



Review Article

Performance indicators of photovoltaic heat-pumps

C. Lorenzo^{*}, L. Narvarte

Universidad Politécnica de Madrid, 28031, Madrid, Spain



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ABSTRACT

In the last few decades, the demand for reversible heating and cooling systems has increased significantly, together with the need to generate energy in a more efficient and sustainable way. Consequently, the concept of solar photovoltaic (PV) powered heat pumps (HP) has become very attractive in order to match the heating/cooling demand with a renewable and environmentally-friendly energy source. This paper presents a review of the different solutions for PV-HP systems that have been studied theoretically and/or experimentally tested, and of the Key Performance Indicators (KPIs) that were mainly used. An analysis of these traditional KPIs has been performed and their boundaries were identified. As a result, new KPIs (PR_{25} , $PR_{ref,25}$, SPF_{PV-HP} and $SPF_{PV-HP,ref,25}$) were proposed for trying to mitigate such limitations, as well as for evaluating not only the quality of the HP and the PV system, but also the quality of their integration and the renewable character of the whole PV-HP system. This paper is aimed to be framed in the common effort of the PV-HP research community to reach a set of KPIs that allow comparing the different future works and, therefore, a set of recommendations and future research lines are also proposed.

1. Introduction

Since 2005, the increasing demand for heating and cooling has given rise to the growth in the market for heat pumps (HPs) worldwide, as HPs are capable of supplying this thermal demand with smaller power consumptions than any other technology. According to the European Heat Pumps Agency, this market increased by 12% in terms of units sold in 2015 (which means an installed electrical power of 2.11 GW) [1] and by 12% in 2016 (2.37 GW) [2]. In energetic terms, the use of these recent HPs saved 11.6 TWh of final energy demand in 2015 and 13.1 TWh in 2016, as well as avoiding 2.3 Mt of CO₂ emissions in 2015 and 2.6 Mt in 2016. This market growth is expected to be maintained in the near future, with estimations of the compound annual growth rate in the range 6.02% [3] to 10.25% [4] for the period 2016–2021. However, even if HP are one of the most efficient technologies for heating/cooling applications, the overall power consumption in Europe in this sector is increasing every year, so greater efforts must be dedicated to achieving the environmental objectives of the European Union for the year 2020, i.e. reducing CO₂ emissions by 20% compared to 1990, increasing the renewable share to 20% and improving electrical efficiency to 20% [5]. In relation to HP technologies, these efforts have focused on using renewable energy sources for powering the heating/cooling installations (for example, the Smart ReFlex project for promoting renewable heating and cooling in

Europe was launched in 2015, supported within the Intelligent Energy Europe program [6]).

Photovoltaic (PV) energy is one of the most promising renewable energy sources for powering HPs and reducing their environmental impact for several reasons. First, PV technology can be applied to big and centralized installations as well as to small and decentralized ones, and its efficiency is almost independent of the size of the system and its application. Second, the cost of PV electricity can be similar to the electricity tariff in applications which lack any energy storage system and even lower in large power systems (bids of 1.9 and 2.3 US cents/kWh were approved in China and Abu Dhabi in 2016 [7]), which makes it competitive with almost any other energy source. This is especially important for cooling applications where the thermal demand matches the PV power generation (midday sunny hours are usually the warmest), and therefore storage devices may be not necessary.

Research into PV-HP is quite recent, as the elevated prices of solar PV panels were an economic barrier until they started dropping in 2010. The first reported experimental study into PV-HP was published in 1997 [8]. It was a hybrid solar Photovoltaic/Thermal (PVT) system that combined a PV module with a thermal collector on its back surface which worked as the evaporator of the HP and helped to reduce the electricity consumption of the system. This electricity could be supplied by the PV array and/or traditional energy sources (i.e. the local grid or diesel generators).

^{*} Corresponding author.

E-mail address: celena.lorenzo@ies.upm.es (C. Lorenzo).

PVT technology is still the most dominant but the reduction in PV prices has brought about increasing attention in Only-PV (OPV) HP systems, in which solar technology is used just for powering the HP. In fact, some studies show that the solar collector is already the most expensive component of a PVT-HP system, so OPV systems help to reduce the initial investment cost very significantly [9, 10, 11, 12, 13].

This interesting scenario contrasts with the lack of review works that summarize the progress of research in this field in general and of the performance of PV-HPs in particular. That was precisely the motivation of this paper, which presents a review of both historic and most recent studies into PV-HP (including both PVT and OPV systems), analyzing the Key Performance Indicators (KPIs) they used and their values. The objective is to check if these KPIs are useful for:

- First, evaluating the performance and the renewable character of the PV-HP from the point of view of the electricity consumed for the thermal conversion. This is done in the framework of both research studies and potential quality control procedures of real systems (for example, in their commissioning).
- Second, comparing the results reported by the different research studies.

As a result of this analysis, this paper contributes to the search of new KPIs for PV-HP systems that make easier the comparison of the results of the research studies and allow checking PV-HP performance quality of the real systems that, in the close future, will reach the market and will be subject to contractual frameworks on their performance and on their use of renewable energy.

This paper is structured in 6 sections: 1) the introduction, 2) a nomenclature section for making the reading of the paper easier, 3) a technology overview of PH-HP systems, 4) a methodology section where we define the traditional KPIs used for this type of systems, we analyze their boundaries and we propose new ones for a better performance assessment, 5) the results obtained for the proposed KPIs and the corresponding discussion, and 6) the main conclusions drawn from this review.

2. Main text

2.1. Nomenclature

In order to facilitate the comprehension of the following sections, Table 1 shows the nomenclature used in this paper to refer to all the different components, parameters and classification categories of PV heat pumps.

2.2. Technology overview

There are different possible criteria for classifying solar HP systems, but one of the most extended is attending to their motive power: thermal, electric and PVT. Thermal HPs can be divided into sorption systems (based on the use of Solar Thermal (ST) collectors), which can be open cycle or closed cycle, and thermo-mechanic systems, mainly the steam jet generator and the Rankine cycle [25]. Electric HPs are classified into OPV/Vapor compression (using PV generators for powering a vapor compressor), the Stirling cycle and thermo-electric systems (based on the Peltier effect) [25]. Finally, hybrid PVT HPs, that combine solar thermal collectors and solar PV generators, can be divided into air and water systems [22]. Those categories that include a PV generator (OPV/Vapor compression and PVT systems) can present stand-alone or grid-connected configurations.

