecessary consumption, reducing the difference between the power consumption and the actual user needs. The fundamental and stated goal is to minimize the overall environmental impact of the energy sector.

However, these smart systems rely heavily on Information and Communication Technology (ICT), raising concerns about the overall environmental impact. This study seeks therefore to comprehensively review existing literature to assess how environmental considerations are tackled into current research on energy management systems at the distribution grid level, and the extent to which it aligns with actual challenges.

Two key findings emerge: first, the current smart grid research tends to focus on cost optimization and not on directly addressing environmental challenges. Secondly, when environmental considerations are addressed, there is no consensus on the positive or negative impact of these systems. Concerns arise regarding potential additional burdens due to impact transfers and rebound effects.

In conclusion, the review emphasizes the need for further research and a more thorough incorporation of environmental considerations in future smart grid development. Key recommendations for future development include the urgency to establish standard interdisciplinary methodologies and systematically measure the embodied impact of developed energy management systems to ensure a sustainable and ecologically responsible transition.

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1. Introduction

Environmental changes are for a long time a pressing matter of concerns and a call for deep changes in our society. This impacts the energy sector, transitioning from a massive central production to a decentralize and local production, mostly relying on renewable energy sources and distributed energy resources. To achieve this transition and enable a seamless integration of those energies, the entire electric system is shifting towards more intelligence [1], integrating new technology of energy as well. Thus, new paradigms and research domain arose, from smart grids to smart homes, developing new energy management strategies to account for those changes and to decrease the environmental impact of the sector.

However, the paradigm shift and the effective implementation of advanced energy management systems crucially depend on the widespread integration of Information and Communication Technologies (ICTs) [2]. These technologies encompass sensors, servers, communication networks, processing capabilities, and remote control systems, which collectively facilitate the monitoring, prediction, optimization, control, and intelligent operation of energy systems [3].

Nonetheless, there is a growing concern regarding the environmental implications of deploying these novel technologies [4] and allocating resources to transition towards a higher proportion of renewable energy sources. This concern is exacerbated by the mounting global challenges of climate change and environmental issues, as evident in the breach of six out of the nine planetary boundaries at the moment [5].

Consequently, there is an urgent need to accelerate the transition towards a cleaner energy production and use. This urgency leads a fundamental yet unaddressed inquiry concerning smart grids: “*What is the overall environmental impact of smart energy management systems?*” There is a legitimate apprehension that the incorporation of additional technology and resources to achieve smartness and enable cleaner energy mixes may potentially counterbalance the environmental benefits.

With existing methods to assess the environmental impacts along various categories not limited to greenhouse gases (GHG), the most widely accepted and scientifically rigorous approach being Life Cycle Assessment (LCA), today’s environmental challenges necessitate the exploration of improved solutions in energy grids. However, the question of environmental impact is not novel, and prior key work in this domain are worth studying.

In 2009, Hledik et al. [6] directly addressed the question “How green is the smart grid?”. By applying their approach to the U.S. power system, their results indicate that the adoption of either a conservative or more technologically ambitious smart grid approach would lead to a substantial reduction in national-level carbon emissions in the power sector, with the potential for reductions of 5% and 16%, respectively, by 2030 at the national scale. However, it is important to note that this study exclusively considers the CO2 impact during the use phase (only the direct emissions) and does not account for the additional technology requirements. Indeed, it considers neither CO2 emissions during the whole lifetime nor the other environmental impacts. Regarding environmental issues presented in Section 3, this value is insufficient to asses the global impact of a smart grid.

One of the earliest studies on real-world cases, examining the impact of smart energy management systems in the Dutch context and often cited in literature reviews, is the work of Vandam et al. [7] from a decade ago. The authors compared three different home energy management systems (HEMS) using LCA and demonstrated that the environmental benefits do not always outweigh the associated costs, depending on the utilization of each system.

In 2014, two notable literature reviews stand out concerning this subject. The first indirectly addresses smart grids, with an emphasis on the environmental impact of Information and Communication Technology (ICT) [4]. The authors highlight the limitations of environmental studies on ICT and strongly recommend considering a broader range of impacts, encompassing human and toxicological aspects, e-waste management, user behavior, rebound effects, and other indirect consequences. The second study focuses on the sustainability of smart systems and underscores the absence of methodologies for assessing the indirect impacts of the involved technologies, emphasizing the need for interdisciplinary approaches [8].

Continuing the discussion in 2017, Moretti et al. [9] summarized and compared the methodologies employed for the economic and environmental evaluation of smart grids in general. Their findings revealed significant variations in results, but they concluded that smart grids contribute to energy and GHG savings due to the extensive deployment of renewable energies. Similar to previous studies, the authors highlighted the lack of standardized methods for assessing the impacts of smart grid systems. Nevertheless, it is important to note that this study targets smart grids in general, without a specific application focus, and does not address the impact of additional technologies or impacts beyond GHG emissions. Consequently, drawing conclusions on the overall environmental issues is challenging, as these concerns extend beyond those emissions.

Most recently, in 2022, Lamnatou et al. [10] conducted a review of research articles on smart grids with a short focus, amongst other consideration, on environmental impact with pre-2016 studies. While emphasizing energy and GHG savings, the authors noted the absence of a comprehensive methodology, especially for incorporating other indicators, while noting that “*the combination of Renewable Energy Sources and smart grids offers many environmental benefits*”. In practice, consequently, drawing definitive conclusions on environmental benefits from these reviews remains challenging.

Abbreviations

EMS	Energy Management System
ESS	Energy Storage System
EV	Electric Vehicle
GHG	Greenhouse Gas
GWP	Global Warming Potential
HEMS	Home Energy Management System
ICT	Information and Communication Technology
IoT	Internet of Things
LCA	Life Cycle Assessment
PV	Photovoltaic
REN	Renewable Energy
SB	Smart Building
SC	Smart City
SG	Smart Grid

From the literature discussed, finding clear answers to the environmental impact of smart grids is a complex task. Existing global studies often do not consider specific smart grid applications or all the parameters involved. This absence of specificity hinders the ability to draw conclusions, to reach a consensus, or to effectively redirect smart grid research in light of the existing methodologies. As a result, there is no comprehensive understanding of environmental challenges on one hand, and on the other, there is a lack of clarity regarding how this issue is addressed in smart grid literature, making it imperative to define and comprehend the existing gap. Therefore, an update to these reviews is required to understand the current trajectory of research and provide a comprehensive understanding of the real impact of smart systems, focusing on specific applications.

To address this problem, the aim of this research is to analyze the gap between existing studies on energy management within smart grids and the actual environmental challenges that motivate it. This work provides recommendation and guideline for future research efforts to fill this gap.

Indeed, the hypothesis behind this review is that the literature on energy management does not systematically evaluate environmental impact of the proposed solutions. It is therefore impossible to assess whether the current research provides a relevant response to the underlying environmental issue at the root of it. Additionally, existing reviews on the matter do not allow for comparisons on equal grounds due to differing scopes, lack of comprehensiveness, and/or focus on a single indicator, thus hindering the identification of gaps or the derivation of clear research directions. The practical resulting implication of this review is to enable and guide research, industry, and policy makers to ensure an adequate and effective future effort regarding the environmental question, by limiting potential impact transfers.

Consequently, the novelty and contribution of this work are threefold:

1. after repositioning the actual environmental challenges in the smart grid domain, this study reviews how the environmental question is addressed in current smart grid literature,
2. then draws a parallel between the former and the latter to highlight and discuss missing gaps,
3. and finally offers precise future research directions and recommendations.

To achieve this, this work focuses on energy management systems at the distribution grid level (see methodology and boundaries in Section 2), and updates existing reviews with recent literature, extending the analysis beyond GHG emissions, and examining how recent research addresses this concern, by comparing current environmental challenges, the stated motivations behind energy management research, and the actual goals and outcomes of these studies. To the best of our knowledge, no prior effort has sought to provide this parallel between contemporary challenges and the objectives pursued in the literature.

To achieve this, the overall method followed throughout this review is the following:

1. Define today's environmental issues that necessitate action.
2. Examine if and how the literature on Energy Management Systems (EMS) positions and responds to these issues.
3. Review the impact studies on all relevant aspects, whether comprehensive or partial, and assess the possibility of reaching a consensus.
4. Propose recommendations to address identified gaps in the literature regarding environmental issues.

