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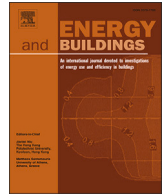
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A methodology for assessing environmental impact of building integrated PV in low carbon footprint electricity generation context

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ABSTRACT

With the growing interest in renewable energy to mitigate climate change, photovoltaics are increasingly relevant due to their limited carbon emissions in the use phase. This study focuses on integrating photovoltaic technologies in countries with low-carbon electricity mixes, specifically the cases of France and Norway. It presents a comprehensive methodology assessing the environmental impact of PV technologies and their application in a French and a Norwegian building. The research includes a case study of a single-family house, modeled in TRNSYS for dynamic thermal systems simulation, operating in both locations. The photovoltaic panels' life cycle assessment is conducted using the SimaPro software and a functional unit of 1 kWh from mono-crystalline panels with an expected service life of 25 years. Such analysis aims to evaluate the environmental impact through key performance indicators during the life span of the photovoltaic panel, from cradle to use with a focus on the raw material use, manufacturing processes, transportation, use phase replacements and electricity production. The indicators analyzed are global warming potential, cumulative energy demand (non-renewable, fossil), energy payback time and energy return on energy invested. The study also explores the impact of different manufacturing, transportation and installation scenarios of the photovoltaic panels, including a 100% European low carbon footprint electricity mix. In summary, the findings demonstrate that in countries with low-carbon electricity production, the use of photovoltaic panels presents a favorable outcome in terms of global warming potential for the French case (25–38.6 g CO₂e/kWh), regardless of their place of manufacturing. For the Norwegian scenarios (spanning 29.5–45.6 g CO₂e/kWh), the life cycle benefit in terms of emission reductions is only evident if the panels are locally produced in Europe. This conclusion is based on electricity from the photovoltaic installation modeled to replace the Norwegian production mix of electricity. Thus, the geographical system boundaries in relation to the replaced electricity is an important parameter. Cumulative energy demand (non-renewable, fossil) was found to vary between 0.34 MJ/kWh and 0.44 MJ/kWh, the Norwegian scenarios consistently showing higher numbers than the French. Energy payback times of the mono crystalline photovoltaic panel ranged between 0.75 to 0.97 years depending on the solar potential of the installation place and the scenarios of manufacturing.

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1. Introduction

The world is currently challenged by global climate change. It is, therefore, time for conscious and sustainable decision-making towards reducing considerably both energy consumption and greenhouse gas (GHG) emissions, breaking with former energy production sources based on fossil fuels, choosing the path of renewable energy sources (RES), and that in all the energy consuming sectors of activity.

There is still room for improvement and integration of RES to satisfy the energy demands in every domain (e.g. industry, transport). In 2022, the International Energy Agency (IEA) reported that RES contributed to over 25% of global electricity production, with solar energy accounting for more than 12% of that share, just behind hydropower at around 16%. However, solar electricity generation is also expected to overcome all the other energy sources, reaching more than 22% by 2027 [1]. As for heat generation, the heating sector is largely dominated by fossil fuels, with RES reaching only 13% of global heat demand in 2022 [2].

The building sector accounts for more than 30% of worldwide energy use and more than 26% of GHG emissions according to the IEA, and nearly 70% of these GHG emissions are indirectly related to emissions for electricity and heat used in buildings to meet the heating, cooling, domestic hot water, and electricity demands [3]. There are multiple key actions to reduce the building sector's environmental impact, starting with the construction of the building by using low-emission materials, its improved thermal performance followed by the change of habits of the users, the use of more energy-efficient systems, and finally the implementation of RES locally which is the focus of the presented study. The objective of many countries by 2050 is to turn their building stock into more energy-efficient, or even zero-emission buildings. In that regard, buildings have a twofold objective: they need to reduce their emissions and meet their energy demand through RES. The RES play a crucial role in the transition towards low-carbon energy and emissions. Among the RES, solar energy is widely available in the built environment, and the deployment of photovoltaic (PV) technology integrated into buildings' envelope has increased in the past years [4].

For countries where the electricity mixes are already decarbonized to a high degree, an urgent question relates to the actual benefits of PV-

generated electricity to replace electricity from national grids. In 2022, the average annual carbon intensity was $78 \text{ g.CO}_2\text{eq/kWh}$ in France vs $29 \text{ g.CO}_2\text{eq/kWh}$ in Norway [5]. In France, it is mostly supplied by nuclear energy up to 70%, which is not considered RES, but has a significant lower carbon foot print than fossil fuel based electricity [6]. In Norway, more than 90% of electricity generation is supplied by hydropower. The share of PV electricity production is still low in both countries: 4,7% in 2022 for France, and less than 1% in Norway [7,8]. In France, the environmental and energy management agency (ADEME) estimates the solar potential for neglected areas and parking lots for 53 GW_p [9], and the research center for sustainable solar cell technology [10] estimates the PV potential for Norway's buildings between 30 and 50 GW_p .

France and Norway aim to reduce the carbon footprint of the building sector through building planning. The National Low-Carbon Strategy (Stratégie Nationale Bas-Carbone - SNBC) is France's roadmap to tackle climate change [11], and one of the key levers is to guide the evolution of the energy mix in the use phase of buildings towards totally carbon-free energy. For heating, cooling and domestic hot water production, preference is given to efficient heat pumps (HP) for individual homes when geographically the use of geothermal or solar thermal (ST) panels is not best suited, alongside a completely decarbonized electricity from PVs. Norway's Climate Action Plan for 2021-2030 aims to reduce considerably the carbon emissions of the country. It will thus support the development of multiple technologies that help cut GHG emissions, among them PV panels to meet the energy demand in buildings and mobility services [12]. For that, the Norwegian government will facilitate the use of locally produced energy such as solar energy with the target to reach 8 TWh of solar energy in 2030 [13], and evaluate by 2040 the impact of the self-consumption of this RES in avoiding further investment for new grid [14].

Several studies indicated the benefits of integrating PV panels with HP demonstrating its ability to optimize energy use and reduce the carbon footprint in different climatic conditions. Mussard [15] stated in their review that in cold climates, powering HP with PV panels presents challenges due to reduced solar output in winter, as PV panels provide a smaller portion of the energy needed for heating compared to cooling

Nomenclature

Acronyms

<i>BIPV</i>	Building integrated photovoltaic
<i>BOS</i>	Balance of the system
<i>CdTE</i>	Cadmium telluride
<i>CH</i>	China
<i>CIGS</i>	Copper indium gallium selenide
<i>CO₂</i>	Carbon dioxide
<i>DHW</i>	Domestic hot water
<i>EF</i>	Environmental footprint
<i>EPD</i>	Environmental product declaration
<i>FR</i>	France
<i>FU</i>	Functional unit
<i>GE</i>	Germany
<i>GHG</i>	Greenhouse gas
<i>GWp</i>	Global warming potential
<i>HP</i>	Heat pump
<i>IEA</i>	International energy agency
<i>KPI</i>	Key performance indicators
<i>LCA</i>	Life cycle assessment
<i>NO</i>	Norway
<i>PV</i>	Photovoltaic
<i>PVT</i>	Hybrid photovoltaic/thermal
<i>RES</i>	Renewable energy sources
<i>RTE</i>	French Electricity Transport System Operator

<i>ST</i>	Solar thermal
<i>TRNSYS</i>	Transient system simulation tool
<i>US</i>	United states

Subscripts

<i>eq</i>	Equivalent
<i>grid</i>	electricity grid
<i>gross</i>	gross area of the PV panel including the frame.
<i>nomSTC</i>	Nominal PV power in standard test conditions
<i>STC</i>	Standard test conditions

Variables

η	Efficiency in %
<i>A</i>	Area in m^2
<i>CED_{nonRenF}</i>	Cumulative energy demand : non-renewable, Fossil (in MJ)
<i>D</i>	Degradation coefficient of PV panel (in %)
<i>E</i>	Electricity (in Wh)
<i>EPBT</i>	Energy payback time
<i>ERoEI</i>	Energy return on energy invested
<i>Lifespan</i>	Lifespan of the PV panel of 25 years
<i>mi</i>	Quantity of materials invested in kg/kWp
<i>P</i>	Power (in Wp)
<i>PBT_i</i>	Impact payback time
<i>SCF</i>	Self consumption ratio

in summer in Shanghai for instance. The review showed, that in Germany, optimizing the size of the HP and incorporating thermal storage can enhance the system's performance in dynamic electricity networks, allowing efficient use of PV energy, even in colder conditions. This approach helps align PV electricity generation with the HP's demand, ensuring more efficient energy use throughout the year. In the systematic review conducted by Wang et al. [16], several studies have compared the energy efficiency of PVs coupled with air source heat pumps (ASHP) against other energy systems. Rabczak et al. [17] analyzes the energy efficiency of combining heat pumps with PVs in energy-efficient homes, focusing on factors such as mechanical ventilation, location, heat loss, and heat source operation. The study demonstrates that integrating HPs with PVs can significantly reduce external energy demand, lower operating costs, and enhance energy self-sufficiency, contributing to GHG emissions reduction in the residential sector. The PV + HP configuration achieves, over a 15-year lifespan, a reduction of 756 kg of GHG emissions compared to traditional energy sources.