As it can be observed, there is a wide variety of HP technologies that makes their comparison very complex (and probably not useful). Therefore, this paper focuses only on PV-HP systems, which include PVT and OPV. Fig. 1-a shows the schematic of a basic direct expansion PVT-HP system (other technologies, such as indirect expansion, and

Table 1

Nomenclature used to refer to all the different components, parameters and classification categories of PV heat pumps.

c	Condenser
com	Compressor
COP	Coefficient of Performance
e	Evaporator
ex	Expansion valve
E_{HP}	Electric energy consumed by the Heat Pump
E_{el}	Electric energy
E_{PV}	Photovoltaic useful DC energy
E_{PV-HP}	PV energy consumed by the Heat Pump
E_{ST}	Solar thermal energy
E_{th}	Thermal energy
EER	Energy Efficiency Ratio
G	Solar irradiance in the plane of the PV generator
G^*	Solar irradiance at STC
G_{HCp}	Solar irradiance during the heating/cooling period
G_{used}	Solar irradiance effectively used by the HP system
G_{useful}	Solar irradiance useful for the HP system
HCp	Heating/cooling period
HP	Heat Pump
KPI	Key Performance Indicator
OPV	Only-Photovoltaic
P^*_{PV}	Nominal power of the PV generator
P_{HP}	Nominal power of the Heat Pump
PR	Performance Ratio
PR_{PV}	Performance Ratio considering only losses associated to the PV system
PR_{25}	Performance Ratio at Standard Test Conditions
$PR_{ref,25}$	Performance Ratio measured with a reference PV module at STC
PV	Photovoltaic
$PV-HP$	Photovoltaic Heat Pump
PVT	Hybrid Photovoltaic/Thermal
Q_c	Thermal power liberated at the condenser
Q_e	Thermal power absorbed at the evaporator
SCR	Self-Consumption Ratio
SF	Solar Fraction
SF_{PV}	PV Solar Fraction
SPF	Seasonal Performance Factor
SPF_{PV-HP}	Seasonal Performance Factor for PV-HP systems
ST	Solar Thermal
STC	Standard Test Conditions
T_{cond}	Condensing temperature
T_{evap}	Evaporation temperature
T_{amb}	Ambient temperature
T_c	Cell Temperature of the PV generator
T^*_c	Cell Temperature of the PV generator at Standard Test Conditions
TMY	Typical Meteorological Year
UR	Utilization Ratio
UR_{EF}	UR considering the irradiance effectively used by the HP system
UR_{HCp}	UR considering the irradiance during the heating/cooling period
UR_{PV-HP}	UR considering the irradiance required to deliver the HP power demand
W_{HP}	Electric power consumed by the Heat Pump

configurations do exist, but for simplicity reasons, we will focus here on direct expansion PVT-HP). It has a PVT collector, consisting of a PV generator with a heat exchanger on its back surface that acts as the evaporator of the system (e). This way, electrical (E_{el}) and thermal energy (E_{th}) are simultaneously generated using only one device. The refrigerant circulating through the evaporator absorbs heat from the PV cells, reducing the temperature of the PV generator and consequently increasing its electrical efficiency, and is evaporated. Then, it enters a compressor (com) that raises its pressure to reach a suitable condensing temperature (T_{cond}). The refrigerant circulates through another heat exchanger that acts as the condenser of the system (c), where it releases heat and condenses into a liquid. Finally, the liquid refrigerant enters an expansion valve (ex) that reduces its pressure to reach a suitable evaporation temperature (T_{evap}), and a new heat pump cycle begins. The PV electricity is used to feed the compressor with an inverter and a battery in the stand-alone configuration or hybridized with the grid to feed the compressor in the grid-connected configuration. The thermal energy absorption at the evaporator from the PV array helps to reduce the electricity consumption, as well as cooling the PV panels, hence making the system more efficient. Fig. 1-b shows the schematic of a basic OPV

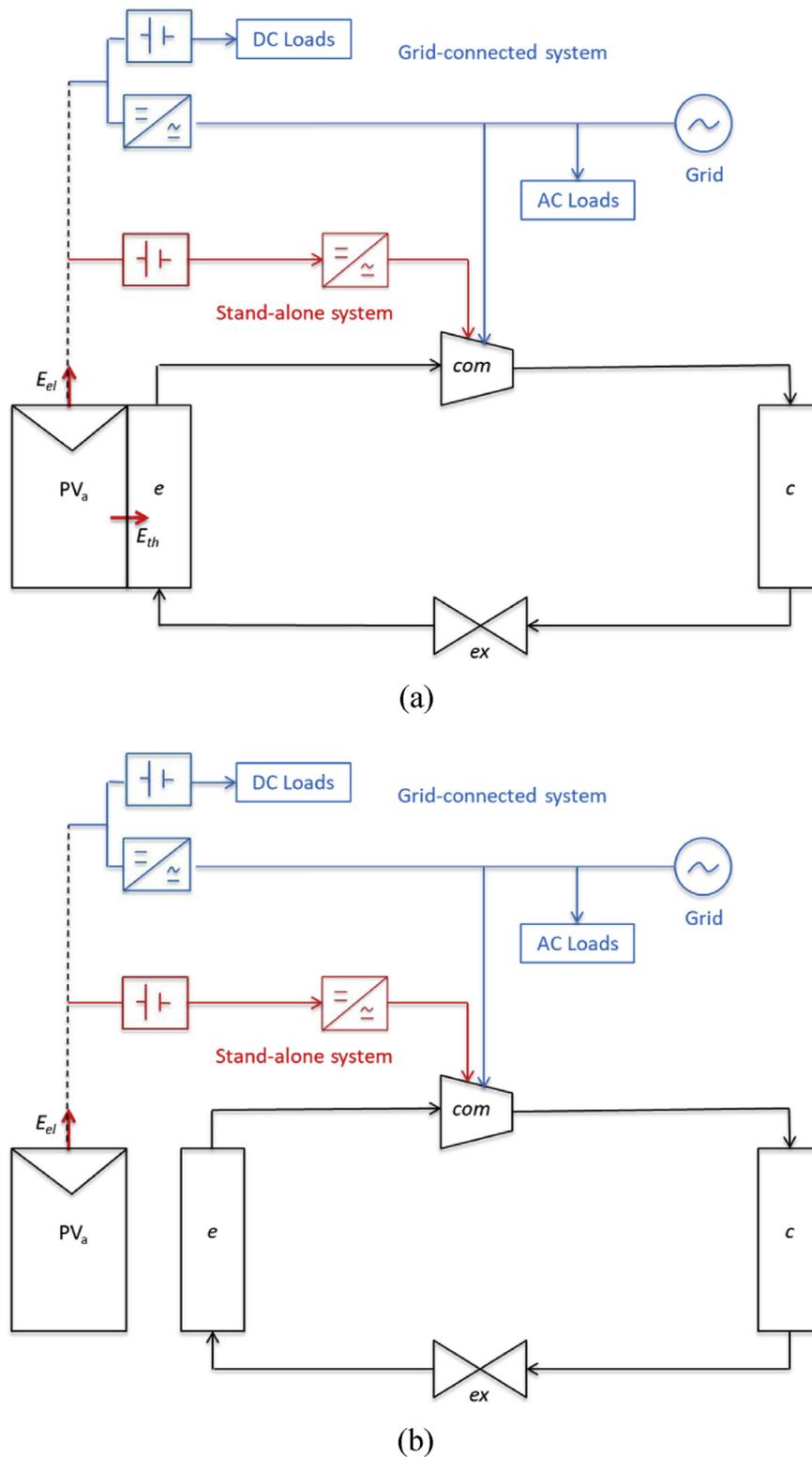


Fig. 1. Schematic of a PVT heat pump system (a) and that of an OPV heat pump system (b), both presenting two possible configurations: grid-connected (in blue) or stand-alone (in red).

heat pump system. The thermodynamic heat pump cycle is similar to the PVT case, but now there is no collector that connects the PV generator and the evaporator, so E_{el} and E_{th} do not depend on each other. Both types of PV-HP (PVT and OPV) can present two main configurations: grid-connected systems (in which the compressor is powered by both the grid and the PV generator) and stand-alone systems (in which the compressor is powered just by the electricity generated by the PV array,

and batteries might be used as back-up for periods when the PV generation and the cooling/heating demand do not match). It must be noted that, although these schematics only consider the electric consumption of the compressor, the commercial heat pumps also present additional electric loads such as valves and fans. These loads are secondary compared to the compressor, but they are not negligible when assessing the performance of the system.