Based on this method, this review is structured as follows: First, the review methodology is presented in Section 2, before repositioning the actual environmental problem in Section 3. Next, this work explores how these environmental considerations are integrated into research on energy management in smart grids (stated objectives, concrete optimization goals and final environmental impacts) in Section 4. This study then reviews the literature on the environmental impact of smart grids in Section 5 and the rebound effect in Section 6, before discussing the gaps in current research and offering recommendations for future work in Section 7.

2. Methodology and perimeter

The focus of this review is on Energy Management System (EMS). An EMS is a comprehensive system designed to monitor, control, and optimize energy usage within various contexts, such as commercial buildings, industrial facilities, or entire utility grids. At its core, an EMS typically consists of hardware and software components that collect and analyze energy data from various sources, such as meters, sensors, and control devices. This data is then used to provide insights into energy consumption patterns, identify areas of inefficiency, and implement strategies to improve energy efficiency and reduce costs. Home Energy Management System (HEMS) is the application of EMS in the residential sector, at the scale of an household. Fig. 1 presents an example of the main component constituting an HEMS.

The overall methodology explained in this section is summarized and represented in Fig. 2. This research is based on a literature review conducted through the following online scientific libraries: IEEE Explore, Science Direct, and google scholar. The survey is limited to include relevant journal literature (therefore excluding conference papers) up to the last 5 years (from 2018 onwards) on energy management in smart grids for consumers at the distribution level, using the following keywords in different combinations: *smart grids*, *LCA*, *Energy Management*, *EMS*, *Home Energy Management System*, *HEMS*, *environmental impact*. To account for research prior 2018, three literature review

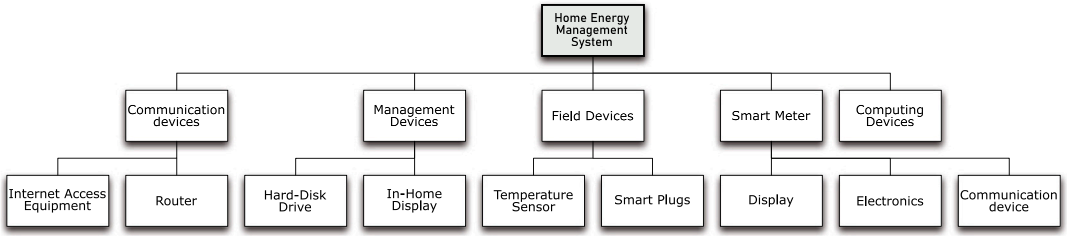


Fig. 1. Example of ICTs involved in an HEMS [11].

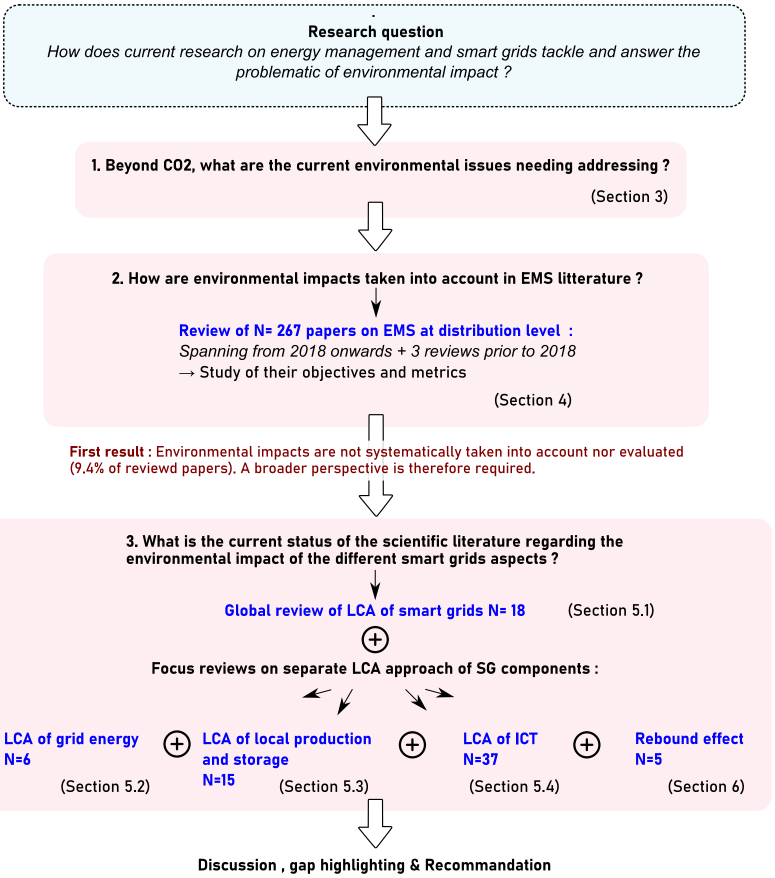


Fig. 2. Summary of research questions and used methodology.

on the subject of EMS have also been included: [12,13], and [14] for energy management in residential sector based on the integration of electric vehicle. Within these five year, a special focus has been placed on more recent year (2022 and 2023) to complete with the most up to date articles the literature review of Section 5, in order to grasp the global motivation and objectives of latest research on energy management in smart grids through the high number of articles on the subject, selecting only the most relevant. An examination has been conducted to ensure that there is no overlap between the reviewed articles and those extracted from literature reviews. Regarding the use of LCA in smartgrid issues, the literature review covers the last 10 years (from 2013 onwards).

As only the distribution level was considered, this perimeter for this selection includes the following applications of the smart grids concept: residential buildings, smart buildings, smart city, electric vehicle, production–consumption balance, integration of renewable, home energy management system (HEMS). Are excluded from this review the research on smart grid for industry and transportation network, stand-alone and off-grid solutions, multi-energy management, as well as study case where the main priority is electricity access (remote areas, disaster-stricken areas ...). In particular, energy management in stand-alone/off-grid micro-grid is not considered in this work, as the main issue is not the same as on the main grid (On this particular subject, an in-depth literature review is proposed by the authors of [15]). As the focus is on energy management at the end of the network, this review also excludes research on smart technology for the grid itself such as transformers, breakers, substation, voltage and frequency control ...

Furthermore, the main focus is to establish a state of the art of the research on EMS, this encompass technical publications and scarce insights on sociological perspectives when collaboration occurred but is not comprehensive in terms of humanities and economy perspectives. While acknowledging that this literature search may not encompass all publications regarding the environmental impact of energy management in smart grids, it is considered to be sufficiently comprehensive to draw some overall conclusions aligned with the objectives of this review. A critic of the proposed state of the art is discussed in Section 7.1.

3. Environmental status and definitions

3.1. Life cycle assessment

Life Cycle Assessment (LCA) is a comprehensive methodology used to evaluate the environmental impacts of a product, process, or technology throughout its entire life cycle. It provides a holistic approach by considering all stages of a product or system's life cycle, including raw material extraction, manufacturing, transportation, usage, and end-of-life disposal. An LCA is standardized by ISO 14040:2006 and ISO 14044:2006 and includes four phases:

1. Goal and Scope Definition.
2. Life Cycle Inventory (LCI).
3. Life Cycle Impact Assessment (LCIA).
4. Interpretation.

In the context of our research, LCA is crucial to understanding the environmental implications associated with the implementation, operation, and eventual decommissioning of advanced energy management ICT-based infrastructure. However, the limitations of this approach must be borne in mind: LCA method quantify the impacts in a specific context, making it suitable for short-term decisions. It is a static tool that does not permit to make dynamic assessment in scenarios for mid and long terms.

3.2. Climate change and CO_2 emissions

The primary goal of smart grid deployment is to mitigate the environmental impact of energy consumption, commonly quantified through Greenhouse Gas Emissions (GHG), often simplified to CO_2 emissions. Monitoring anthropic CO_2 emissions is crucial due to their role in climate change. The electricity sector is particularly concerned by the CO_2 emissions as electricity production is responsible for approximately 40% of the global emissions. Analyzing CO_2 emissions is challenging, and the main complexity to calculate the carbon footprint of a product or solution lies in its dependency on the chosen time scale within its life-cycle. The Greenhouse Gas Protocol [16], suggest to choose a scope of mitigation among three standard scopes (Scope 1, 2, and 3). Scope 1 concerns direct emissions, as illustrated by the use of the Eco2mix tool from the French transmission system operator RTE [17]. The direct CO_2 emissions are in this context a relevant indicator as they are supposed to represent the state of the grid at a given time. Scope 3 exploration becomes more relevant, by encompassing indirect emissions from raw material extraction to end-of-life. The French Agency for Ecological Transition provides a Scope 3 carbon database [18]. The Life Cycle Assessment (LCA) method, considering a product's manufacturing and its end-of-life impact is also based on the scope 3.