Since PVs technologies have no or few operating GHG emissions [18], it is important to focus on the embedded emissions and energy costs from their other life stages to conduct a fair comparison of one PVs technology to another, and with the other energy sources. This paper aims to investigate the environmental performance of PV, by testing different manufacturing scenarios in a context of countries where electricity is decarbonized to a high extent.

2. Background

2.1. PV technology

The PV modules are characterized according to their cell type and their energy generation. Table 1 summarizes the different PV technologies and their respective energy efficiencies for standard test conditions according to the latest efficiency advances [19].

The 1st generation silicon based PV technology represents over 95% of the market due to its cost-effectiveness and maturity [20]. The present study focuses on evaluating mono crystalline PV modules that are more

efficient than the Poly crystalline ones. To expand the use of PV technologies, it is essential to assess their environmental impact early in the planning and decision-making process. This evaluation should cover all life stages, including material extraction, manufacturing, distribution, installation, use phase, and end-of-life recycling.

The manufacturing phase of a silicon based PV panel involves a five-stage process starting with the production of ultra-pure polysilicon hence Fig. 1 [20]. The polysilicon is melted and molded into large blocks, known as ingots. These ingots are then sliced into wafers. The wafers are further processed to fabricate PV cells, which constitute the essential units for converting sunlight into electricity. Last, the solar cells are interconnected, encapsulated and framed to create the final PV module.

Today, China is the largest producer for all three sub-components (cells, wafers, polysilicon), accounting for 85-97% of global installed capacity at each stage in the supply chain. Over time, this supply chain concentration has increased, particularly for certain components. In silicon wafer production, China's dominance has grown significantly, from around 80% of production in 2010 to over 95% in recent years. Similarly, manufacturing capacity for cells and modules, which accounted for 55-60% in 2010, has risen to over 85% for cells and 80% for modules by 2022. In the case of polysilicon, China's share of global manufacturing capacity has increased from less than 30% in 2010 to over 85% in 2022 [21].

2.2. Insights from previous research on PV environmental impact assessment

Assessing the environmental performance of PV panels has been a center of interest among the scientific community for many years. The literature abounds with references investigating the different types of PV technologies and at the different stages of their life cycle. LCA is a frequently used tool for such analysis. It allows for a life cycle perspective on energy and material flows, and the associated potential impacts of these flows (e.g., global warming potential (GWP), human toxicity). The LCA needs input data from the whole life cycle, i.e. of the materials used and extraction processes, the manufacturing steps and processes,

Table 1
PV technology type panels [19].

Solar cell	1 st generation: Silicon based		2 nd generation: Thin film			3 rd generation: multijunction technology				
	Mono crystalline	Poly crystalline	Amorphous	CdTE	CIGS	Nanocrystal	Polymer	Day sensitized	Perovskite	Concentrated
Efficiency	>20% %	15-17%	6-8%	9-11%	13-15%	7-8%	3-10%	9-10%	39-40%	15-31%

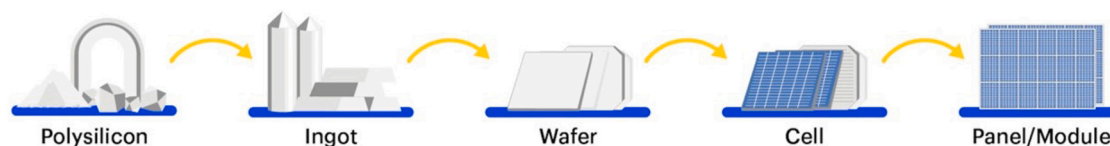


Fig. 1. PV manufacturing steps.

the means of transportation and distribution from the assembly part to the installation place, and recycling scenarios. The scope also involves all the components of the installation phase other than the PV panel itself, including inverters, mounting structures, wiring, tracking systems, junction boxes, and monitoring equipment, necessary for the proper functioning, integration, and operation of the PV panel within the larger energy system, also known as the balance of system (BOS).

In the following sections, the KPIs integrated in the methodology analysis of this present work are introduced. Most of them are commonly used in the field of PV panels, and each KPI outlines a different aspect to support decision makers and/or end-users in their choice of PV technology. For each criterion, a definition retrieved from literature is given, as well as case study applications of the criterion to give orders of magnitude for the values of these indicators in the literature, useful to discuss the results of our case study. It is relevant to bear in mind that these definitions of criteria will change to adapt to the methodology of this current study, and since the various literature studies and the present one do not examine exactly the same PV panel technologies or even with the same efficiency, the results on the KPIs will vary.

2.2.1. Life cycle GHG emissions

Focusing on the GHG perspective, PV panels are evaluated throughout their life span in terms of the GHG emissions related to their manufacturing, assembling, material extraction, transportation, installation, and end of life as per international and European standards on LCA in general (ISO 14040:2006) and on LCA in building products (EN 15804+A2:2019).

Previous studies, such as Kavian et al. [22] have investigated life-cycle GHG emissions of different types of PV panels: Poly crystalline, mono crystalline, and thin-film cells, coupled with a ground source HP. The experimental data of the Fthenakis and Alsema [23] study was used which indicated that the amount of climate change potential for the poly crystalline, silicon thin film, and mono crystalline are 37, 30 and 45 gCO_{2eq}/kWh , respectively. In Nikolic et al. [24], the value taken is 50 gCO_{2eq}/kWh produced during the first years of the operation of the panels taken from the British Center for Alternative Energy. In Yaghoubirad et al. [25], they took an average value for mono crystalline PV panels, based on literature equal to 32 gCO_{2eq}/kWh . In Perez et al. [26], the indicator used to describe the GHG emissions is the GWP indicator, that was equal to 61 gCO_{2eq}/kWh for a mono crystalline BIPV operating in New York. The life cycle CO_2 emissions was 45 gCO_{2eq}/kWh for a mono crystalline PV panel in Alsema and de Wild-Scholten [27]. In Desideri et al. [28], a mono crystalline PV panel with a tracking system also scored a GWP equal to 45 gCO_{2eq}/kWh in Italy.

2.2.2. Cumulative energy demand

The cumulative energy demand (CED) is a resource use category in LCA, assessed by evaluating and summing all the energy inputs associated with the entire life cycle of the system. Frischknecht et al. [29] defines the different approaches to this, for instance how the energy harvested concerns different forms of energy and a differentiation is made

between the renewable and non-renewable ones. In most LCA databases, the CED results for any energy source, system or process, are given for eight impact categories showing different energy resources which are i) non-renewable fossil source, ii) non-renewable nuclear source, iii) non-renewable primary forest, iv) renewable biomass, v) renewable wind, vi) renewable solar, vii) renewable geothermal and viii) renewable hydropower energy source [30]. The CED also takes into account the “heating value” of different forms of energy sources and apply efficiency and energy factors to each one [29]. Based on this heating value, a high-value or low-value CED can be defined. Some LCA methods recommend to focus only on the non renewable: fossil fuel energy use, for instance the environmental footprint EF method [31]. In Kim et al. [32], the low-value CED, also called the fossil fuel consumption, is calculated for a mono and poly crystalline PV panels, and is equal to 0.56 MJ and 0.44 MJ of fossil fuels per 1 kWh of produced electricity respectively, considering the manufacturing, use and end-of-life phases of the panels.

2.2.3. Energy payback time

The energy payback time (EPBT) expressed in years is a frequently used indicator. It refers to the period it takes for a PV panel to generate the same amount of energy that will be used during the life cycle of the panel [33].

Ziemińska-Stolarska et al. [34] conducted a review of literature on concentrated PV (CPV) systems. This technology had a better module efficiency compared to a regular PV system thanks to the concentrating device, but it adds materials that will increase the technologies environmental impact. Indeed, according to results of the authors, energy payback time can range from 0.22 to 4.7 years. In Fthenakis and Alsema [23], energy payback time in the early 2000's are 1.7, 2.2, and 2.7 years for ribbon, multi, and mono crystalline technology respectively. In Bhandari et al. [35], the average EPBT ranged between 1.0 and 4.1 years. In ascending order, the module types were ranked as follows: cadmium telluride (CdTe), copper indium gallium diselenide (CIGS), amorphous silicon (a-Si), Poly crystalline silicon, and mono crystalline silicon. In Lamnatou et al. [36], the EPBT of a 150 kW_p PV plant composed of mono crystalline panels ranged from 2 to 3 years depending on the location of its operation.