Solar technologies can be especially beneficial for cooling applications, as the thermal demand matches the solar power generation (sunny hours are usually warmer), reducing the need to use storage systems. In particular, PV-HPs present a great potential due to their low electricity consumptions and to the reduction in the cost of PV panels. Furthermore, the same HP installation can be used for both heating and cooling applications. However, there is a lack of review works that summarize the most recent research in this field. Table 2 presents a summary of recent reviews into solar cooling systems and solar HPs. It can be observed that most of them focus on ST technologies, and very few mention PVT and/or OPV systems, which are precisely the scope of this review.

2.3. Method for the critical analysis of KPIs for PV-HP systems

The method that we propose to review the identified studies has three objectives: first, describing the KPIs used in these studies; second, analyzing their suitability to evaluate the performance and the renewable character of PV-HP systems and identifying their boundaries, and third, proposing new performance indicators that consider the performance of the PV generator, of the heat pump and of their integration and that make easier the comparison of the results of the different studies. These new indices are based on the traditional ones but appropriately adapted to the specific characteristics of the PV-HP systems. Finally, the traditional and the new proposed KPIs will be reported/calculated and discussed in section 2.4.

2.3.1. KPIs used in the reviewed studies

The performance of heat pump systems, in terms of how efficiently they transform electrical energy into thermal energy, is typically evaluated through the Coefficient of Performance (COP) when operating in heating mode or through the Energy Efficiency Ratio (EER) when operating in cooling mode. These indicators are defined as follows:

$$COP = \frac{Q_c}{W_{HP}} \tag{1}$$

$$EER = \frac{Q_e}{W_{HP}} \tag{2}$$

where Q_c is the thermal power released at the condenser, Q_e is the thermal power absorbed at the evaporator and W_{HP} is the electric power consumed by the HP unit under certain test conditions.

The Seasonal Performance Factor (SPF) is the ratio between the total useful thermal energy generated (E_{th}) and the electric energy consumption of the HP unit (E_{HP})—usually including all its electric loads, not only the compressor—over a whole year of operation or over a complete heating/cooling season:

$$SPF = \frac{E_{th}}{E_{HP}} \tag{3}$$

A HP system is considered renewable (independently of how its electrical consumption is generated) if its SPF is greater than 2.5 [42]. Some precautions must be taken when using the SPF [43]:

- It is similar to the average COP or EER, but not identical. Even though, we found that some authors consider them to be equivalent.
- It is important to know the boundaries of the system under evaluation, especially if only the electricity consumption of the compressor is considered, or if additional electric loads are also included.
- The SPF can be reported for shorter periods than a year or a heating/cooling season, but it must be properly indicated.

For ST-HP and PVT-HP systems, the Solar Fraction (SF) is generally used to assess how much thermal energy (absorbed at the evaporator or liberated at the condenser, depending on the application) is provided by the solar collector, contributing to reducing the electricity consumption

of the system. SF presents values of between 0 and 1, and it is given by Eq. (4):

$$SF = \frac{E_{ST}}{E_{th}} \tag{4}$$

However, the SF only evaluates the use of the solar thermal collector and it is independent of the PV system, so it is not included in this analysis. Instead, we define PV Solar Fraction, SF_{PV} , (also presenting values of between 0 and 1) representing the share of the total electricity consumed by the HP that has been generated by the PV generator, as shown in Eq. (5):

$$SF_{PV} = \frac{E_{PV-HP}}{E_{HP}} \tag{5}$$

where E_{HP} is the total electric energy consumed by the HP unit, regardless of how it is generated, and E_{PV-HP} is the PV energy consumed by the HP, both directly or after being stored in a battery.

For PVT-HP and OPV-HP systems, there are three commonly used performance indicators to evaluate the PV contribution: the Performance Ratio (PR) for evaluating the performance of the PV generator, the Self-Consumption Ratio (SCR) and the PV Solar Fraction (SF_{PV}) for evaluating the quality of the coupling between the PV generator and the compressor of the HP. The PR represents the ratio between the PV energy that is actually delivered to the heat pump and the PV energy that could have been ideally generated for a certain period of time, and it is given by Eq. (6):

$$PR = \frac{E_{PV}}{\frac{P_{PV}}{G} \int G(t) dt} \tag{6}$$

where E_{PV} is the useful (meaning that it is either used for powering the compressor, for charging a battery or exported to the grid) energy pro-

Table 2

Recent reviews into solar cooling technologies and solar heat pump systems, including ST, PVT and OPV.

Solar Cooling systems	
Reference	Focus
[14] G. A. Florides et al.	ST and PV solar cooling for buildings
[15] A. M. Papadopoulos et al.	ST and electric air-conditioning
[16] C. A. Balares et al.	ST air-conditioning
[17] H-M Henning et al.	ST air-conditioning
[18] D. S. Kim et al.	ST and electric solar refrigeration
[19] L. A. Chidambaram et al.	ST cooling with thermal storage
[20] K. Moradi et al.	PVT cooling
[21] I. Sarbu et al.	ST and electric solar cooling
[22] F. Shan et al.	PVT cooling
[23] D. Zhao et al.	Electric cooling (only thermoelectric systems)
[24] S. Pintaldi et al.	ST cooling with thermal storage
[25] A. Allouhi et al.	ST, electric and PVT cooling
[26] A. J. Alazazmeh et al.	ST and electric solar cooling
[27] M. Zeyghami et al.	ST cooling (only thermo-mechanic)
[28] S. R. Reddy et al.	PVT cooling
Solar Heat Pump systems	
Reference	Focus
[29] O. Ozgener et al.	ST heat pumps for heating applications
[30] O. Kara et al.	ST heat pumps, direct expansion systems
[31] M. Y. Haller et al.	ST heat pumps
[32] P. Omojaro et al.	ST heat pumps
[33] Z. Mohd. Amin et al.	ST heat pumps for heating applications
[34] R. Shukla et al.	ST heat pumps for water heating applications
[35] J. Ruschenburg et al.	ST heat pumps for heating applications
[36] R. S. Kamel et al.	PVT heat pumps
[37] M. S. Buker et al.	ST heat pumps for water heating applications
[38] V. Kapsalis et al.	ST heat pumps with thermal storage
[39] M. Mohanraj et al.	ST and PVT heat pumps
[40] M. Mohanraj et al.	ST and PVT heat pumps
[41] S. Poppi et al.	ST, PVT and OPV heat pumps for heating applications

Table 3
Definition of the factors proposed for the PR factorization for PV-HP systems.