3.3. Climate change and global warming potential

At this stage, only CO_2 emissions have been introduced. Other gases, along with anthropogenic sources of emissions, are responsible for the impact of the greenhouse effect on the global climate. This is the case for methane (CH_4) and nitrogen oxides (NO_x). Contrary to the CO_2, these gases are chemically decomposed in the atmosphere and thus have different lifetime and cycles. To facilitate the estimation of their impact on global climate change, the CO2 equivalent (CO_{2eq}) is used to calculate the global warming potential. The global warming potential (GWP) represents the energy absorption by the emissions of one ton of a particular gas during a specified time frame, typically over 100 years, in comparison to the emissions of one ton of carbon dioxide (CO2). Thus this permits to estimate the impact of a gas on the climate change, considering its own cycle in the environment. In order to estimate the impact of energy consumption on the climate change, it is necessary to consider the scope 3 for all the Greenhouse gas emissions, which can be a substantial task.

3.4. What about global environmental impact?

The complexity of assessing environmental impact takes a step forward when considering global effects of human's activities on the environment. Attempting to solve climate change may shift the environmental burden, as exemplified in discussions around metal extraction for renewable energies and smart grids. In [19], the authors estimate GHG emissions from copper extraction and propose solutions to mitigate the mining sector's impact, revealing ongoing debates on the sector's growth. Resource depletion is an other indicator of the impact of human's activities on the environment. This question is raised for the energy transition, with the french transmission system operator report [20] discussing uncertainties in metal supply necessary to the energy transition in France. According to the report [21], the question of the resources is not a stock problem but a fluxes one. The question is not really whether there are enough resources but whether the ability to extract the resources in time considering the growth of the demand for a fast transition. Beyond resource availability, considering the broader impacts of an activity is essential for societal development strategies. In energy production, mining can significantly damage the environment and human health, exemplified by the Fundão tailings dam failure (2015) [22].

For a more global assessment of the impact on the environment, [23] identifies nine planetary boundaries, thresholds beyond which Earth's system could destabilize. By crossing these boundaries, the Holocene stability period could be compromised, affecting the development of human society. The principal constraint lies in overtaking one boundary may affect another. For instance, crossing the land system change boundary could affect the biosphere integrity. Relatively to the energy transition, [24] presents the impact of the mining sector growth on the biodiversity. The biosphere integrity boundary could, in turn, affect the climate change boundary by reducing the carbon sink of biosphere as it is explained in the IPCC report 'The physical sciences basis, chapter 5' [25]. Examining how the energy transition affects these boundaries is crucial, with awareness that six of the nine have already been crossed [5].

3.5. How to take a decision based on environmental impacts?

Finally, some models permit to elaborate scenarios to assist decision-making in terms of energy. These models are named Integrated Assessment Models (IAM). The two Integrated Assessment Models (IAMs) with the most significant scientific impact are the World 3 model, upon which the book *The Limits of Growth* is based [26], and the DICE model [27], which provides nuanced results. Some of other models are presented in [28], in which the authors provide a literature review on the subject. It is important to notice that these are only mathematical model based on hypothesis known at a certain time, but integrating the whole environmental impacts is very challenging as some feedback loops exist. These loops brings uncertainties as they have not already been observed as the Earth's system evolved constantly.

Quantifying the environmental footprint can be challenging and requires expertise in various disciplines (such as climate science chemistry, water and soil chemistry, Biology, …). Assessing environmental impact requires a collaboration between experts in all fields of science. This is why the work of IPCC is one of the significant scientific contribution in history. Considering the impacts of an economic activity is, on one hand, very challenging and exhaustive, but in the other hand, is necessary in order to contain the damages made on the system earth. That is why solutions developed to address one specific environmental problem should check if they do not destabilize another indicator of environmental stability.

4. Objectives of energy management in smart grids

4.1. Stated motives for smart grid research

First, a review of the latest articles on energy management in smart grids helps us understand the stated motives behind these studies,

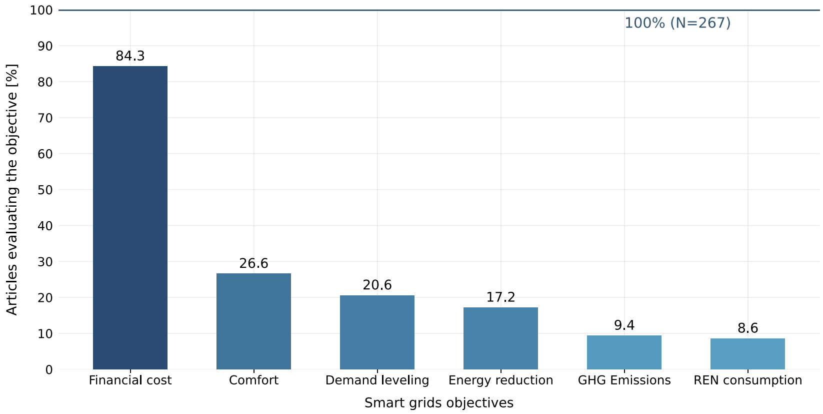


Fig. 3. Objectives repartition of energy managements strategies in smart grids (Review of 267 articles).

regrouped in Table 1. For each article, the overall objective and motivation behind the proposed research (as presented in each introduction) are differentiated from the actual objective of the proposed energy management (defined as mathematical objectives during the optimization). The majority of these articles (97%) present the main motivation for their research in an adapted version of the following statement: *Given the current environmental situation and the significant impact of the energy sector on the planet, there is a growing need to incorporate renewable energy sources into the electricity mix. However, achieving this integration requires the implementation of better production integration and demand-side management, which is where smart grids come into play, by enabling energy management strategies that meet these challenges.* Some highlight also (alone or in parallel with the environmental and climate crisis) the increased energy demand at the world scale, that must therefore be covered with sustainable production.

However, taking a broader perspective, it becomes evident that the environmental aspect is not a prominent focus in many studies within this field, as observed in the following section. This can be illustrated by the following example: Climate change is cited in 2012 as the driver for the electrical network transition towards smart grids in a special issue of *Applied Energy* [29]. Citing this later research however, a review of 459 Smart grid project in Europe in 2015 never mention any environmental fallout of the observed SG [30].

It is therefore interesting to see how this motivation has been effectively translated into proposals and research results in the reviewed literature.

4.2. Objectives of optimization in energy management

Energy management in a smart grid is based on optimizing decision variables (energy flows) in order to achieve precise objectives and maximize or minimize indicators. There are numerous optimization techniques for energy management, but they differ mainly in the way in which the problem is formulated (considered stakeholders, size, communication means, production means, level of centralization, …). For a more in-depth treatment of this specific point, the interested reader can refer to the recent literature review on the subject [15,31]. It should also be noted the rise of artificial intelligence techniques in this field, opening up new possibilities, particularly for solving complex problems or those involving a large number of variables [32,33]. Since climate change and the reduction of environmental impact are the motivation for research on smart grids, as presented in Section 4.1, it is interesting to see how these concerns and objectives are reflected into the energy management solutions proposed by scientific research. Table 1 summarizes the findings of the review of 267 studies on energy management.

To regroup these findings on energy management objectives, Fig. 3 regroup the number of reviewed studies for per objective. It should be noted that each EMS may have more than one objective and therefore be counted in different categories. Furthermore, it should be kept in mind than one objective may influence other (eg.: a decrease of consumption leads to bill reduction, or a bill reduction in a dynamic pricing scheme may help the integration of REN, …) but the goal is to highlight the direct objectives pursued by the different proposed algorithm.

Objectives will be reviewed in order of importance, and the consideration of the environment will be assessed. All articles refer to smart grids, a precision on the perimeter is given in Table 1, to specify if the focus is at the general grid level (SG) or more locally at city scale (SC), neighborhood or even house scale (HEMS), or building scale in general (Smart building (SB) for residential, tertiary, industrial, or the three of them mixed). Additional equipment considered are Energy Storage Systems (ESS), EV (Electric Vehicle), Renewable production (REN).

4.2.1. Financial cost

From the observed literature, cost minimization is the most pursued goal (84.3% of the reviewed studies) as price is the main lever of EMS, especially for demand response program in residential smart grids [34,35]. This category actually represents different objectives for different stakeholder and different perspectives for researchers. The literature offers a variety of price related objective: decreasing the tariff if it is in line with demand or production [36,37], maximizing profit for the consider stakeholder (consumer, building manager owner, retailer, producer, parking lot manager, aggregator) [38], lowering the price for the community [37], reduce maintenance costs [39], reduce investment costs, reduce load curtailment cost [40].