2.2.4. Energy return on energy invested

The energy return on energy invested (ERoEI) is another frequently used indicator. Unlike EPBT, it is dimensionless, and it is a measure of the energy efficiency of the entire life cycle of the PV system. It represents the ratio of the usable energy produced by the PV panel over its operational lifetime to the total energy input required for the manufacturing, transportation, installation, maintenance, and decommissioning of the PV panel. A distinction is made between three different types of ERoEI depending on the boundaries considered: the standard or primary ERoEI, the point of use or final ERoEI, and the extended ERoEI, where the latter covers the full life cycle perspective [37]. For a PV system in Switzerland, the standard ERoEI ranged from 9 to 10 and from 7 to 8 for the extended one in the work of Rauegi et al. [38].

2.2.5. Different manufacturing scenarios

Three papers have conducted studies to explore the impact of different manufacturing location scenarios on the impact of PV panels. Starting with [39], they explored the effect of solar potential and electricity mix on the environmental impact payback (PBT_I) of a poly crystalline solar panel. Three different scenarios of PV manufacturing were tested, where each scenario consisted of all the steps taking place in one location at a time, either in China, Europe or the United States (US). Their scope included the distribution as well as the use in five different US cities (Phoenix, Indianapolis, Miami, Los Angeles, Seattle). The results show that the PBT_I is generally shorter than the average panel lifetime (30 years) but varies significantly based on impact category, solar potential, and electricity mix. Globally, the PBT_I was shorter for almost all the impact categories, the more solar potential the European made PV panels are operating in. Müller et al. [40] covered a one location at a time for all the manufacturing steps, a German, an average European and a Chinese scenario, and the transportation of the panel from the end of the manufacturing phase to an average European installation. The scope excluded the BOS and installation. The results were given by functional unit of kWp then kWh for a glass-backsheet and glass-glass PV module. Concerning climate change potential per kWp , glass-backsheet (glassglass) modules produced in China, Germany or Europe performed equivalent GHG emissions of 810 (750), 580 (520), and 480 (420) $kgCO_{2eq}/kWp$, respectively. In Gazbour [41], the scenarios chosen were more detailed since each manufacturing step occurred in a specific location, either Chinese or European, and a scenario involved both Norway and France. The scope of the work integrated the manufacturing and installation phases of a mono crystalline module, its BOS, but without considering the PV in a building integration in the two countries, and evaluated the impact of these scenarios on the climate change potential, EPBT and ERoEI.

2.3. Research gap and motivation of the paper:

In the context of countries with low-carbon electricity production mix, the environmental impact of PV panels takes on even greater significance to attest on the relevance of their use. Since the manufacturing phase of the PV panels has often showed to contribute with most emissions and resource uses, the purpose of the hereby presented work is (i) to explore different manufacturing scenarios in terms of location for PV panels, (ii) to investigate the subsequent consequences of changing transport distances, and (iii) to include the additional materials and products needed for installation at the building, i.e. BOS, inverter and mounting frame.

The objectives of this present work is to assess the environmental impact of installed PV panels, in a context of countries with low-carbon footprint energy mix. To do so, a comparison on the global warming potential, GHG avoided and CED non-renewable, fossil (CEDnrenF) between mono crystalline mounted roof PV panels with different manufacturing/distribution/installation scenarios, including a hypothetical European scenario and electricity mixes of France and Norway is conducted. Energy payback time and return on energy invested are also calculated.

A methodology will be addressed in the following chapter, presenting the different steps starting from the input definition, the analysis regarding both the energy and environmental aspect, and outputs retrieval. Following that, the methodology will be applied to calculate life cycle GHGe and energy uses of PVs in a residential building system, considering two different locations and energy mixes.

3. Method and development

The workflow displayed in Fig. 2 presents the methodology driving this study to quantify environmental KPI for PV panels in a building application.

Table 2

PV panels characteristics for energetic and environmental modeling.

Characteristic	Values
Nominal power at STC	$P_{nomSTC} = 450W_p$
Module efficiency at STC	$\eta_{STC} = 20.85\%$
Gross area	$A_{gross} = 2.16 m^2$
Module total weight without packaging	24.20 kg
Power temperature coefficient	-0.35%/K
Lifespan	25 years
Degradation coefficient 1 st year	$D_{1^{st}year} = 2\%$
Degradation coefficient over 25 years	$D_{Lifespan-1} = 0.55\%$
Wafer size	M10
Wafer thickness	150 μm
Cell type	mono crystalline
Cell number	60
Front sheet	Glass 3.2 mm
Encapsulant	EVA
Back sheet	PET
Frame	aluminum

It uses input parameters regarding their energy performance and environmental characteristics, loads relative to the building and weather data the building and PV panels are operating in. Then energy and LCA simulations are conducted using respectively TRNSYS [42] and SimaPro [43] software. On the one hand, the TRNSYS simulation outputs provide the whole PV panels installation's ($P_{PVtotalinstall}$) annual electricity production $E_{PVannual}$, from which the electricity production during the whole lifespan of the panels $E_{PVlifespan}$ is calculated taking into account the degradation coefficient. On the other hand, the LCA simulation provide the global warming potential and the CEDnrenF. These retrieved outputs allow to quantify the final KPIs and are summarized in Table 9. This study will be carried out for a roof-mounted mono crystalline PV panel technology.

3.1. Inputs

3.1.1. PV panel technical and environmental description

The PV panel studied is a mono crystalline mono-facial phosphorus doped (P-type) module, its energy performance and environmental characteristics are displayed in Table 2. Its efficiency is aligned with the most efficient PV panels according to latest updates in November 2023 [44]. These characteristics were retrieved from the technical sheets provided by the manufacturer concerning the nominal power, module efficiency, area, weight, power temperature coefficient, lifespan and degradation coefficient. For the other characteristics, i.e. the wafer sizes and thickness, cell number, type of front and back sheets, encapsulating and material for the frame, are collected from the environmental product declaration (EPD) of the PV panel from the INIES database [45].

3.1.2. Weather data

For this study, the PV panels are installed on a building's roof operating in two different climates. The first location concerns the city of Chambéry, in southeast region of France. The second location is the city of Trondheim in center region of Norway. According to the Köppen climate classification, the city of Chambéry is on the boundary between the humid subtropical (Cfa) and oceanic climates (Cfb) and it benefits from a mountain climate, characterized by dry, hot summers and moderate winters with frequent temperatures below freezing, especially at night. While, the city of Trondheim has continental sub-arctic climate (Dfc) with cold winters and mild summers. For the weather data, weather files are retrieved from Meteonorm [46] data base v7.3.3. Interpolated data from other location for both temperature and solar irradiation are used for both cities.

Fig. 3 shows the monthly global solar irradiation on a horizontal surface for both cities. From the weather files, the total annual solar irradiation for both locations accounts for 1229 $kWh/m^2 \cdot year$ in Chambéry and 923 $kWh/m^2 \cdot year$ for Trondheim which represents 25% less.