$PR_{PV} = \frac{E_{PV}}{P_{PV}^* / G^* \times \int G_{used} dt}$	This is the PR considering only losses strictly associated to the PV system itself, i.e., actual versus nominal peak power, dirtiness, thermal and DC/AC conversion losses. It is intrinsic to the technical quality of the PV component and its maintenance.
$UR_{HCp} = \frac{\int_{HCp} G dt}{\int G dt}$	This is the ratio of the total irradiation throughout the heating/cooling period, HCp, to the total annual irradiation (Fig. 2-a). It is intrinsic to a given application of heating/cooling. Note that it can only be applied to the annual period.
$UR_{PV-HP} = \frac{\int G_{useful} dt}{\int_{HCp} G dt}$	This is the ratio of the irradiation necessary to deliver the power required by the heat pump to the total irradiation throughout the HCp (Fig. 2-b). It is intrinsic to the heating/cooling system design; specifically it depends on the type of heating/cooling system (at constant or at variable power), the ratio between the PV peak power and the PV power required for heating/cooling, and on the tracking geometry.
$UR_{EF} = \frac{\int G_{used} dt}{\int G_{useful} dt}$	This is the ratio of the irradiation required by the heat pump during the heating/cooling scheduling to of the irradiation necessary to deliver the power required by the heat pump.

duced by the PV generator, P_{PV}^* is the nominal power of the PV generator, G^* is the solar irradiance under Standard Test Conditions (STC) and G is the solar irradiance received in the plane of the PV generator. The PR for grid-connected PV systems is traditionally defined in terms of the AC energy. However, most studies included in this review only reported DC energy and no DC/AC efficiency, so we have instead defined the PR in terms of DC energy.

The SCR (which also presents values between 0 and 1) represents the share of the total PV energy generation that is consumed by the compressor of the HP system, and it is given by Eq. (7):

$$SCR = \frac{E_{PV,HP}}{E_{PV}} \quad (7)$$

2.3.2. Boundaries of the used KPIs

There are some boundaries to these KPIs when comparing the results of the different studies and when evaluating the quality of PV-HP performance, both in real systems and in contractual frameworks (for example, in commissioning procedures).

The first boundary is the influence of the local climate conditions in the performance of PV-HP. The same high-quality PV-HP will have a lower value of PR in Spain than in Denmark just because the mean ambient temperature in Spain is higher, leading to higher thermal losses in the PV system. These losses are not related to the quality of the system but to the operating climatic conditions in the location where the PV-HP has been installed. Something similar happens with the SPF, COP and EER, which are highly dependent on the ambient and room temperatures

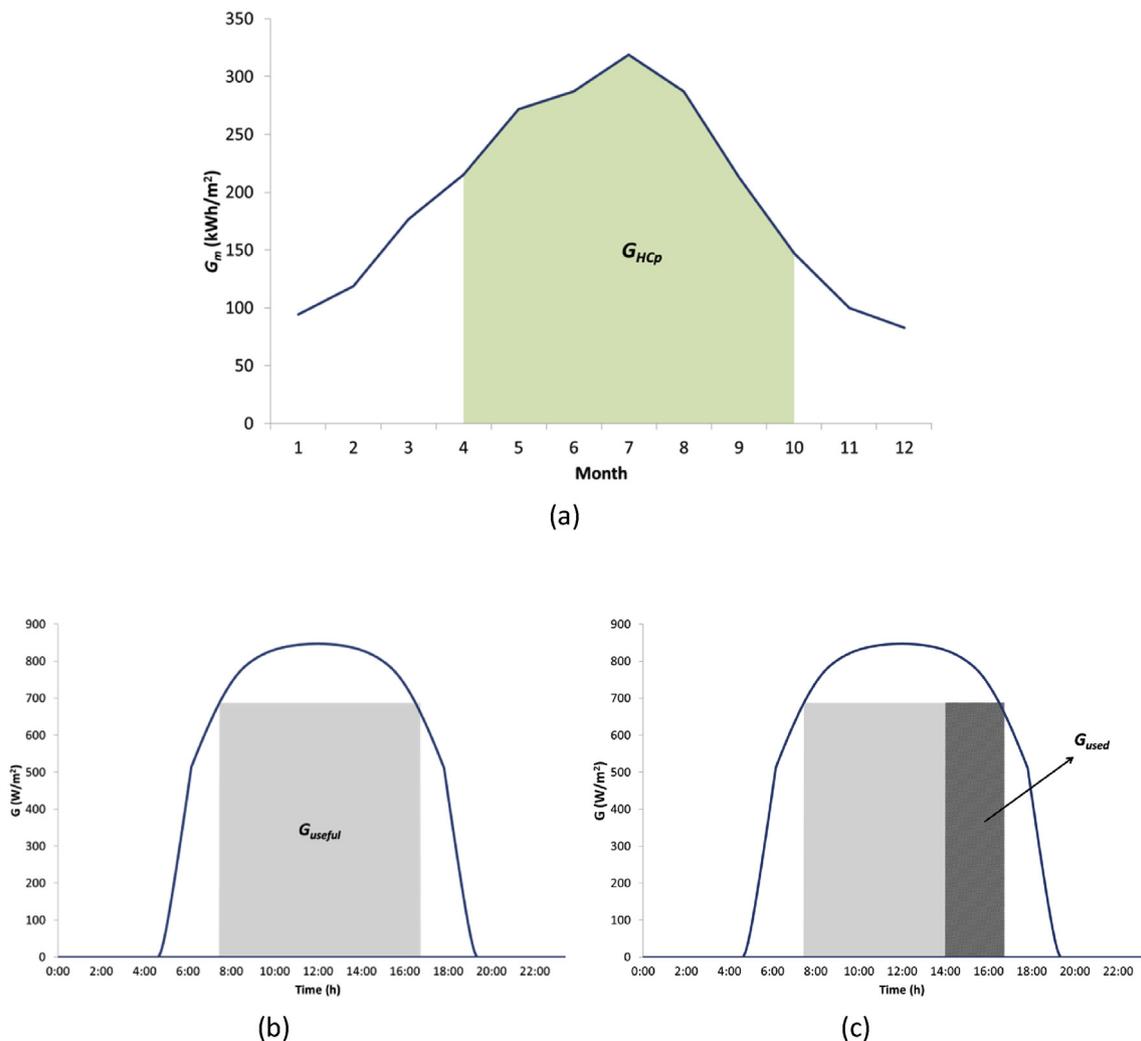


Fig. 2. Graphical representation of the different irradiations considered: (a) $\int G_{HCp}$ is the irradiation during the heating/cooling period (HCp), (b) $\int G_{useful}$ is the useful irradiation during the HCp determined by the design of the PV HP system; and (c) $\int G_{used}$ is the irradiation used effectively by the system.

[43]. This dependence is not linear and is not the same for different technologies and models of HPs. This makes it very difficult to compare the performance results of studies carried out in different climatic regions.