This over-representation of price in the sought objectives can be explained by several factors: it is the most simple, meaningful and direct indicator in the relationship between consumer, producer and retailer and the first lever consumers use to choose between the offers they receive. New energy management systems seek therefore to optimize this parameter and to find the appropriate business model (appropriate as “profitable for all stakeholders”) in the current or future legislative framework. For example, studying the interaction of smart houses in a smart city, using Particle Swarm Optimization (PSO), [41] reaches reduction of house electricity bill from 2.4 to 26.2%.

Indeed, price signal helps guide consumers’ choices, depending on the type of production or grid constraints. This objective is therefore not unrelated to environmental concerns as it may support the integration of renewables: e.g. [38] minimizes the aggregated electricity bill of all smart home consumers in the neighborhood area by increasing the utilization of local renewable energy generation. For this purpose, the proposed pricing scheme is a combination of time of use pricing, Feed-in tariff and incentives.

The main barrier to assessing the effectiveness of the inclusion of this objective in terms of environmental impact, when used expressively for this purpose, is that this impact are retrospectively never assessed in any of the reviewed research in Table 1.

Table 1
Main characteristics of the reviewed publications on smart grids objectives (N = 267).

Year	Perimeter	N	Cost	Comfort	Leveling	GHG	REN	Energy	Others	Ref.
2015	HEMS	1	1		1					[42]
2015	HEMS	65	53	38		2		13		[12]
2017	HEMS	1	1		1					[43]
2017	SC	1	1			1				[44]
2017	SG	3	3			1	2	2		[45]
2018	HEMS	1	1	1		1				[46]
2018	HEMS	1	1	1			1			[47]
2018	SG	1	1			1				[48]
2018	SG at all scales	5	5		3	2	1	1		[49]
2019	SG	1	1		1	1				[50]
2020	HEMS	1	1	1	1		1			[51]
2020	EV	1	1		1			1		[52]
2020	SG	1	1			1				[53]
2021	HEMS	8	7	2				4		[54]
2021	SG + REN + ESS	1	1			1	1		1	[55]
2021	HEMS	1	1			1				[56]
2021	SB	16	15	12	4	2		2		[32]
2021	EV	1				1				[57]
2022	EV	102	87	3	19	5	3	11	6	[14]
2022	HEMS + PV + ESS	1	1							[37]
2022	HEMS	1	1	1	1					[58]
2022	Mix SB	1	1		1			1	1	[59]
2022	Mix SB	1					1			[60]
2022	Mix SB + EV	1	1							[61]
2022	HEMS + EV + PV	1	1		1					[62]
2022	SG + REN + ESS	1	1	1	1		1		1	[63]
2022	HEMS	1	1		1					[64]
2022	HEMS + EV	1				1		1	1	[65]
2022	SG	1	1				1			[66]
2022	Market scale	3	2				2		2	[67]
2022	SG at regional scale	1					1		1	[39]
2022	HEMS	1	1	1			1			[31]
2022	HEMS	1	1	1			1			[68]
2022	SG + REN	1					1			[69]
2022	SG	1	1							[70]
2022	HEMS	1	1	1		1				[40]
2022	SB + EV + ESS	1	1	1						[71]
2023	HEMS + EV + REN	1	1		1					[41]
2023	HEMS + REN	1	1				1			[38]
2023	HEMS + REN + ESS	1					1			[72]
2023	SB + ENR + ESS	1	1		1					[36]
2023	HEMS	1	1			1				[73]
2023	HEMS + REN + ESS	1	1	1	1			1		[74]
2023	HEMS + REN + ESS	22	17	3	14	1		7	1	[75]
2023	HEMS+REN+ESS+EV	1	1			1				[76]
2023	SG at regional scale	1	1				1			[77]
2023	HEMS + EV	1	1	1				1		[78]
2023	HEMS + EV + ENR	1	1		1		1			[79]
2023	HEMS + PV	1		1			1			[80]
2023	HEMS	1	1	1	1					[81]
2023	HEMS	1	1					1		[82]

4.2.2. Comfort

The second most observed objective, but far behind cost, is the user/consumer comfort (26.6% of the reviewed studies). This search for comfort also encompasses many underlying objectives: planning equipment as closely as possible to the user's wishes, keeping the temperature of the dwelling/building within an acceptable range [47,71], charge of the EV at the desired state of charge at a chosen time [71], or respecting user preferences in terms of electricity source [51] or time of use of their appliances [58].

To cite but one: In a previous publication on DSM in the residential sector [51], we proposed for example a parameter of flexibility, representing the accepted time shift of the consumer appliances, and a parameter of REN consumption, resulting in a comfort-metric measuring the final shift between devices and their initial planning and a satisfaction metric measuring the percentage of energy consumed from REN sources.

Although not related to the environmental aspect, this second place of comfort amidst optimization objectives can be explained. This is because, in the absence of a legal or contractual obligation, a loss of user comfort influences them to override direct load control system or even leads to disengagement from DSM program [35].

4.2.3. Demand leveling

Third observed objective (20.6% of the reviewed studies), smoothing the load curve enables to decrease the peak as well as unpredictable fluctuation. In addition to preventing energy congestion in the grid, decreasing peaks also may restrict the short-term use of polluting and costly production means and postpones the construction of larger infrastructures in the long term. The most used metric is the Peak to Average Ratio, presented for example in [78], as the ratio of peak power to the average power of load curve. Achieving a Peak to Average Ratio reduction involves a quadratic formulation of the objective function to be minimized, as observed for example in [51,62].

Although often directly associated with positive environmental benefits (but it depends on the mix in question [83]), the extend of a positive environmental gain is not measured in the reviewed literature.

4.2.4. Energy reduction/consumption losses

One of the most direct approaches to reducing the impact of the energy sector is the reduction of energy consumption, which is however not the priority for the presented EMS. Although present at 5th place in the rankings (see on Fig. 3), it does not aim to reduce direct consumption by consumers, as all reviewed EMS work at constant energy. In the concerned research, it refers to *energy efficiency*, either as the energy efficiency of the required IoT infrastructure [74], as losses reduction [59,61,78,82], or, as explained in [45]:

> *These significant limitations of the classical definition of energy efficiency highlight the need to shift to a new ‘environmental efficiency’ concept that is capable of capturing the flexibility inherent in smart multi-energy buildings to actively respond to dynamic prices, carbon intensities and system needs.*

An example of this revised definition is presented in [65], where the authors manage to decrease the primary energy consumption by optimizing the use of combined heat and power, PV and EV, without affecting the district energy consumption.

4.2.5. GHG emission/impact

Environmental impact, always cited as a driver for research, as explained in Section 4.1, is directly presented in 9.4% of the reviewed studies. Proposed EMS including the environmental impact refer in fact to greenhouse gas emissions (GHG) of the consumed energy. The methodology observed in 88% of the literature is to include the GHG content of energy for each source on their entire life cycle (and the average content for the energy taken from the grid) expressed in terms of equivalent-CO_2, and the optimization of energy flows minimizes the total emission. Based on this method, the authors of [56] reached for example up to 38% of GHG reduction.

To take this method a step further besides CO2, the same way of reducing emission may be extended to other GHG: e.g. [55] includes CO_2, SO_2, NO_2 for each kWh from the grid and each distributed generation system, and reaches reduction of these GHG between 13 and 19%. The limit of these approaches, is that the average GHG content of grid electricity is not representative of real-time impact of consumed electricity [84]. Therefore, the authors of [57] use the marginal GHG content of electricity to account more precisely for the actual effect of energy production at a given time of the day, and reach a decrease of 6% of GHG emission while charging EV.

From this literature, the range of GHG emission decrease range from 2% to 64%, and due to the small number of studies on the whole corpus, it is difficult to conclude on the effectiveness of these management techniques in terms of environmental impact. In addition, the life cycle impact of the required technology (IoT, servers, infrastructure, …) to support the proposed EMS is not taken into account. The next Section 5 will explore the current research on these particular questions.

4.2.6. REN integration and consumption

In the scope of this review, the integration of renewable energies is scarcely represented in mathematical formulation of objectives functions (8.6% of the reviewed literature). This can be explained for three reasons: firstly, this objective is rather directly related to grid-disconnectable microgrids (not in the scope of this review) [15]. Secondly, REN consumption and integration can be included in the optimization process as a constraint rather than an objective. And finally, this objective may be already taken into account through cost or emissions reduction objectives, as explained previously in Sections 4.2.1 and 4.2.5 respectively. Both of those objective can even be pursued at the same time to favor the integration of REN [55].