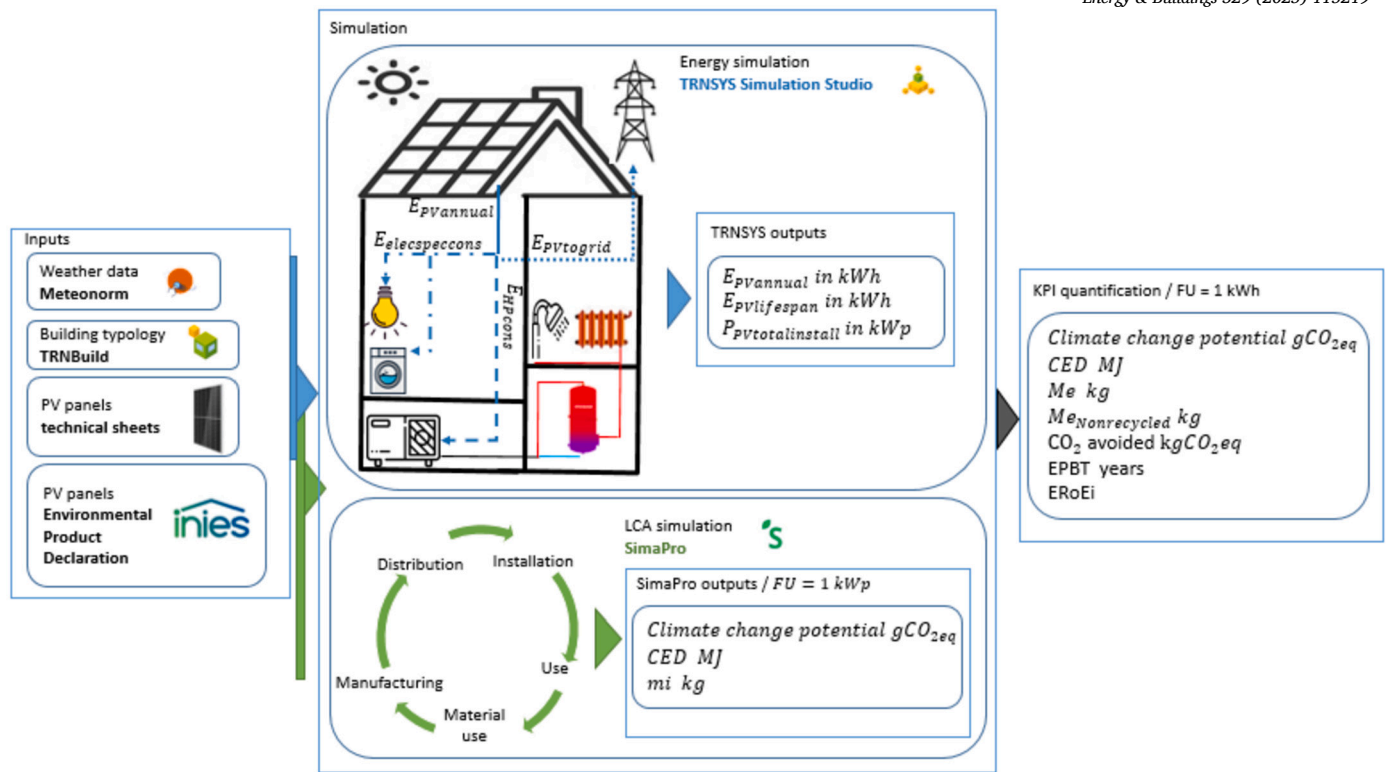


Fig. 2. Methodology of the study.

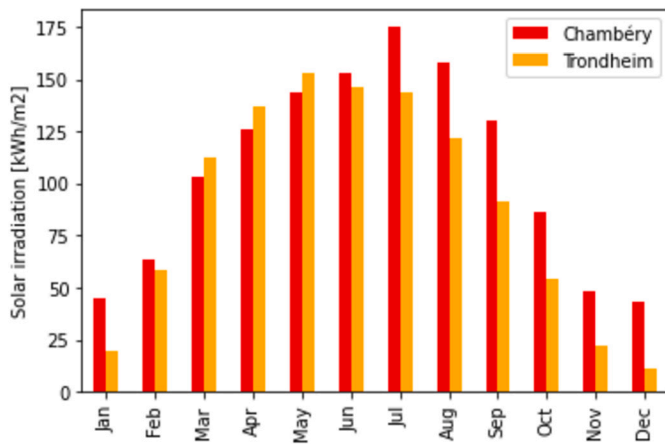


Fig. 3. Monthly global horizontal solar irradiation of Chambéry and Trondheim.

This will allow testing the PV panels in two different solar conditions. Apart from the quantity of solar irradiation occurring on a surface, both locations being in a middle latitude for France, and high latitude for Norway, will highlight the influence of the sun position in the electricity production. For that, PV panels should be tilted depending on the locations to increase the irradiation impinging on a surface.

3.1.3. Case study building, energy systems and loads

The building considered to test the methodology is a single family detached house modeled using the TRNSYS type 56 building model. It has a total area of 170 m², 90 m² of heated and cooled space and a solar roof area potential of 16.6 m². Two people are supposed living in such building: the domestic hot water (DHW) consumption is assumed 104 l/day. Specific electricity profile is assessed using CREST model v2.2.1 [47]. It was assumed $E_{elecspccons} = 2280 kWh$ annual specific electricity consumption yearly. The air infiltration rate of the living rooms was set at 0.685 vol/h and 1.1 vol/h in the attic. The internal heat gains

due to the occupants and equipment were also added: they account for 137 and 25 W respectively.

Concerning the energy systems of the house, the PV panels are coupled to an air to water HP that constitutes the only heating system of the house as shown in Fig. 4 [48]. Two storage tanks for the heating and DHW loops are connected to the HP. It was assumed that the house is connected to the grid that offers the possibility to feed the over produced electricity into it. In order to assess the self-consumption potential of the system, the PV electricity produced is considered to be supplied to the different sinks: the HP, the specific electricity consumption and the electricity grid.

3.2. Energy simulation

3.2.1. Model description

For the study, existing types in the TRNSYS library are used. Fig. 5 is a simplified scheme that shows how the different components are linked to each other. Concerning the PV panels, type 835 from Tess library described in Danny [49] and Lämmle et al. [50], is used. The specificity of this type is that in addition to modeling a PV panel, it can be coupled with existing models of ST panels to form a hybrid photovoltaic thermal (PVT) panel, while maintaining the same electrical characteristics of the PV panel. Another specific Tess library type used concerns the HP modeled using Type 941, representing a single-stage reversible air-to-water HP. It utilizes user-supplied data files containing capacity and power data based on inlet water and air temperatures, while also considering the effects of air humidity by accepting either air relative humidity or absolute humidity ratio as inputs. The Meteonorm weather files are read using weather type 15 and it provides the data required by the PV panels and the HP to operate. Specific electricity and domestic hot water needs are retrieved from user defined files. The building type 56 provides the heating loads, leading to a realistic dynamic electricity consumption linked to dynamic heating demand from the building linked to the thermal storage working with thermostat temperature control signals, and influences the self-consumption and grid balance in

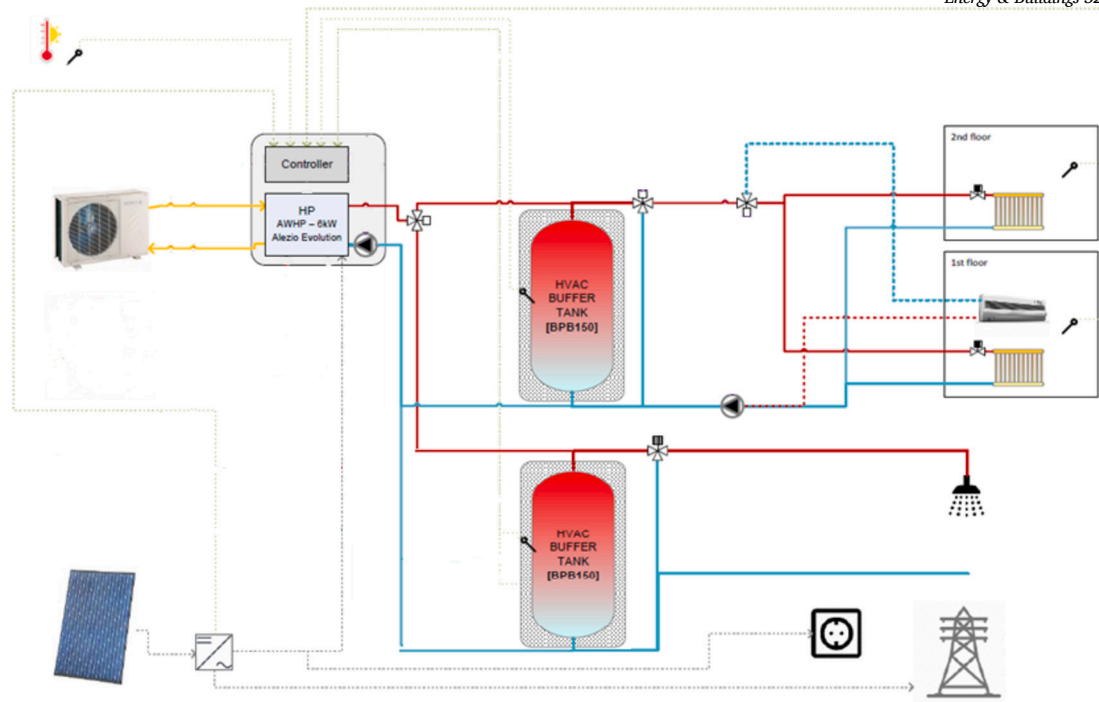


Fig. 4. Building's energy systems configuration.