The second boundary is the influence of the time span of the studies. As the used KPIs depend on the operating conditions, they may vary along the year. If the time span is short, the KPIs will show different values depending on the period of the year when the measurements have been taken. This effect is attenuated in long time spans as the KPI values are not affected by particular operating conditions but by mean values. This is why the use of the SPF and PR over a whole year is generally recommended. However, these annual time spans are useful for simulation studies but they may not be so useful for experimental analysis or for commissioning tests, which must be done in short time spans.

The third boundary is related to the different HP technologies used in the reviewed studies. While 95% of the PV market is crystalline-silicon technology [44], the variety of HP technologies is much wider and therefore a general comparison of their performance may have no sense. This is why this review focuses on the performance analysis from the electrical-consumption point of view and its renewable character. So, for a given thermal demand, we will only consider the HP electrical consumption (in other words, its index SPF) regardless of the technology, and how much of that electricity comes from a renewable energy source (i.e. PV). It is important to clarify the frontier of the system under analysis: most studies consider all the electric loads of the HP unit, but some consider only the compressor. In any case, in this review we indicate which HP is water to water, air to air, etc., and what application it is used for (i.e. water/space heating/cooling) as additional information that can be useful for the reader. Other aspects such as the initial investment, size and surface occupation are not here considered, but are key aspects to select one HP technology or another.

2.3.3. New performance indicators for PV-HP systems

When approaching the performance evaluation of a PV-HP system, a combination of the aforementioned indicators would help to integrate three different characteristics of the system to evaluate: the quality of the heat pump (characterized by COP, EER and/or SPF), the quality of the PV generator (characterized by the PR), and the quality of the integration of the two systems (characterized by SCR and SF_{PV}).

An important aspect to take into account is that the PR, as traditionally defined, is highly affected by factors that do not depend on the quality of the PV system when coupled to a HP, such as the heating/cooling period (which could be different over the whole year), the daily heating/cooling demand profile (which depends on the application and the user behavior) or possible failures of the compressor or any of the components of the heat pump. If the heat pump does not operate during sunny hours, whether because there is no thermal demand or because the compressor has technical problems, the E_{PV} will be zero during these periods, even if the PV generator is performing well, so the PR values will be lowered. Regarding these considerations, the PR is factorized by distinguishing between irradiation losses for three essentially different

reasons: the non-heating/cooling period, the intrinsic characteristics of the PV-HP system design and the external factors:

$$PR = PR_{PV} \times UR_{HCp} \times UR_{PV-HP} \times UR_{EF} \tag{8}$$

The meanings of the four factors from Eq. (8) are given in Table 3, where HCp is the heating/cooling period determined by the particular application, G_{useful} is the available useful irradiance during the HCp determined by the relationship between the P_{PV}^{*}, the PV generator structure and the type of heating/cooling system that will determine the power requirements throughout the day, and G_{used} is the irradiance effectively used by the system.

To clarify these concepts, G during HCp G_{HCp}, G_{useful}, and G_{used} are shown in Fig. 2 for a hypothetical constant power heat-pump system. The example of constant power has been selected for reasons of simplicity and the clarity of the explanation. It can be shown that G_{HCp} is the total irradiance during the heating/cooling period determined by a certain application (Fig. 2-a). G_{useful} is the irradiance required to deliver the constant power required by a certain heat pump (Fig. 2-b). It is worth noting that with irradiances below G_{useful} the heat pump will not be able to work because the power required will not be reached, and irradiances higher than G_{useful} will be partially wasted because the system works at constant power. Finally, G_{used} is the part of G_{useful} that has been used effectively as a result of the scheduling of heating/cooling selected by the end-user (Fig. 2-c). In this last figure, the irradiance from 7 am to 2 pm was wasted because of the heating/cooling scheduling rather than technical problems in the PV system.

It is worth noting that storing PV energy in a battery for its later use or feeding it into the grid are possible solutions for avoiding the reduction in PR due to external factors and it would have the effect of extending the G_{useful}. Unfortunately, published studies do not generally provide the information needed to calculate these utilization ratios (URs), so we were not able to include their values in this review. However, we strongly recommend their use for future works.

Finally, a new performance indicator (SPF_{PV-HP}), resulting from the combination of the traditional SPF with the PR, SCR and SF_{PV}, is proposed in Eq. (9):

$$SPF_{PV-HP} = SPF (1 + PR \times SCR \times SF_{PV}) \tag{9}$$

where PR is defined in Eq. (8), and SPF_{PV-HP} and SPF are extended to different time spans (hourly, monthly or yearly) as will be later discussed in this section.

SPF_{PV-HP} will be equal to the traditional SPF if there is no PV energy generation and/or use (PR = SCR = SF_{PV} = 0); SPF_{PV-HP} will double the traditional SPF if the PV generator performs ideally and all its electricity production is used for powering the compressor in stand-alone regime (PR = SCR = SF_{PV} = 1). SPF_{PV-HP} will be applied for both heating and cooling applications.

The main motivation for proposing this new KPI SPF_{PV-HP} is that it combines the performance quality of the HP (SPF), of the PV system (PR_{PV}), its utilization ratios (UR_{HCp}, UR_{PV-HP} and UR_{EF}) and of the

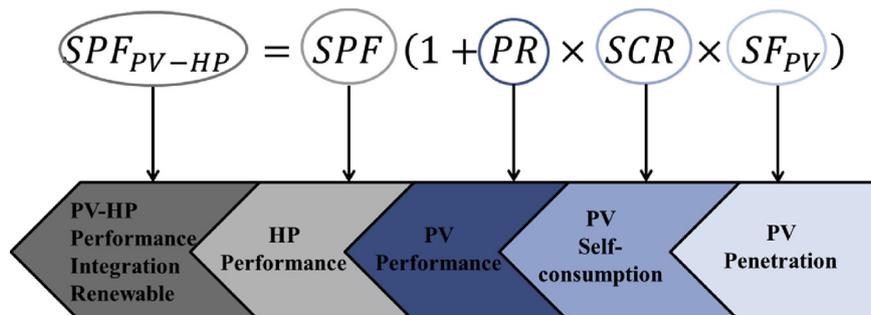


Fig. 3. Factors proposed to calculate SPF_{PV-HP} and their conceptual meaning.

Table 4

Description of the studies about PVT and OPV HP systems included in this review, including the information required to know if they are comparable or not. The nomenclature used for the HP technology and application is explained in Table 5.