However, with the evolution of energy market and especially the emergence of citizens and renewable energy communities introduced by the *Clean energy for all Europeans package* (with the Renewable Energy Directive (RED II) in 2018), the REN integration is supported locally by the goal of self-consumption [85]: New energy communities are looking to increase their self-consumption, while being connected to the grid, where in the past, local energy was simply sold back to the grid. Various example of such approach may be found in the literature, focusing of the possibility of energy sharing to absorb a locally generated renewable: e.g. with storage, using particle swarm optimization algorithm [38], using Mixed-integer linear programming [72], with EV using type-2 fuzzy logic [79], or using Recurrent Trend Predictive Neural Network based Forecast Embedded Scheduling [80]. Among those studies, only one effectively measure the evolution of REN integration [72]: proposing a smart battery management system, the authors reached a decrease between 25 and 30% of energy fed to the grid.

4.2.7. Others objectives

Besides those objectives, a variety of others are observed in the literature, but are not representative of EMS connected to the grid as they are specific to each study case and beyond the scope of the present review. Amongst other, the following objectives related to [14,55,63] can be cited:

- Consumers: availability of energy (capacity of the system to deliver power to consumers), availability of the vehicle (for EMS based on EV),
- Aggregator, balance manager or retailer: deviation from the forecast or from the production [53].
- Grid: quality of energy (voltage, frequency), stability of the grid, transformer overload minimization, increase service life of storage.

5. Inclusion of LCA in smart grid

As shown in Section 4.1, the environmental situation is the first stated motivation for research on energy management and towards smarter grids but only 9.4% of the observed studies tackle this question and none of them measures the overall impact of the proposed solutions. Methodologies such as LCA (see Section 3.1) do exist and this section presents therefore the findings of a literature review on the use of LCA in smart grids (as a whole or in parts).

5.1. LCA for energy management systems

The difficulty lies in finding literature presenting the details of the environmental analysis, to be able to compare and discuss the contributions of smart grids on this issue. For example, a working group studying the french national program “smart electrical networks” show positive environmental impact, but without the underlying method and perimeter, the results are difficult to compare with other studies [86]. The authors do, however, underline the strong need for a global method to perform such analysis, together with social and economic impacts.

Table 2
Reviewed studies of LCA for SG (N = 18).

Source	Studies	Scale	Scope	Impacts
[7]	1	HEMS	3	Ecopoints
[9]	6	SG	1–2	2
[10]	3	SG	1	2
[56]	1	HEMS	1	2
[87]	1	HEMS	1	2
[88]	1	SB	3	1
[89]	1	HEMS	3	18
[90]	1	HEMS	3	Ecopoints
[91]	1	HEMS	1–2	4
[92]	1	HEMS	3	2
[93]	1	HEMS	–	–

Focusing on the residential context of energy management system and smart grid, eleven useful articles, regrouped in Table 2 tackle the question of environmental impact and sustainability.

The starting point of the literature stand is given by a review from 2017 [9] looking at both economic and environmental impact evaluation of smart grids over 17 studies over the 15 year period prior 2015. The findings indicate that the reduction in greenhouse gas emissions spanned from 10 to 180 gCO2/kWh while the extent of primary energy savings varied between 0.03 and 0.95 MJ/kWh. These differences were a result of specific grid mix of each country and the defined system boundaries, underlying the authors' conclusion that there is currently no established approach for evaluating the economic and environmental consequences of SG systems. It should be noted firstly that the observed environmental impact are reduced to gas emissions, and secondly that the boundaries of the selected studies ranged from HEMS to entire national energy industry and the scope, as defined in Section 3, is neither discussed nor mentioned. Therefore these results cannot be transposed directly for this work. In addition, a review of 20 studies from literature prior to 2016 mentioned in the introduction shows the following findings [10]: there is no general methodology to assess environmental impact, but smart grids (this study is not specific to residential smart systems) seems to offer a reduction in CO2 emissions and energy saving. As methodology differ in each article and only CO2 is considered, no conclusion can be drawn.

Cited previously, [56,87] study the impact of an HEMS but here only considering GHG emission of the energy source (Scope 1) and neither the management system itself nor other impact category, showing reductions in impact of up to 60%.

From this date time (before 2016), two interesting studies concerning the residential sector may be pointed out in order to grasp the challenges of environmental impact of energy management systems [7, 88].

The authors of the first study [7] outline the lack of research at that time concerning lack of research on life cycle impact assessment of HEMS. On the basis of eco-costs indicator, taking into account necessary sensor, display, and overall ICT network for three compared systems, they also suggest that the overall impact regarding scope 3 varies depending on the type of HEMS employed, and if used over too short period of time and for relatively low savings, environmental burden may exceed the benefits. Additionally, no positive return on investment were observed over the 5 year study. Focusing on net zero energy building, [88] also point out the lack of research including LCA of such building as it means that the definition of net zero energy building needs then to be revised, especially when taking scope 3 into consideration. Here, constituent materials and energy systems of the building are discussed together and the authors conclude that further exploration of this research path is essential to create a more robust evaluation framework, incorporating the development of assessment tools and metrics.

From the last 5 years (2017 inward), 4 studies discuss the question of the impact of smart technologies in the residential sector.

Using LCA in a Finnish context to assess the impact of smart house automation along 18 environmental indicators on scope 3, the authors of [89] revealed that extensive technology deployment might have a counterproductive effect, primarily because of the high electricity consumption associated with the sensor network, automation system, and computing devices. Moreover, the results demonstrated a direct correlation between the number of inhabitants in a household and the environmental impact of home automation. The authors therefore suggest that HEMS may only be beneficial/relevant for large households regarding environmental benefits. A worst-case scenario of a single-person household witnessed a 15% increase in environmental impacts, while a five-person household experienced a 3% increase. Other findings show that the manufacturing phase contributed significantly more to environmental impacts than the use phase, across various categories, and that integrating hourly impact factor for the energy drawn from the grid is crucial to precisely evaluate the impact (positive and negative) of HEMS. These discoveries underscore the importance of identifying the optimal balance at which technology can effectively contribute to decarbonization and that impact transfers should be discussed. Indeed, as the authors warn: "*great care should be taken when realizing the trade-off between the components of a smart metering system and the electricity it consumes*", and that "*a wider range of automation architecture is likely to result in a broader palette of environmental impacts of smart buildings*".

Focusing only on residential heating in Flanders, the question is asked the other way round in [90], by evaluating how much must be saved for the system to be profitable from an environmental point of view. Depending on dwelling consumption and using LCA ecopoints (and do not detail each impact categories), the authors find a necessary annual reduction of 2 to 4% to ensure environmental benefit for the considered heating systems involving smart thermostat and smart meter. Thus, the authors point out that the smart system is mostly relevant in the case of high consumption.

HEMS impact from a life cycle perspective is also tackled by [91] in Germany with smart heating, using an interdisciplinary user-driven approach. Here, only production and use phase are considered for the heating system (Scope 1 and 2), and use phase for the IT infrastructure (Scope 1). Focusing on 4 impact categories (Climate Change (GWP), Primary Energy Demand (PED), Abiotic Depletion (ADP) and Ecotoxicity (Ecotox)), the result show that savings of GWP and PED are tied to a minimum savings of 6% of annual heating energy over 2.4 years and 3.1 years respectively, while for ADP and Ecotox, the system adds to the existing environmental load. This study shows therefore that LCA and user perspective should be taken into account to determine the total environmental effects of smart homes and that smart systems are not always environmentally relevant. The possibility of transferring the impact from one technical solution to another is also highlighted in the following study [92], which demonstrates that the proposed EMS of a study case building including a battery, reduces the carbon footprint thanks to a local PV production but increases the total primary energy consumption (Using Scope 3) due to embodied energy and losses of added systems which demonstrates that the proposed EMS of a study case building including a battery, reduces the carbon footprint thanks to a local PV production but increases the total primary energy consumption (Using Scope 3).

As shown by the studies cited above, efficiency is not just a technical issue but rely also on how users use energy systems. Therefore, Furszyfer Del Rio et al. [93] investigated how culture (in Japan, the United Arab Emirates, the United Kingdom, and the United States) influences, promotes or hinders the effectiveness of this system, and asked the question if *smart home technologies truly do promote sustainability goals*. This study highlights that the interviewed experts do not associate smart home technologies with sustainability, as they indeed promote energy awareness but also lead to rebound effect, unreliability, new material inputs, and other embodied externalities. Thus pointing out that to unlock the potential sustainability advantages of smart technologies in the residential sector, these technologies must be developed

Table 3
Selected studies regarding LCA for grid energy (N = 6).