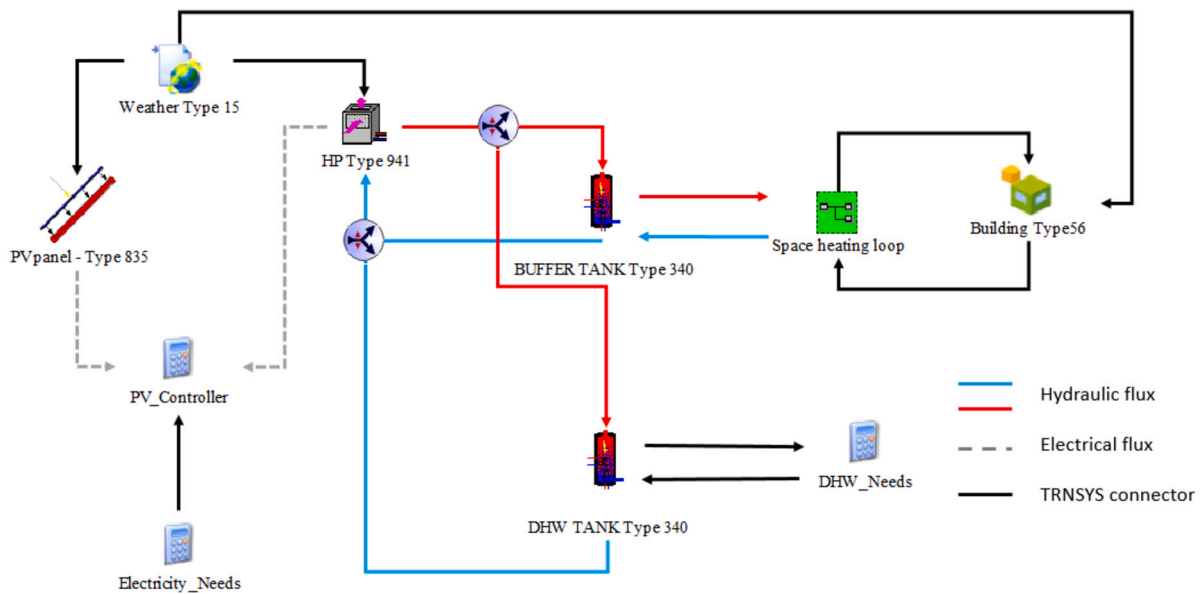


Fig. 5. Simplified TRNSYS diagram of the energy simulation modeling.

given weather conditions and electricity consumption linked to heating demand.

3.2.2. Application to Norway and France case studies

The building's orientation is such that the roof on which the PV panels are installed faces south. A parametric study is conducted on the PV tilt roof angles values ranging from 0° for a horizontal PV installation until 90° for a vertical one to find the optimal one for Norway and France. Fig. 6 displays the results of the total annual PV installation productions $E_{PV\ annual}$.

For the rest of the analysis, the evaluation of the PV production that will be used for the KPIs quantification, will only concern the optimal PV configurations. For both location, the south orientation corresponding to an azimuth angle equal to 0° is the optimal one for the roof's facade

direction. As for the tilt roof angle of the PV panels, it will be equal to 32° and 44° for the French and Norwegian case respectively.

Considering the house's solar roof area potential of 16.6 m², and the PV panel gross area of 2.16 m², the PV installation is composed of 7 panels of nominal power at STC $P_{nomSTC} = 450W_p$ per panel, therefore the total nominal power of the installation is equal to $P_{PV\ total\ install} = 3.15 kW_p$. From the TRNSYS simulations, the DHW annual needs reach 1478 and 1703 kWh annually for Chambéry, in France and Trondheim, in Norway. The building operating in both locations defines two different heating needs, that correspond to keeping a set point temperature of the heated areas at 19°C during winter and inter season. The total heating needs are equal to 12492 kWh in Chambéry and 16510 kWh in Trondheim. Since the heating loads are satisfied by the HP, the total energy consumption of the house is 100% electric and corresponds to

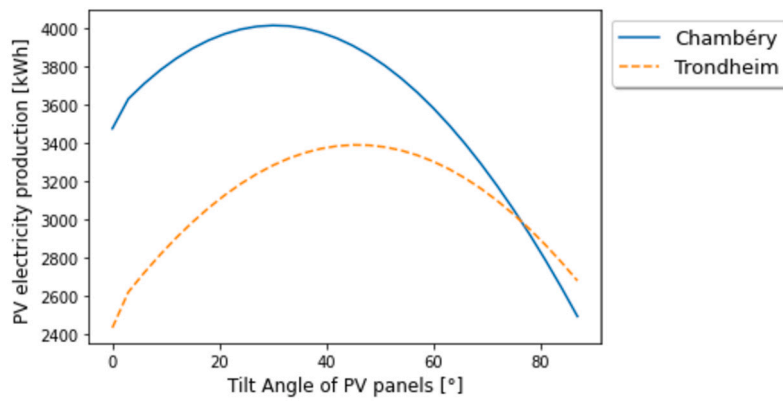


Fig. 6. PV annual electricity production in function of their tilt angles.

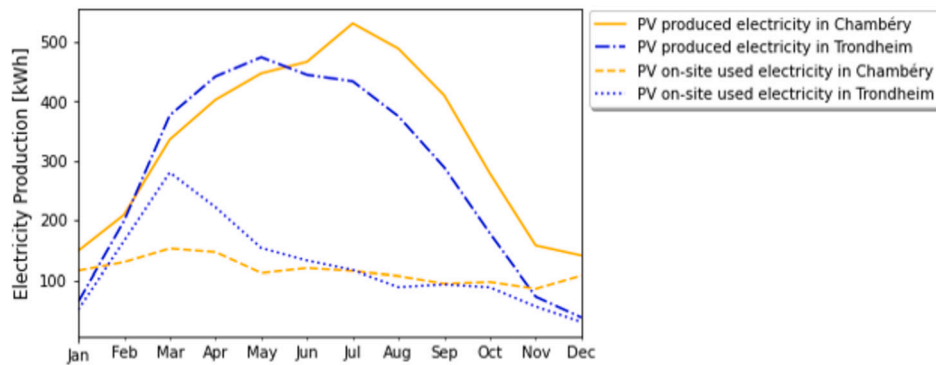


Fig. 7. The monthly PV electricity production and self consumption in France and Norway.

the electrical consumption of the HP E_{HPcons} and $E_{elecspcons}$ the specific electricity consumption of the house’s appliances. The E_{HPcons} is equal to 6450 and 8645 kWh annually for the HP for France and Norway respectively. The $E_{elecspcons}$ is independent of the location and is equal to 2280 kWh annually.

In the graph in Fig. 7 are drawn the monthly productions and self-consumption of the PV panels installation in Chambéry and in Trondheim. The total annual electricity production $E_{PVannual}$ of the total PV installation is respectively 4011 and 3380 kWh for Chambéry and for Trondheim without taking into consideration the degradation coefficient. The share of the electricity produced by PV is directly consumed on site by the building. Such electricity share is calculated step by step through the TRNSYS simulations and integrated each month through the TRNSYS simulations. This annual self-consumption E_{PVused} is equal to 1378 and 1472 kWh for Chambéry and for Trondheim.

The self-consumption ratio, or supply cover factor (SCF), is also calculated. It represents the share of PV production that has been used on the installation site. It is defined as the ratio between the annual self-consumed PV electricity and the total annual PV electricity produced according to equation (1) in Bockelmann et al. [51]:

$$SCF = \frac{E_{PVused}}{E_{PVannual}} \quad (1)$$

Table 3 summarizes the results of the annual produced and self-consumed PV electricity, as well as the results for the SCF for both location. The electricity to the grid $E_{PVtogrid}$ is the annual amount of the PV panels electricity fed to the grid, and is equal to $E_{PVannual} - E_{PVused}$.

In the spring period between March and April, cf. Fig. 7, the PV panels in Trondheim produce more energy than those installed in Chambéry, as the solar irradiation in Trondheim was higher than in Chambéry during this time, cf. Fig. 3. Since spring is still part of the heating season in both countries, with greater heating needs in Trondheim than in Chambéry, this results in a higher self-consumption ratio in Norway

Table 3

Energy outputs for both locations.

	France	Norway
$E_{PVannual}$	4011 kWh	3380 kWh
E_{PVused}	1378 kWh	1472 kWh
$E_{PVtogrid}$	2632 kWh	1907 kWh
SCF	34%	43%

compared to France. It is important to note that self-consumption is a key aspect in optimizing the use of PV panels, contrary to the expectations of certain countries, such as Norway with its Green Industry Initiative program [14], which may emphasize energy independence over feeding excess PV electricity into the grid. While self-consumption reduces the need for battery storage in some configurations (e.g., isolated houses), it is crucial to highlight the role of grid flexibility in absorbing surplus PV electricity, which ultimately increases the share of renewable energy sources (RES) in the electricity mix.

3.3. LCA based KPI

The essential steps of an LCA, according to the international standards ISO 14040, start with defining the goal and scope by establishing the purpose, boundaries, the impact assessment method and the functional unit (FU) of the product studied. The following step is to conduct the inventory analysis by compiling data on inputs and outputs of the processes throughout the life cycle stages of the product. Next is performing the impact assessment that consists of translating the inventory data into environmental impacts. Finally, the results are synthesized and interpreted.