Ref.	HP Tech.	Syst. App.	Exp/Sim	Time span	Location	G (W/m ²)	T _{amb} (°C)	T _c (°C)
[8]	A-W	W-H	E	8h (H)	-	-	-	-
[51]	A-W	W-H	E	8h (H)	-	-	-	-
[52] ^b	A-A/W	SW-H	E	4 days (H)	Hefei (China), Lat: 31.88°N, Long: 117.25°E	606	13.7	31.9
[53]	A-W	W-H	E	7h (H)	Hefei (China), Lat: 31.88°N, Long: 117.25°E	603	15.8	33.9
[54] ^b	A-A/W	SW-H	S	8h (H)	Hefei (China), Lat: 31.88°N, Long: 117.25°E	-	-	-
[55] ^b	A-W	W-H	S	3h (H)	-	800	25	49.0
[56] ^b	A-W	W-H	E	5h (H)	-	700	36	57.0
[57] ^a	A-A/W	SW-H	E	1 year (Y)	Frankfurt (Germany), Lat: 50.7°N, Long: 8.41°E	261	13	20.0
[58] ^b	A-A	S-H	E	8h (H)	-	837	22.1	47.2
[59] ^b	A-A	S-H	E	9h (H)	Coimbatore (India), Lat: 10.98°N, Long: 76.96°E	650	32	51.5
[60] ^b	A-W	W-H	E	1h (H)	Nottingham (UK), Lat: 52.93°N, Long: 1.18°W	800	21.7	45.7
[61]	W-W	W-H	S	1 year (Y)	Nice (France), Lat: 43.2°N, Long: 7.25°E	-	-	-
[62]	W-W	W-H	S	1 year (Y)	Cythelia (France), Lat: 45.54°N, Long: 5.91°E	-	-	-
[63]	W-A/W	SW-H	E	8h (H)	Hong Kong (China), Lat: 22.2°N, Long: 114.1°E	-	25.3	-
[64] ^b	A-W	W-H	S	6h (H)	-	699	36.1	57.1
[65] ^b	W-W	W-H	E	8h (H)	Beijing (China), Lat: 39.9°N, Long: 116.3°E	656	37	56.7
[66] ^b	W-A	S-H	E	7h (H)	Beijing (China), Lat: 39.9°N, Long: 116.3°E	637	3.7	22.8
[67]	W-W	S-H	S	1 Sunny day (H)	Washington DC (USA), Lat: 38.91°N, Long: 77.22°W	-	-	-
[68] ^a	W-W	S-H	S	1 year (Y)	Montreal (Canada), Lat: 45.56°N, Long: 73.87°W	380	10.8	20.0
[69] ^b	A-W	W-H	S	9h (H)	Lhasa (Tibet), Lat: 29.67°N, Long: 91.13°E	764	6.2	29.1
[70]	A-W	W-H	S	8h (H)	Salerno (Italy), Lat: 40.77°N, Long: 14.79°E	-	-	-
[71] ^b	A-A	W-H	E	2h (H)	-	610	24.5	42.8
[72]	A-W	W-H	S	4h (H)	-	-	-	-
[73] ^a	A-W	S-H	E	1 day (H)	Madrid (Spain), Lat: 40.42°N, Long: 3.68°W	589	5.5	20.7
[74] ^b	W-W	W-H	E	8h (H)	Shanghai (China), Lat: 31.18°N, Long: 121.48°E	525	15.28	31.0
[75] ^b	W-A/W	SW-H	E	7h (H)	Cardiff (UK), Lat: 51.48°N, Long: 3.18°W	717	19.50	41.0
[76] ^a	W-W	SW-H	S	Heating season (M)	Vicenza (Italy), Lat: 45.55°N, Long: 11.45°E	392	8.7	19.7
[77]	W-W	W-H	E	33 days (M)	Copenhagen (Denmark), Lat: 55.7°N, Long: 12.6°E	-	-	-
[78] ^a	W-W	SW-H	S	Heating season (M)	Vicenza (Italy), Lat: 45.55°N, Long: 11.45°E	392	8.7	19.7
[79]	A-W	S-H	S	Heating season (M)	Saskatoon (Canada), Lat: 52.13°N, Long: 106.68°W	-	-	-

PVTgrid – connected

PVTstand – alone

(continued on next page)

Table 4 (continued)

Ref.	HP Tech.	Syst. App.	Exp/Sim	Time span	Location	G (W/m ²)	T _{amb} (°C)	T _c (°C)	
[80] ^a	A-W	S-H	S	1 year (Y)	Kragujevac (Serbia), Lat: 44.02°N, Long: 20.92°E	363	15.1	24.7	
[81]	A-W	W-H	E	1 year (Y)	-	-	-	-	
[82]	A-W	W-H	S	1 year (Y)	Stuttgart (Germany), Lat: 48.8°N, Long: 9.2°E	-	-	-	
[83]	A-W	W-H	S	1 year (Y)	Neuchâtel (Switzerland), Lat: 46.98°N, Long: 6.92°E	-	-	-	
[84]	A-W	W-H	S	1 year (Y)	-	-	-	-	
[85]	A-W	S-H	S	1 year (Y)	Kgs. Lyngby (Denmark), Lat: 55.78°N, Long: 12.47°E	-	-	-	
[86]	A-W	W-H	S	1 year (Y)	Pretoria (South Africa), Lat: 25.73°S, Long: 28.18°E	-	-	-	
[87] ^a	A-W	W-H	E	4,5 h (H)	Winterthur (Switzerland), Lat: 47.48°N, Long: 8.72°E	279	16.1	23.2	
[88]	A-W	S-H	S	1 year (Y)	Munich (Germany), Lat: 48.13°N, Long: 11.57°E	-	-	-	
[89]	A-W	S-C	E	5 h (H)	Rapperswil-Jona (Switzerland), Lat: 47.22°N, Long: 8.82°E	-	-	-	
[90] ^a	A-W	S-CH	S	1 year (Y)	Naples (Italy), Lat: 40.83°N, Long: 14.25°E	470	18.7	31.0	
[91]	A-W	SW-H	S	1 year (Y)	Stuttgart (Germany), Lat: 48.8°N, Long: 9.2°E	-	-	-	
[92] ^a	A-A	S-C	E	Cooling season (M)	Alicante (Spain), Lat: 38.33°N, Long: 0.47°E	506	22.9	36.1	
[93]	A-W	S-C	E	1 year (Y)	Zhuhai (China), Lat: 21.48°N, Long: 113.03°E	-	-	-	
[94]	A-A	S-C	S	Cooling season (M)	Puigverd de Lleida (Spain), Lat: 41.53°N, Long: 0.73°E	-	-	-	
[95] ^a	A-A	S-H	S	1 year (Y)	Reutlingen (Germany), Lat: 48.48°N, Long: 9.13°E	347	12.7	21.8	
[96]	A-A	S-C	E	1 year (Y)	Kumasi (Ghana), Lat: 6.72°N, Long: 1.6 °W	-	-	-	
[97] ^a	A-A	S-CH	E	1 year (Y)	Alicante (Spain), Lat: 38.33°N, Long: 0.47°E	486	19.2	32.1	
[98]	A-W	W-H	S	1 year (Y)	Chemnitz (Germany), Lat: 50.5°N, Long: 12.55°E	-	-	-	
[99]	A-A	S-C	E	Not specified	-	-	-	-	
[100] ^a	A-W	S-H	E	1 day (H)	Madrid (Spain), Lat: 40.42°N, Long: 3.68°W	554	12	26.9	
[101] ^a	A-A	S-H	S	1 year (Y)	Munich (Germany), Lat: 48.13°N, Long: 11.57°E	327	16.6	25.7	
[102]	A-W	W-H	S	1 year (Y)	Adelaide (Australia), Lat: 34.93°S, Long: 138.58°E	-	-	-	

OPV/grid – connected

OPV/stand – alone

^a Experimental or simulated studies for which the ambient conditions G, T_{amb} and T_c have been obtained with the simulation tool SISIFO [47].^b Experimental or simulation studies for which the T_c has been obtained from G and T_{amb}, using Eq. (12).