Source	Type	Country	Year
[84]	Review	–	2017
[89]	Study-case	Finland	2017
[94]	Review	–	2011
[95]	Database	France	2022
[96]	Study-case	France	2016
[97]	Review	–	2021

and produced while taking into account not only economic factors but also the social and environmental consequences of their utilization.

To summarize these findings regarding the sustainability of smart system at distribution scale, several observations emerge: the main one is that it is challenging to find a consensus among the limited number of articles that address this issue comprehensively. Key aspects requiring further research include:

- Assessing whether technological advancements result in overall sustainability improvements, impact of the technology itself is often overlooked.
- Taking into account real user engagement (or disengagement), which may negatively influence these findings.
- Environmental assessments predominantly focus on GHG emissions, with limited utilization of mid/end-point and LCA methodologies. In cases where multiple impacts are considered, not all categories demonstrate savings and benefits, and sometimes even add to the burden. The possibility of impact transfer should be carefully examined.
- The time frame for considering network impacts significantly affects the results and should also be methodically considered.

Considering the above, further investigation into LCA for grid energy, technology, and rebound effects is warranted and will be therefore discussed in the next sections.

5.2. LCA for grid energy

The primary discussed topic concerning environmental impact of energy is the impact of the electric grid itself. Although it is specific to each country, it is nevertheless interesting to identify the critical points for taking it into account in the analysis of smart grids, as it has a major impact on the evaluation of energy management systems. The discussed studies of this section are regrouped in Table 3.

The fundamental problem observed in the studies cited in this article is that no unified methodology is available to study the impacts of smart on the same comparative basis. This problem was already observed in the literature over 10 years ago [94], and still persists [84], although some initiatives are being set up on a national scale. One example is the carbon database *"Base Carbone"* from the french ecological transition agency, a public database of emissions factors helping companies to produce any carbon accounting exercise (legally required in France) [95]. The above-cited and more recent literature review on grid LCA [84] underlines two remaining barriers: the definition of the functional unit must be unified in order different studies to be compared and secondly, electricity mix, losses and end of life infrastructure must be very precisely evaluated as they have a great influence on the total impact. Future steps would therefore be to propose an international common frame of reference on those questions.

The two other challenges remaining for grid electricity LCA are the time step considered and the environmental impacts considered (beyond GHG), necessary to effectively assess outcomes in smart grids project and help decision-makers, as shown on the most recent review on the subject [97]. Two exemples of these effects: First in [89], the authors show that a smart management system, even using hourly data to include grid impact, may only be beneficial in environmental terms for large consuming households; secondly in [96]: looking at the french national grid, the authors highlight that employing an annual average composition rather than hourly composition data result in an impact undervaluation of up to 39% for Abiotic Depletion Potential (ADP) and 36% for Global Warming Potential (GWP). Thus, showing both the importance of detailed data for the grid as well as the value of not only considering GHG emission.

Table 4
Reviewed studies regarding LCA for production and storage (N = 15).

Source	Perimeter	Scope	Impacts
[98]	CHP + PV	2	5
[99]	PV + storage	3	3
[100]	PV + Storage	3	5
[101]	PV + Storage	1	1
[102]	PV + Storage	1	1
[103]	PV + Storage + HP	2	1
[104]	PV + Storage	2	1
[105]	PV + Storage	2	eco-points
[106]	Storage	2	eco-points
[107]	PV + Storage	2	1
[108]	Storage	1	4
[109]	Storage	2	1
[110]	Storage	1	5
[111]	Storage	2	4
[112]	Storage	2	12

5.3. LCA of residential production and storage

Another aspect tackled by smart systems on distribution grid is the management of local energy production, mainly PV systems, which can be facilitated by the use of EMS, sometimes coupled with a storage system. Furthermore, as mentioned in Section 4.2.5, environmental impact of energy management solution is often calculated only based on the production impact. It is therefore worth reviewing the use of LCA on such system to emphasize what is already being covered in the literature as well as research gaps. The discussed studies of this section are regrouped in Table 4.

The key challenges on this topic are once again the consideration of environmental impact beyond GHG to enable informed decision making and avoid impact transfer from one solution to an other as summarized in [113,114]. Although these recent studies do not focus on local renewable energy production and EMS, they can be referred to by interested readers as they effectively highlight the growing concerns about environmental impacts that need to be considered, which extend beyond CO2 emissions (impact on inhabitants, eutrophication, dried up rivers, deforestation, . . .).

Considering respectively 5, 3 and 4 different impacts for PV systems in Portugal [98], in Denmark [99], or in Spain [100], impacts transfers are systematically observed, and it should be noted that the EMS itself is not taken into account. Overall however, studies focusing on CO2 alone show an improvement on this criterion [101–104], but the scope is either reduced to the use-phase only or using only average grid data as evoked in Section 5.2.

By opening up the discussion to a broader vision of environmental impact, a study case in Italy of residential PV and storage focuses on economic incentive to achieve an economic and environmental optimum [105]. Aggregating environmental impact from LCA using an *environmental score*, the study reaches an improvement on the score but this aggregation makes it difficult to discuss impact transfer. It should be noted that in this study and a further one [107], cost is highlighted as one of the barrier for additional environmental benefit.

Since storage technologies weight heavily on the environmental impact assessment of HEMS, it is interesting to observed that research on this topic exists and bring answers for this part to be considered in smart grid impact, accounting for other indicators in addition to CO2. From the literature, the challenges on this topic are the following: [108]

Table 5
Selected studies regarding LCA for ICT (N = 37).

Source	Studies	Perimeter	Scope	Impacts
[4]	29	ICT	1–3	–
[93]	1	ICT in SG	3	1
[115]	1	ICT	1–3	1
[116]	1	HEMS appliance	3	7
[117]	1	IoT for SB	3	1
[118]	1	ICT for HEMS	1	1
[119]	1	ICT for HEMS	3	1
[120]	1	ICT	–	–

compared four storage solutions along 4 en environmental indicators and highlighted the lack of proper studies about batteries and peripheral components, showing that the significance of power electronics may frequently be underestimated ; Three studies show that the environmental performance of storage systems is application dependent and linked to the electricity source used for storage [109–111], with [110] adding that no battery performs better than the others in all considered impacts, a phenomenon observed further by [106,112].

5.4. LCA of ICT

The studies conducted thus far have not taken into account the impacts associated with the communication infrastructure required for energy management, which is in addition to that of the electricity grid, and has its environmental implications. This is especially relevant in light of increasing concerns about the environmental impact of digital technology.

However, in the studies referenced in the preceding sections, these concerns related to the ICT sector are not addressed. Therefore, there is a valid interest in examining existing research on this topic: the studies regrouped in Table 5 are discussed in this section.

A past [4] (2014) and an updated review [115] (2021) point out several shortcomings of research concerning impact of digital technology: The main concerns are about addressing a wider range of environmental impact beyond GHG (such as those affecting humans and ecosystems), accurately modeling the management of electronic waste and considering user behavior to take into account rebound effects and indirect consequences. The ICT sector is estimated not to be on a path to reduce emissions and that the impact assessment made in the literature may be underestimated, with a share of global GHG emission in the range of 2.1–3.9% instead of 1.8–2.8%.

In parallel, the difficulty stemming from single case studies of the reviewed literature is to draw a conclusion: Indeed, when energy saving are observed from the use of ICT and IoT in energy management, environmental impact of the infrastructure is shown to be either negligible (eg. in [117]) or to transfer the observed impact (eg. in [116]). A more detailed approach is taken in Germany by [118]: they demonstrated that the operation and production phases of hardware have the most significant environmental impact and that for an average household (annual consumption of 3500 kWh), energy-saving should reach at least 2.7% to balance the direct impact of the ICT infrastructure, in the average scenario. One of the parameter observed to be crucial to help assessing this effect is the considered lifetime of the equipment [119]. There is therefore an urgent need for methodologies to assess the benefits of such HEMS system to calculate the overall system balance.

To conclude this section, the literature review from the study performed by Furszyfer et al. [93] also underline this unclear environmental balance between benefits and cost in the use of ICT in smart grids, and question therefore the sustainability of such systems as they rely heavily on connected devices whose impact has been shown to be growing in the last years. This potential unsustainability may be observed at each stage of the life cycle of the equipment: *from conception when software algorithms are trained, and resources are extracted for products, to the electricity demanded from data centers*. They also highlight a concern of the International Energy Agency discussed in Section 6: *Digital technologies could reduce the energy intensity of providing goods and services, some could also induce rebound effects that increase overall energy use* [120].