3.3.1. Goal and scope definition

The goal of the LCA is to assess the cradle-to-use GHGe and cumulative fossil energy uses from PVs in the French and Norwegian grid

mix contexts, by the use of building application cases as described in Table 2.

The Simapro software is used as well as the Ecoinvent database v3.9, cut-off allocation. Simapro and Ecoinvent are considered the most accurate tools in LCA due to their comprehensive databases, rigorous data collection methods, and extensive coverage of life cycle inventory data across various industries and regions, ensuring reliable and scientifically robust assessments of environmental impacts. Among the different impact assessment methods available in the LCA calculation, the environmental footprint (EF) reference package 3.1 is used. The use of EF is part of the EU commission recommendation 2021/2279 to measure and indicate the environmental performance of products and organizations throughout their life cycle. The indicator from the EF3.1 method used to describe the global warming potential is the global warming potential in a 100 years time horizon (GWP100). This indicator, expressed in kg CO_2 -equivalents, is crucial when studying the environmental footprint of a system or product, as it assesses its contribution to changes in global average surface-air temperature and subsequent impacts on climate parameters such as storm frequency, rainfall intensity, and flooding frequency [31]. The CEDnrenF indicator will serve to quantify the KPIs that are the EPBT, ERoEI using the TRNSYS energy simulations outputs. The CEDnrenF is assessed using the abiotic depletion potential (ADP): fossil fuels indicator from the EF3.1 method that takes into account the non-renewable energy resources in their fossil fuel form.

The FU in which the LCA results are calculated in the LCA is $1 kW_p$ of electricity production capacity with a maximum of 2% of production the first year and 0.55% the remaining years based on reference lifetime of 25 years with a mono crystalline PV panel. The final FU used to quantify the KPI and evaluate the impact of the same PV panel as recommended in Frischknecht et al. [52] is $1 kW_h$ of PV electricity produced. The initial FU in $1 kW_p$ from the LCA modeling step, is converted to the kW_h using the electricity produced in the 25 years from the TRNSYS simulations. Following the European EN 15804 standards for modularity in environmental product declarations, the life cycle modules included in the analysis are: production of PV system components (PV module, inverter, BOS) and mounting installation (life cycle modules A1-A3), transport to the installation site (module A4) and replacements (module B4) of the inverter and BOS after 15 years of use.

3.3.2. Life cycle inventory

At this stage, all the processes required to build the final product, which is the $1 kW_p$ of PV panels, are brought together to design the product stage. The different stages are the selection of the processes for the manufacturing part, then the processes that concern the distribution and installation part, and the inventory of materials.

The LCA is performed across several scenarios that examine variations in manufacturing, transportation, and installation, as outlined in Table 4. Scenarios 1 and 2 serve as the baseline cases, where PV panels are manufactured, transported, and installed according to the most common market configurations. These panels, predominantly produced in China, are then shipped and installed in France (scenario 1) and Norway (scenario 2). These reference scenarios are crucial for understanding the typical environmental impact of PV panels available in the market today.

Scenarios 3 through 6 explore how the environmental performance of PV panels changes depending on the location of their manufacturing and transportation distances. In scenarios 3 and 4, the early stages of production—polysilicon processing, ingot formation, and wafer production—are carried out in Germany and Norway, where plants for these processes are well-established [53]. Despite this shift in the supply chain, the cell assembly remains in China due to the economic benefits it offers through lower costs. However, in an effort to localize the production and reduce emissions related to module assembly using a Chinese energy mix, the module assembly occurs in the country of installation, either France or Norway.

Scenarios 5 and 6 introduce a hypothetical approach where all stages of silicon processing are carried out in Norway. This scenario reflects the country's potential to further develop its silicon manufacturing capabilities. Then, the cell and module assembly are performed locally, either in France (scenario 5) or Norway (scenario 6), where the PV panel will be installed. This setup minimizes the environmental burden associated with global supply chains by reducing transportation between production stages and bringing more of the manufacturing process closer to the final installation site.

The transportation, referring to the shipping of the module from the place it was assembled in to the place of installation, is described in Table 5. For the reference scenarios (1 and 2), PV panels are shipped from China to the final installation sites in France and Norway, involving long container ship journeys and significant overland transport by lorry, which corresponds to transportation cases 1 and 2. In contrast, scenarios 3, 4, 5 and 6, which involve module assembly in France and Norway, reduce transportation emissions as the panels are distributed locally within the country of installation. The transportation scenarios correspond to case 3 for the French case and case 4 for the Norwegian one.

In order to conduct the LCA modeling, information about the process for the different PV manufacturing steps are necessary. These steps corresponds to a PV module retrieved from internal database [41], and its manufacturing corresponds to the processes described step by step in Table 6.

Table 6 outlines the key manufacturing steps for PV panels, such as polysilicon production using the Siemens process, ingot formation with Czochralski purification, wafer production via diamond wire cutting, and cell manufacturing using PERC technology. These processes, from raw silicon to module assembly, are modeled in the LCA to assess their environmental impact. In the various scenarios, these manufacturing steps take place in different locations—China, Germany, France, and Norway—each with a distinct energy mix. The scenarios thus reflect how the environmental footprint of PV panels varies based on where these processes occur and the local energy mix used in each country. This approach highlights the significance of production location in the overall environmental impact of the panels.

The material composing the PV module are the same independently from the manufacturing, distribution and installation scenarios previously described in 4. The scope includes the materials used for the manufacturing of the PV panel as well as the one used for the PV installation on the roof. In Table 7 are displayed the quantity of materials per functional unit of $1 kW_p$. The quantity of the aluminum, steel and copper used for the mounting and roof installation of the PV panels, is retrieved from Underwood et al. [54], by taking the average of the range considered for roof-mounted PV modules for each material. Glass represents the biggest share of material use in a PV panel since the module considered is dual glass to enhance its toughness and resistance. The second most used material is aluminum for the frame, support and mounting structures. Plastic composes both the encapsulating and back sheet. Copper is used for interconnecting the cells, the junction boxes that are part of the BOS, is part of the inverter's compositions as well as the module to module cabling. The inverter is also composed of steel, and silver is used for its conductive power in the cell.

4. Results and discussion

4.1. Life cycle impact assessment (LCIA)

The results that are discussed in the following are intermediate results and concern the global warming potential (GWP) in $kg.CO_2eq$ and the CEDnrenF in MJ and are displayed in Table 8 for the whole manufacturing, distribution and installation phases, per initial FU of $1 kW_p$.

To highlight the weight of each stage in the overall environmental impact, the Figs. 8 and 9 show the ratio of each of the three stages. The two graphs show that in terms of GWP, the transportation has a minimal

Table 4
PV manufacturing places.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Polysilicon	China	China	Germany	Germany	Norway	Norway
Ingots	China	China	Norway	Norway	Norway	Norway
Wafers	China	China	Norway	Norway	Norway	Norway
Cell	China	China	China	China	France	Norway
Module	China	China	France	Norway	France	Norway
Transportation	Case 1	Case 2	Case 3	Case 4	Case 3	Case 4
Installation	France	Norway	France	Norway	France	Norway

Table 5
PV panels transportation scenarios.

	Module assembly place	Expedition place	Reception place	Installation	Total kms by mean of transport
Case 1	Chinese factory	Shanghai Harbour	Marseille Harbour	Chambéry	657 kms Lorry and 19734 kms in container ship
Case 2	Chinese factory	Shanghai Harbour	Trondheim Harbour	Trondheim	354 kms Lorry and 20515 kms in container ship
Case 3	French factory		Chambéry		305 kms Lorry
Case 4	Norwegian factory		Trondheim		80 kms Lorry

Table 6
Manufacturing processes of the PV panel used in the LCA's hypotheses.

Step	Process
Polysilicon	Siemens process
Ingot	Czochralski purification
Wafers	Diamond wire cutting
Cell	PERC process
Module	Monofacial

Table 7
PV material inventory per kW_p .