Table 5
Nomenclature used in Table 4 to describe the HP technology and the application of the system.

Nomenclature	Application
W-H	Water heating
S-H	Space heating
SW-H	Space and water heating
S-C	Space cooling
S-CH	Space cooling and heating
Nomenclature	Technology
A-A	Air to air
A-W	Air to water
A-A/W	Air to air and/or water
W-A	Water to air
W-W	Water to water
W-A/W	Water to air and/or water

integration of the two systems (SCR and SF_{PV}). This way, SPF_{PV-HP} can be seen as an indicator of the system performance, including the integration of the subsystems (meaning the heat pump and the PV generator), and the renewable character of the PV-HP: a high value of SPF_{PV-HP} would mean a high efficiency of the HP, a high and efficient use of PV electricity and, therefore, a good integration of both systems. Fig. 3 illustrates this:

The maximization of SPF_{PV-HP} has several implications for a PV-HP designer. It obliges the designer to select an efficient HP and to size the PV system balancing the different factors. A high ratio P_{PV}^*/P_{com} would lead to a high value of SF_{PV} but to low values of PR and SCR. On the contrary, a low ratio P_{PV}^*/P_{com} would lead to high values of PR and SCR but to a low value of SF_{PV}. So, a balance exercise will be necessary. Moreover, external factors to the quality of the PV-HP, evaluated by UR_{HCP}, UR_{PV-HP} and UR_{EF}, will also affect the PV-HP performance and will oblige to adapt the PV-HP design to the specific restrictions and needs of the final application of the HP and its user.

The designer will lose the physical meaning of SPF and PR when using SPF_{PV-HP} but, on the contrary, the designer will be able to evaluate not only the quality of the HP or of the PV system separately but also the quality of its integration and the improvement of the renewable character of the whole system. In any case, our proposal is not that SPF_{PV-HP} substitutes the other KPIs that constitute it but to evaluate both the SPF_{PV-HP} and its seven factors. The reader could be surprised that to assess the

quality of a PV-HP system it is necessary to consider 8 KPIs but, this way, in case of a low or unexpected value of SPF_{PV-HP} the causes can be easily evaluated. This can be particularly useful in a commissioning procedure, so that responsibilities can be assigned if necessary (to the manufacturers of the components, to the designer responsible for their integration, or to the use of the system by the end user).

The drawback of using this new KPI is that it is necessary to register not only the different thermal and electrical energies related to SPF, SCR and SF_{PV}, but also the irradiance on the plane of the PV generator, G, to calculate the PR.

SPF_{PV-HP} does not solve the limitations corresponding to the different time spans and climatic conditions that impede the results of the different studies to be comparable, but its variation with the different climatic conditions can be attenuated by using the PR₂₅ instead of the PR [45], defined in Eq. (10):

$$PR_{25} = \frac{E_{PV}}{\frac{P}{G} \int G(t) [1 - \gamma(T_c(t) - T_c^*)] dt} \tag{10}$$

where γ is the coefficient of variation of the PV power with the solar cell temperature, and $T_c(t)$ is the solar cell temperature of the PV generator and T_c^* is the solar cell temperature at Standard Test Conditions (25 °C).

The PR₂₅ has the same meaning than the PR but eliminating the thermal losses caused by different ambient temperatures. Therefore, it allows comparing PV systems in different climatic conditions. The drawback of using the PR₂₅ is the obligation to register not only G but also the solar cell temperature, T_c , of the PV generator. Regarding the time span, it is also possible to attenuate its effect using a reference PV module to measure G and T_c ([46]). This way, the constancy of PR_{ref,25} is kept even in short intervals of evaluation. Following this trend of thought, it is possible to define a SPF_{PV-HP, ref, 25} using the PR_{ref,25}:

$$SPF_{PV-HP, ref, 25} = SPF (1 + PR_{ref, 25} \times SCR \times SF_{PV}) \tag{11}$$

This indicator is not completely free of the influence of the climatic conditions and different time spans, as SPF still depends on them, but such influence is importantly mitigated thanks to the PR_{ref,25}. It would be ideal to obtain a similar modification of the SPF to some STC, but it is difficult to find a general mathematical model due to the big variety of technologies, models and applications. This is the reason why we propose to extend the time span of SPF to other than yearly values but informing

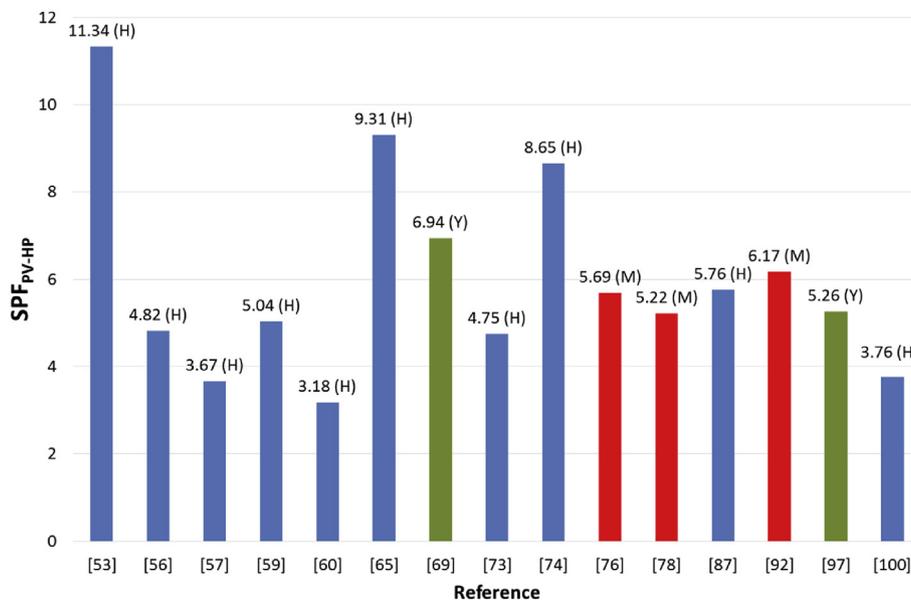


Fig. 4. SPF_{PV-HP} values obtained for the 15 studies included in this review that provided enough information. Values corresponding to hourly time spans (H) are in blue, to monthly time spans (M) in red and to a whole year (Y) in green.

Table 6

Values of the traditional and new performance indicators obtained for all of the studies included in this review, together with the ratio between the nominal PV power and the nominal power of the HP system.