6. Rebound effect

Beyond the purely technical aspect of the smart technologies is the concern for rebound effect, which is rarely considered and which can limit the gains calculated by technical studies, or even prove to be counter-productive in energy and environmental terms. The rebound effect in energy consumption refers to the phenomenon where efficiency gains or cost savings from energy-saving technologies or behaviors lead to increased energy use, offsetting some of the initial savings. This occurs due to factors such as increased usage of the more efficient technology or the adoption of additional energy-consuming activities enabled by cost savings. To tackle this effect, research should consider approaches that are more focused on usage.

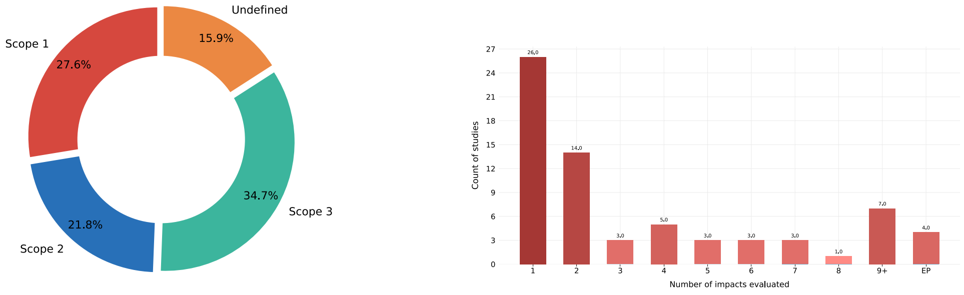
This claim is supported in [121], studying the actual utilization of HEMS and the extent to which they facilitate alterations in behaviors in daily life on real-life case studies in Sweden. The results of the literature review carried out by the authors show that the degree to which smart technologies effectively assist households in reducing and adjusting their energy consumption over time has demonstrated variability, raising questions about their environmental advantages and may even lead to an increase in energy usage due to higher expectations in terms of comfort lifestyle standards. This can be explained, according to the authors, by the lack of a clear user-oriented vision in a technology developers driven domain. The key points of this study is the need for better user integration in smart home energy management systems while recognizing that these systems, on their own, cannot bring about the shift towards more sustainability. This latter point is also supported by the literature review and findings of Walzberg et al. [122] studying this rebound effect in smart home. They show that one of the main parameter to limit rebound effect is the choice of metric used in electricity management. In particular, they point out that switching from an environmental indicator to a price indicator for management purposes results up to a 5-fold increase in the rebound effect, and even more on certain periods.

Furszyfer et al. [93], cited in Section 5.4, also back up this observation based on their literature review across 4 countries: they show that from an energetic point of view, the real potential of net energy saving of smart home technologies is unclear and in the best-case scenario, it could be “*likely positive*”. The main reason is that these technologies are used to improve comfort and satisfaction, which might also encourage unsustainable energy consumption practices. Therefore, determining the actual savings is challenging and uncertain, as they predominantly hinge on the actions, engagements, and overarching societal elements of users. To tackle this problem also observed for zero energy buildings in Europe, Kylili et al. [123] call for more investigation to be carried out on the social attitude of the buildings users towards environmental issues, to limit and prevent rebound effects. This claim of unclear environmental benefit is further supported by Tiradoherrero et al. [124] studying smart home systems, point to the lack of research on these issues, encouraging more intensive ways of life, but also add a concern regarding the aggravation of domestic energy related vulnerabilities and inequities. As expressed by the authors: “*technologies and people co-shape each other in unintended ways*”.

7. Discussion

7.1. Critical evaluation of the state of the art

The comprehensive review of the literature reveals several points. The first two positive aspects are the existence of studies and methodologies concerning the Life Cycle Assessment (LCA) of energy and



(a) LCA Scope repartition (b) Evaluated Indicators repartition

Fig. 4. Disparities in LCA approaches of the reviewed studies (N = 69).

information systems, as well as a body of research on the usage aspects of these technologies. Nevertheless, the major weakness lies in the lack of integration of these studies into research on Energy Management Systems (EMS). Thus, the relevance of the current state of the art of EMS is poor from an environmental perspective. The current direction of research on optimizing energy flows at the residential scale primarily focuses on financial perspectives, with optimizations mainly based on financial costs (84.3%) rather than environmental aspects, which are only implicitly considered through secondary objectives.

If the proposed state of the art allows to observe and discuss the gaps of the field and recommendations to be made by observing the current direction taken, further research should investigate:

1. Firstly, as environmental consideration is observed to be only indirectly considered: to what extent do the objectives of reducing consumption, reducing fluctuations, and integrating renewable energies actually address the environmental issue in the context of EMS. The issue is that it is difficult to draw conclusion with the current state of research, but further investigation could reveal that current EMS do improve the environmental impact of electrical grids.
2. and secondly, how environmental and financial objectives (cost being the observed preferred research direction in the field) could align, by expanding the state of the art to economic literature.

The second problem highlighted in Section 5 concerns the targeted literature on LCA regarding smart grids, both as a whole and in its specific parts. Indeed, the approaches used, the methodologies, and the metrics evaluated are too disparate to enable reaching a meaningful conclusion. To emphasize this observation, Fig. 4 illustrates the distribution of the scope used in the reviewed studies of Sections 5.1, 5.3 and 5.4 and the distribution of these studies regarding the number of environmental impacts evaluated (respectively on Figs. 4(a) and 4(b)).

7.2. Research gap

Taking a step back from all the literature presented in this article, from the issues raised to the various solutions proposed, it is interesting to summarize and highlight the gaps in current research on energy management in smart grids.

The main gap that emerges is the non-alignment of research objectives/studies with the environmental issues of our time, as outlined in Section 2. This gap is summarized on Fig. 5. Indeed, the majority of research on energy management system do not measure the impact of the proposed solutions, even if environmental issues are presented as the driving force behind those research. Moreover, in the limited number of studies that have endeavored to investigate their impact, no consensus on the environmental benefits of smart solutions emerges. A perfect example of this problem is illustrated by the author of [31] in 2022, stating without source that "*SG is more efficient, environmentally friendly and more sustainable than the traditional power grid*", while, as demonstrated throughout this research, the literature does not provide a response to this question. To understand the depth of this gap, it can be divided into two problems.

The first main problem is that globally, studies do not address environmental issues. Despite numerous challenges beyond GHG emission (climate change, resource depletion, ecosystem destruction, human health, …), stated to be the primary motivation for research on smart grids, it is evident that the environmental aspect is not reflected in the actual objectives of energy management systems in the literature. An example is the literature review by Good et al. [45], bringing sustainability as one of the main driver for smart grid at distric level, but the reduction of environmental costs is then cited as *one of the services that smart districts could offer* and therefore often not considered. Indeed, the main tendency observed in Section 4 is that:

1. the objectives are not directly related to the environment, and in the majority of cases, it is primarily the price that is considered. The environment may be indirectly targeted through the price if the business model incentives virtuous behavior, through the integration of renewable energy sources (REN), or through the reduction of peaks.
2. the environmental impact of the proposed solutions, even through the indirect objectives mentioned above, is not measured; the impact on the price is often the only one measured.

The second problem is that when environmental impact is measured, which is rare as seen in Sections 4 and 5, it is only partially done, either by:

1. not considering the entirety of the system: especially the added components. Indeed, there are growing concerns about the environmental impact of ICT, and yet in smart grids, most offered services are based on those technologies, especially for EMS requiring more data and control;
2. not considering the entire life cycle of the system: the use phase is most often the only one considered;
3. not taking into account all environmental impacts (mainly just CO2 and GHG) and therefore not discussing the possible impact transfer;
4. not discussing possible rebound effect, which can reduce or even cancel out possible benefits.

Finally it should be emphasized that, from the few studies including the research of environmental impact of smart system using scope 3, no net environmental benefit is observed as in the best case scenarios, an impact transfer is observed, except in specific case.

Within this specific context, arriving at conclusions and making well-informed decisions proves to be a challenging endeavor. Before addressing the field's needs and providing recommendations for future research, it is valuable to grasp the obstacles hindering progress and the existing point from which to proceed.