Material investment m_i	Total in k_g/kW_p
Glass	39.17
aluminum (Al)	18.1
Copper (Cu)	2.7
Plastic	6.7
Silicon	2.6
Steel	0.62
Silver (Ag)	0.01475
Total m_i	69,9

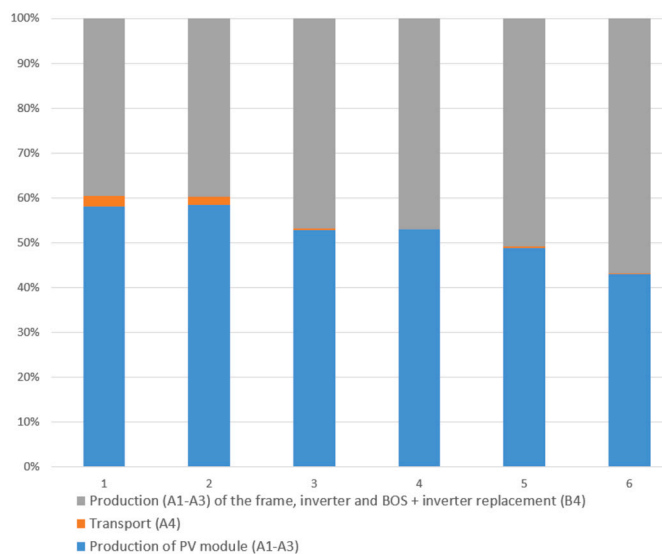


Fig. 9. Share of total CEDnrenF from production of PV module, transportation and production/replacement of system components.

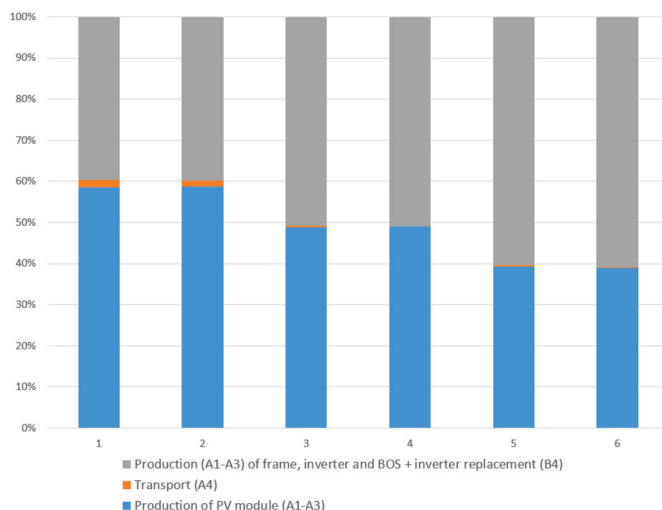


Fig. 8. Share of total GWP from production of PV module, transportation and production/replacement of system components.

impact (of the order of 2% for scenarios 1 and 2 and is nearly 0% for the remaining scenarios) compared to the production and replacements of PV module and system components (mounting frame, inverter, BOS). The PV system components account for between 39% and 58% of total global warming potential, and the more decarbonized the PV production scenario, the greater is the impact. On the other hand, the PV module transportation also accounts for approximately 2% of total CEDnrenF in the scenarios 1 and the scenario 2, where modules are distributed from their assembly site in China to their installation sites in Chambéry and Trondheim.

4.2. KPI definition and application to the case study

In this section, the KPI definitions retrieved from the literature, are presented and integrated in the environmental impact assessment methodology, as well as their quantification while applied to the case study.

In order to have the impact of the whole PV installation per kWh , the LCA outputs per kW_p are divided by the total electricity production in kWh/kW_p obtained with the TRNSYS simulations for both sites, Chambéry and Trondheim, over the PV panel lifespan taking into account the degradation coefficient in Table 2.

Table 8
LCA Results for a $1kW_p$ FU.

FU = $1kW_p$	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
GWP $kgCO_2eq$	1220.5	1217.4	946.2	941.7	788	786.6
CEDnrenF MJ	11701	11657	11773	11736	10790	9677

Table 9
Summary of the variables (simulation outputs) used in the methodology.

Variables		Unit	Definition
TRNSYS outputs	$E_{PVannual}$	kWh	Annual PV electricity production
	$E_{totalcons}$	kWh	Annual total electricity consumption
	E_{HPcons}	kWh	Annual HP electricity consumption
	$E_{electspecons}$	kWh	Annual specific electricity consumption
	E_{PVused}	kWh	Annual PV self-consumed electricity
	$E_{PVtogrid}$	kWh	Annual PV electricity fed to the grid
SimaPro outputs	Global Warming Potential	gCO_{2eq}/kW_p	global warming potential
	CEDnrenF	MJ/kW_p	Resource use, fossils
Post processing outputs	$E_{PVlifespanspan}$	kWh	PV production during the lifespan
	$P_{PVtotalinstall}$	kW_p	Total PV installation's nominal power at STC

Table 10
LCA results for a $1kWh$ FU.

FU = $1kWh$	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Place of installation	France	Norway	France	Norway	France	Norway
GWP gCO_2eq	38.6	45.7	29.9	35.3	25	29.5
CEDnrenF MJ	0.37	0.44	0.37	0.44	0.34	0.36

The total PV production $E_{PVlifespanspan}$ is calculated using the equation (2):

$$E_{PVlifespanspan} = E_{1^{st}year} \left(1 + \sum_{n=1}^{Lifespanspan-1} (1 - D_{Lifespanspan-1})^n \right) \quad (2)$$

$E_{1^{st}year}$ is equal to the annual PV production $E_{PVannual}$ from the TRNSYS simulation multiplied by $D_{1^{st}year}$ the 2% degradation of the PV panel in its first year of use as described in the PV panel technical characteristics in Table 2, and $D_{Lifespanspan-1}$ the degradation coefficient taken for the PV panels equal to 0.55% for the remaining years until its lifespan equal to 25 years.

The total PV production of the installation $E_{PVlifespanspan}$ is equal to 99663 kWh and 83984 kWh for France and Norway respectively for the total installation $P_{PVtotalinstall} = 3.15 kW_p$. In order to obtain the LCA outputs of global warming potential and CEDnrenF per kWh , the outputs per kW_p are divided by the PV production in kWh per $1kW_p$, which is equal to $E_{PVlifespanspan}/P_{PVtotalinstall} = 31639 kWh/kW_p$ and 26661 kWh/kW_p for France and Norway respectively.

4.2.1. Global warming potential and CEDnrenF

The results for the global warming potential and CEDnrenF impact per kWh are displayed in Table 10, for PV module (A1-A3), other system components (A1-A3 + B4) and transportation (A4) phases combined. In terms of global warming potential and total CEDnrenF, there is 22% and 14% gain between a production scenario occurring both in Europe and China (scenarios 3 and scenario 4) and the 100% Chinese reference (scenarios 1 and scenario 2). For the hypothetical scenario with all production steps in Norway and in France (scenarios 5 and scenario 6), there is 35% and 21-29% GHG reduction compared to the 100% Chinese reference (scenarios 1 and scenario 2). The location of the PV manufacturing plays an important role in the environmental impact of the PV panel due to the energy mixes of the countries where the processes are conducted. France and Norway represent a great potential to reduce this impact for a process in the rest of the Europe and even a worldwide one.

The annual average global warming potential and CEDnrenF of $1 kWh$ of electricity production of France and Norway are given in Ta-

ble 11. They are taken from the Ecoinvent database v3.9 using the same LCA EF3.1 method as the one used in the PV panel Simapro simulations.

In all the production scenarios presented in Table 10, the PV panels have less carbon impact than the French electricity mix for $1 kWh$ of electricity. Whereas for Norway, only the hypothetical production scenario 6 is nearly equivalent, although still higher than the electricity production mix (29.5 vs 27,6 gCO_2eq/kWh). Looking at the CEDnrenF of the PV panels in the different scenarios in Table 10, and the CEDnrenF of France's and Norway's electricity production mix in Table 11, PV panels in scenarios 1, scenario 3 and scenario 5, require over thirty times less primary energy in MJ per kWh than the French electricity mix that relies on energy sources that require a high quantity of fossil fuel in their production. Norway's electricity mix CEDnrenF is relatively low and is equal to 0.57 MJ since it relies mainly on hydropower, but all the PV panels in scenarios 2, scenario 4 and scenario 6 require fossil fuel resources.

4.2.2. CO2 avoided

The hereby presented case study highlights a certain type of application for PV panels installed in a house to meet its needs. As this house's energy requirement is electrical power due to the use of a HP, and as it forms part of a global network by being connected to the electricity grid, the interest in using PV panels in this context can be questioned. From a purely building point of view, the impact of using a solar system or not can be calculated, on the latter's global warming potential. To do this, the criteria of CO_2 avoided is introduced, which corresponds to the PV annual self-consumed electricity multiplied by CO_2 emissions of the produced electricity mix of the country following the equation (3):

$$CO_2 \text{ avoided} = \int_1^{8760} E_{PVused}(t) * (CO_2 \text{ emissions electricity mix}(t) - CO_2 \text{ emissions PV panels}(t)) dt \quad (3)$$

Since PV offers intermittent energy production, this indicator was calculated by taking into account the real carbon cost of the energy mix on an hourly basis, taken from the Electricitymaps [5] open source data.

Table 11
Environmental impact indicators for France and Norway's of 1 kWh of the electricity production mix.