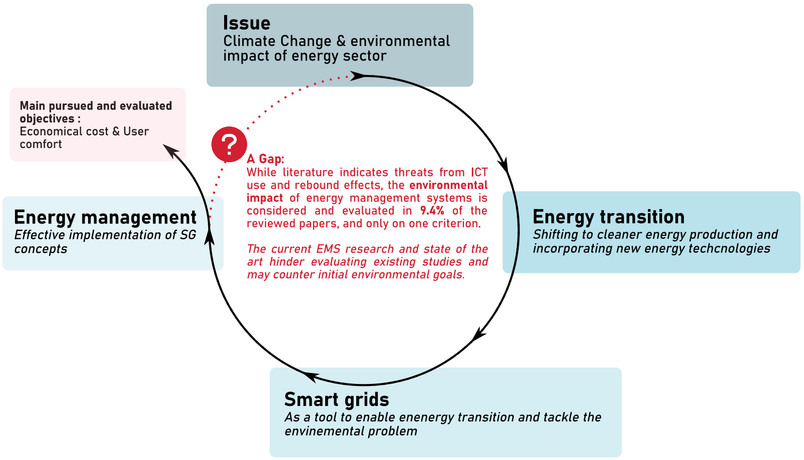


Fig. 5. Illustration of the gap between current research and the initial motivation of energy transition and smart grids.

7.3. Scientific challenges

In the few studies that attempt to see the problem comprehensively and address this question, there is no consensus from the smart grid side, and there are even more concerns from the ICT side. The subject is indeed complex, and following obstacles standing in the way of filling this gap should be highlighted from the literature reviewed in this work:

- The growing complexity of smart systems, as they encompass more energy technologies as well as ICTs, make it difficult to take full account of equipment and usage.
- The difficulty in obtaining relevant data for assessment, especially since impacts depend heavily on the specific study case (e.g. hourly data of electricity mix may change the outcome, management strategies impact batteries life cycle and therefore the environmental balance, . . .). Specific and corresponding data are therefore required but not always available.
- From the LCA perspective, difficulties are to consider all the impacts in comprehensive way without increasing the complexity of the optimization, and to defining a functional unit and scope (including infrastructure and end of life as well).
- Reducing environmental impact often comes into conflict with reducing short term financial costs. Considering the long-term costs of climate change is difficult to address at a business scale without adequate regulation; therefore, the limitation of all study using the paid price as the main metric for optimization.
- LCA is only a picture of todays impact, but the results may varies in future context (mix/environment), it could be therefore difficult to draw conclusion for the future.
- LCA is very sensitive to methodological approach, therefore the need for methodological standard regarding smart grids.
- To grasp impact transfers and rebound effect, a broader scope of existing methods must be considered by incorporating other disciplines. Interdisciplinarity is therefore the key, including even human and social sciences, to understand real and effective application of smart solutions by users, as the expected effects can be reduced or even canceled, and this can even lead to social exclusion or marginalization [123,125].

7.4. Recommendations

To address this gap and overcome these obstacles, it is essential to simultaneously pursue the following two directions:

1. Conduct a systematic evaluation of the environmental aspects of the proposed EMS, discussing the findings from an environmental standpoint, as this forms the fundamental motivation behind this research. Indeed, there is a pressing requirement for a more substantial body of research on each part of smart grids, ranging from equipment to energy management strategies themselves, to contribute to the advancement of standardized methodologies.
2. Simultaneously, the smart grids research community should work on establishing a systematic methodology: From network emissions to additional equipment and all the way through the equipment's various life cycle stages, the finale objective is to facilitate research comparisons. To achieve this:
   - The main tool already exists: LCA is well-established and proven to be useful in other domains. Hence, there is a requirement to tailor it for smart systems by establishing boundaries, defining the functional unit for assessing and comparing solutions, and integrating it into a more comprehensive methodology.
   - A global methodology must then be developed, with a holistic vision of the problem, considering all possible impact of the system regarding known environmental problems, since they are comprehensively documented.
   - Hence, it is crucial to establish a bridge between various disciplines, the main one being: economics (to develop environmentally-aligned business models), environmental science (to assess impacts), information technology (for ICT), and sociology (to address rebound effects). Indeed, as observed from the literature reviewed in this work, when impact assessment is not conducted directly and integrated into the research process, it becomes challenging, if not impossible, to evaluate the worth and significance of the proposed research.
   - Furthermore, user aspect of smart grids should be carefully discussed during the assessment phase, to prevent counter effect, as the effective success of smarter systems relies heavily on users themselves [126].
   - The systematic use of the price as the main optimization criteria should be discussed. However, if financial aspects stay the main metric to optimize energy flows in EMS, then methodologies to align prices and environmental consideration should be developed. This can be accomplished through LCA, thereby contributing to the development of economic models that are environmentally informed.

The next step for further research on the long run is then to find the optimum between the technology implemented, the data that is processed (and therefore the level of ICT involved), and the service required (from the grid, from the user or from the society). The goal is not to discard smart technologies, as they proved to be useful, especially in certain context (e.g., as highlighted by Chakraborty et al. in India with old and inefficient network for example [127]), but if the impacts are merely shifted rather than diminished, how relevant is this for the future, especially when considering that 6 out of 9 planet boundaries have already been surpassed?

The goal is therefore to achieve equilibrium in the services provided by quantifying all facets of the issue, enabling informed discussions, even if some aspects may be compromised. Decision-makers and society must have a clear understanding of what is being enhanced and what is being compromised when investing resources on smart systems.

7.5. Practical implication

The main and immediate implication of this work is to realign research with the objective of addressing environmental challenges.

From a research perspective, this entails systematically considering and measuring the impact of proposed solutions as a priority. The primary objective should be the environment, which needs to be integrated into political and financial constraints.

For research both within and outside the field, as well as for industry, this means opening up to other disciplines as these are not issues that can be tackled alone. The future development of these technologies and systems will only make sense within this interdisciplinary framework (including LCA, humanities and economy), to envision and enable new exchange models based on varying degrees of technology.

On a broader scale, this work contributes to the paradigm shift needed to address environmental issues and change the narrative, shifting the vision from the pursuit of “decarbonization” to “reduction of the embodied impact” [128].

However, considering these impacts cannot be done without a framework that allows for it. Therefore, on a national and continental scale, this requires new changes both legislatively (e.g., enabling different energy exchanges [129]) and economically (ensuring that finance does not override the environment but rather accompanies it).

The ultimate goal is to prevent impact transfers, avoiding scenarios where pursuing one aspect leads to deterioration on an other. A concrete example in terms of UN development goals would be to prevent that the realization of ensuring Clean Energy (Goal 7) leads to damaging life on land (Goal 15) or below water (Goal 14).

In conclusion, the practical implication of this review is to empower and guide research, industry, and policymakers to ensure adequate and effective future efforts regarding environmental issues, by limiting potential impact transfers.

8. Conclusion

The growing significance of smart grids within the energy sector, accelerated by the global environmental crisis and the imperative to reconfigure power systems for mitigating their environmental footprint and assimilating novel, eco-friendly technologies, raise questions regarding the efficiency of these emerging technologies and the relevance of the sector’s chosen trajectories.

The originality of this research is therefore to present and conduct an analytical review of the evaluation and integration of environmental considerations within smart grid research, and to identify gaps and clear research directions for the future of the field. The fundamental question raised in this review is as follows: *Does the research in energy management for smart grids and the proposed solutions align with today’s environmental imperatives?* This encompasses both the environmental ramifications of the proposed solutions and the research orientations. Indeed, the review of existing literature reveals that, in practice, this environmental facet has remained understudied, with management solutions predominantly assessed from a financial perspective while accommodating user comfort, as opposed to their intended environmental objectives: additional required components enabling EMS are not sufficiently included in impact assessment, as well as their entire life cycle, and the impact of users’ effective utilization of the solution is disregarded. Furthermore, the limited research on this subject fails to reach a consensus, with specific impact assessments or evaluations of individual systems indicating potential additional environmental burdens. Consequently, the current body of literature does not facilitate clear decision-making in the face of potential impact transfers.

In summation, the two main key findings are: that existing literature, pursuing predominantly cost oriented objectives (84% of reviewed articles), does not adequately address the actual environmental issue; and that there is therefore a need for systematic assessment of environmental impact in research on SG. Since the tools exist, the main practical implication for the domain is the need for interdisciplinary approaches (LCA, economy, sociology) to account for all the aspects affected by energy management.

This state of the art, focused on engineering articles database, warrants further investigation: indeed reviewing literature from humanities and economy in future work is essential to expand and refine the given recommendations. Achieving this will lead to greater practical consensus, enabling governments, research, and businesses to engage their efforts, economic structures, and future engineering developments to systematically address the environmental issue, and in an effective manner. The key lies in ensuring development that does not compromise other objectives.

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.

Data availability

No data was used for the research described in the article.

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