Market for electricity, medium voltage Electricity, medium voltage Cut-off, U	France	Norway
global warming potential gCO_2eq	77.6	27.6
CEDnrenF MJ	11.62	0.57

Table 12
GHG avoided quantification from the LCA results per kWh for the different production scenarios.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
$CO_2avoided\ kgCO_2eq$	23.3	-20.5	35.3	-5.5	42.1	3.4

The amount of CO_2 avoided is calculated and displayed in Table 12 for the six scenarios. During the first year of use, the PV panel installation in the case study participated in avoiding, depending on the manufacturing scenarios for the French case, which corresponds to scenarios 1, 3 and 5, respectively 23.3, 35.3 and 42.3 $kgCO_2eq$ in France in comparison to the case where the house uses only the electricity from the grid. While it represents only 8, 10 and 11% of GHG avoided compared to the reference 100% grid electricity case, it is important to note that the electricity from the PV production and fed to the grid, and thus has participated in decarbonizing the French electricity mix. The integration of more RES in the electricity mix will help in the low-emission transition many countries are aiming for. For the Norwegian cases, the introduction of PV panels enhances the amount of GHG compared to using the electricity from the grid. Only for the scenario 6 is a positive gain but only of 3.4 $kgCO_2eq$. This illustrates how the use of low-carbon energy production mixes in calculations about avoided electricity may lead to the conclusion that PV installations are not beneficial in a GWP assessment. However, from a market perspective, the Norwegian electricity grid is connected with the rest of Europe, where direct emission factors alone (i.e. not including life-cycle perspective of grid infrastructure) was 258 $g\ CO_2e/kWh$ in 2022 [55]. Thus, using market-based CO_2e -factors for the electricity would change notably from using the Norwegian production factor. This indicator questions the relevance of PV installation in countries with low-carbon electricity production mixes such as Norway's at 29 $g\ CO_2e/kWh$. Such aspects of CO_2e -factors have been discussed in literature such as Pinel et al. [56], Grinham et al. [57].

4.2.3. Energy return on energy invested (ERoEI) and energy PayBack time (EPBT)

The ERoEI is calculated from the CEDnrenF obtained by the LCA simulations for the different scenarios, and the production of the PV panel in its 25 years lifespan. The CEDnrenF (in MJ) expressing a primary energy needs to be converted to kWh of equivalent electricity. For that, a ratio known as the efficiency of the electricity grid and equal to $\eta_{grid} = 11.4\ MJ/kWh$ in de Wild-Scholten [58] is used. The ERoEI follows the equation (4):

$$ERoEI = \frac{E_{PV\ lifespan} \cdot \eta_{grid}}{CEDnrenF} \quad (4)$$

The EPBT is the ratio between the CEDnrenF and the energy produced in one year of the PV panel. Taking the average PV production per year $P_{PV\ oneyear}$ as the total PV production over the lifespan divided by $lifespan$ the number of years, the EPBT can be derived from the ERoEI following equation (5) and expressed following equation (6):

$$ERoEI = \frac{P_{PV\ oneyear} \cdot lifespan}{CEDnrenF} = \frac{lifespan}{EPBT} \quad (5)$$

$$EPBT = \frac{lifespan}{ERoEI} \quad (6)$$

The results for the EPBT and ERoEI for the different scenarios are displayed in Table 13.

The EPBT is higher in all the scenarios of PV installed in Norway than the ones in France due to the less electricity produced due to the lower irradiation impinging on the PV panel. The range of the EPBT obtained in this study are aligned with the latest PV technologies and for almost all the scenarios is less than one year. Only scenario 2 passes slightly out one year. For the ERoEI, the values found are higher than the ones found in the literature for the PV panels, especially for the scenarios involving European production (see Table 4). This confirms the importance of the production location on the environmental impact of PV panels.

4.3. Limitations of the study

In this section, the inherent limitations and assumptions in the study are acknowledged, aiming to provide a transparent evaluation of the research methodology and findings. While these assumptions were essential for framing the research questions and guiding the analysis, they may have influenced the interpretation of the results.

Concerning the energy modeling part, the dynamic simulation were assessed using the TRNSYS software, that may not always capture the full complexity of the system or may oversimplify certain aspects, leading to deviations between simulated and actual performance. For the LCA simulations, only the Ecoinvent database was used, and like any modeling approach, it requires simplifications and assumptions to represent complex real-world systems. These assumptions can introduce uncertainties and may not always capture the full complexity of the system being assessed.

5. Conclusion and future perspectives

This study explores the use of PV panels in regions already relying on clean energy sources for electricity production. As the global pursuit of cleaner energy gains momentum, it is crucial to grasp the role that PV panels play in the energy transition. The main results of the KPIs quantification per kWh are summarized in Table 14.

The conducted study highlights the significance to opt for PV panels as follows:

- Local European production scenarios for PV panels are very interesting for countries with low-carbon grid mixes, so that the PV panels can benefit from the low-carbon electricity grid in. In order to deploy PV more broadly in these countries, effort should be made to maintain the development of local polysilicon and wafers factories as well as the cell manufacturing.

Perspectives to this study can be as follows:

- LCA Comparisons: Conduct more extensive LCA comparing PV panels with other solar RES such as ST collector and hybrid PVT panels, specially on the material use and end-of-life aspects.
- Digitalisation: the digital era is transforming the global energy system by increasing data, analytics, and connectivity, offering potential improvements in energy efficiency but also risks of higher

Table 13
ERoEI and EPBT quantification from the LCA results for the different manufacturing scenarios.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Place of installation	France	Norway	France	Norway	France	Norway
PV lifespan production kWh	99663	83984	99663	83984	99663	83984
PV lifespan production kWh/kWp	31639	26661	31639	26661	31639	26661
<i>ERoEI</i>	30.8	26.1	30.6	25.9	33.4	31.4
<i>EPBT</i> _{year}	0.81	0.96	0.82	0.97	0.75	0.80

Table 14
Summary of the KPI quantification applied to the case study.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Place of installation	France	Norway	France	Norway	France	Norway
GWP (gCO_2eq)	38.6	45.7	29.9	35.3	25	29.5
CED _{nrenF} (MJ)	0.37	0.44	0.37	0.44	0.34	0.36
CO_2 avoided ($kgCO_2,eq$)	23.3	-20.5	35.3	-5.5	42.1	3.4
<i>ERoEI</i> (-)	30.8	26.1	30.6	25.9	33.4	31.4
<i>EPBT</i> (year)	0.81	0.96	0.82	0.97	0.75	0.80

energy use, requiring careful management by policymakers to maximize benefits and minimize negative impacts. In response, the IEA has initiated a collaborative effort across multiple agencies to investigate how digitalization can enhance energy efficiency and provide policy recommendations. Research should focus on the integration of smart control systems to optimize the synergy between photovoltaic panels and heat pumps. These systems, such as advanced monitoring, automation, and predictive maintenance algorithms, can further enhance energy efficiency, increase self-consumption of renewable energy, and reduce GHG emissions. In the work of Baraskar et al. [59] of a German household, a smart-grid controlled PV-HP-battery system achieved 43% self-consumption of PV electricity over 12 months, and an increased solar fraction of the heat pump from 36 to 98% using a SG-Ready mode. SG-Ready mode optimizes energy use by adjusting the heat pump's operation to maximize the use of surplus photovoltaic electricity and fully charged batteries, boosting temperatures when PV power is available and reverting to normal when it's not. Kemmler and Thomas [60] also found that combining HP with PV can significantly enhance PV self-consumption in residential buildings. Using a thermal energy storage and an intelligent control that optimizes heat pump operation by aligning it with high PV power production times, their method enables up to 41% of annual electricity consumption to be covered by PV power.

- Economic Viability: investigate the economic aspects of PV panel adoption, especially in regions with a low carbon footprint. Analyze the cost-effectiveness of integrating PV panels into existing energy infrastructures, considering factors such as long-term maintenance costs and economic benefits to local communities. Also, taking into account the cost of investing in local PV panel manufacturing plants and its impact in the final cost of the produced PV modules is a relevant aspect.
- Policy Implications: examine the impact of different policy frameworks on the adoption of PV panels, with a focus on local manufacturing. Investigate how government regulations influence the decisions of manufacturers and consumers in the renewable energy sector.

CRedit authorship contribution statement

Hafsa Fares: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Gabriele Lobaccaro:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Nouha Gazbour:**

Writing – review & editing, Validation, Software, Resources, Data curation. **Freja Nygaard Rasmussen:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **David Chèze:** Writing – review & editing, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Nolwenn Le Pierrès:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Etienne Wurtz:** Validation, Supervision, Methodology, Investigation.

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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Data availability

Data will be made available on request.

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