Ref.	P_{PV}^*/P_{HP}	COP_{nom}	COP_{av}	SPF_H	EER_{nom}	EER_{av}	SPF_C	SCR	SF_{PV}	PR	SPF_{PV-HP}	
[8] ^a	-	-	-	-	-	-	-	-	-	-	-	
[51] ^a	-	-	-	-	-	-	-	-	-	-	-	
[52] ^a	0.58	-	5.4	-	-	-	-	1.00	0.98	0.81	-	
[53] ^a	0.58	-	6.5	6.68 (H)	-	-	-	0.74	1.00	0.94	11.34 (H)	PVTgrid – connected
[54] ^a	0.58	-	-	5.26 (H)	-	-	-	1.00	0.74	-	-	
[55]	-	-	4.8	-	-	-	-	-	-	-	-	
[56] ^a	0.21	-	4.8	4.48 (H)	-	-	-	1.00	0.10	0.82	4.82 (H)	
[57]	-	-	-	4.24 (Y)	-	-	-	1.00	0.79	0.81 ^c	6.94 (Y)	
[58]	-	-	-	-	-	-	-	-	-	-	-	
[59] ^a	0.34	-	3.5	3.24 (H)	-	-	-	1.00	0.16	0.84	3.67 (H)	
[60] ^a	-	-	4.6	4.81 (H)	-	-	-	1.00	0.05	0.95	5.04 (H)	
[61]	-	4.9	4.34	-	-	-	-	-	-	-	-	
[62]	4.97	5.1	-	-	-	-	-	-	1.00	-	-	
[63]	-	-	-	4.01 ^b (H)	-	-	-	1.00	0.44	-	-	
[64] ^a	-	-	-	3.89 ^b (H)	-	-	-	-	-	-	-	
[65] ^a	0.39	-	-	2.77 ^b (H)	-	-	-	1.00	0.21	0.69	3.18 (H)	
[66] ^a	1.59	-	3.18	-	-	-	-	1.00	-	0.79	-	
[67]	1.15	-	-	-	-	-	-	0.96	1.00	-	-	
[68]	1.38	5.3	-	-	-	-	-	0.29	1.00	0.83 ^c	-	
[69] ^a	1.68	-	6.01	5.50 (H)	-	-	-	0.77	1.00	0.90 (NS)	9.31 (H)	
[70] ^a	2.00	-	-	-	-	-	-	0.75	1.00	0.99	-	
[71]	-	-	2.88	-	-	-	-	-	-	-	-	
[72] ^a	-	-	-	-	-	-	-	0.37	1.00	-	-	
[73]	-	-	3.5	3.16 (H)	-	-	-	0.64	1.00	0.78 ^c	4.75 (H)	
[74]	-	-	-	5.51 ^b (H)	-	-	-	0.91	1.00	0.63	8.65 (H)	
[75]	-	-	-	-	-	-	-	-	-	-	-	
[76]	1.48	-	-	3.64 ^b (M)	-	-	-	0.67	1.00	0.84 ^c	5.69 (M)	
[77]	-	-	-	6.86 (M)	-	-	-	1.00	1.00	-	-	
[78]	1.71	-	-	3.62 ^b (M)	-	-	-	0.53	1.00	0.84 ^c	5.22 (M)	
[79]	4.82	3.27	-	3.44 (M)	-	-	-	0.75	1.00	-	-	
[80]	0.34	3.5	-	-	-	-	-	0.10	0.30	0.80 ^c	-	
[81]	2.67	3	-	-	-	-	-	-	-	-	-	
[82]	-	-	-	3.1 (Y)	-	-	-	0.38	0.40	-	-	
[83]	2.75	-	-	-	-	-	-	0.41	-	-	-	
[84]	3.27	3.06	-	-	-	-	-	0.37	0.38	-	-	
[85]	1.00	-	-	-	-	-	-	0.91	1.00	-	-	
[86]	-	-	-	-	-	-	-	-	-	-	-	
[87]	2.00	4.4	-	3.6 (H)	-	-	-	1.00	0.80	0.75 ^c	5.76 (H)	
[88]	3.33	-	-	-	-	-	-	0.58	0.67	-	-	
[89]	-	-	-	-	-	-	-	-	-	-	-	
[90]	1.82	3.19	-	-	3.32	-	-	0.77	0.61	0.80 ^c	-	
[91]	1.00	-	-	-	-	-	-	0.70	0.50	-	-	
[92]	0.82	-	-	-	4.10	-	5.15 ^b (M)	0.39	0.65	0.78 ^c	6.17 (M)	
[93]	1.08	-	-	-	-	-	-	0.50	0.50	0.82	-	
[94]	-	-	-	-	-	-	-	-	-	-	-	
[95]	1.69	4.6	-	-	-	-	-	0.82	0.40	0.80 ^c	-	
[96]	1.30	-	-	-	3.13	-	-	-	0.51	-	-	
[97]	0.82	3.83	-	3.83 (M)	4.09	-	5.15 (M)	0.41	0.54	0.83 ^c	5.26 (Y) *	
[98]	6.94	3.8	-	3.16 (Y)	-	-	-	-	-	-	-	
[99]	-	-	-	-	-	3.30	-	-	-	-	-	
[100]	-	-	-	2.9 ^b (H)	-	-	-	0.37	1.00	0.80 ^c	3.76 (H)	
[101] ^a	0.83	3	-	-	-	-	-	0.97	1.00	0.86 ^c	-	
[102]	-	3.5	-	-	-	-	-	-	-	-	-	

^a These studies only consider the electricity consumption of the compressor, without additional electric loads such as fans or valves.

^b These studies define the COP and/or EER in terms of energy instead of in terms of power. We have assigned the reported values to the SPF, according to the definition used in this review.

^c PR values obtained with the simulation tool SISIFO [47].

* Calculated from a yearly SPF of 4.44, which is the mean value of SPF_H and SPF_C. The system operated in cooling mode from May to October and in heating mode from November to April.

about the time span together with the value of SPF_{PV-HP}. This way it is possible to reconcile the need to evaluate studies based on short-time experiments (from one day to several weeks) with the caution of not comparing results corresponding to different time spans.

2.4. Results and discussion

2.4.1. Review of the described KPIs for the studies considered

Table 4 presents the information about all the studies included in this review that permit to know if they are comparable or not. That is the HP technology used, the application of the system, whether it is experimental (E) or simulated (S), the reported time span -which can be

classified as hourly (H), monthly (M) or yearly (Y)- and the average ambient conditions along the test period -global irradiance on the plane of the PV generator (G), ambient temperature (T_{amb}) and the consequent cell temperature (T_c). Cells with ‘-’ correspond to those cases where information was not available. T_c is not usually measured or simulated, because it is not necessary for obtaining the traditional KPIs. For being able to calculate the new KPIs proposed in section 4.3, we have estimated T_c in the following cases:

- When the location, orientation, inclination and nominal power of the PV generator were known but no test conditions were reported, we obtained G, T_{amb} and T_c with the simulation tool SISIFO [47]. For each specific location, SISIFO downloads the Typical Meteorological Year (TMY) from PVGIS [48] and the corresponding daily irradiance

profiles are derived by selecting the Erbs model [49] for breaking down the global values in direct and diffuse components and the Perez model [50] for transposition from horizontal to in-plane diffuse irradiances. No shadowing losses were considered.

- When G and T_{amb} were reported, T_c was calculated using the following approximation:

$$T_c = T_{amb} + 30 \frac{G}{G^*} \tag{12}$$

that corresponds to a standard value of the Nominal Operation Cell Temperature (NOCT) of 44 °C [103].

Table 5 presents the nomenclature used in Table 4 for the different HP

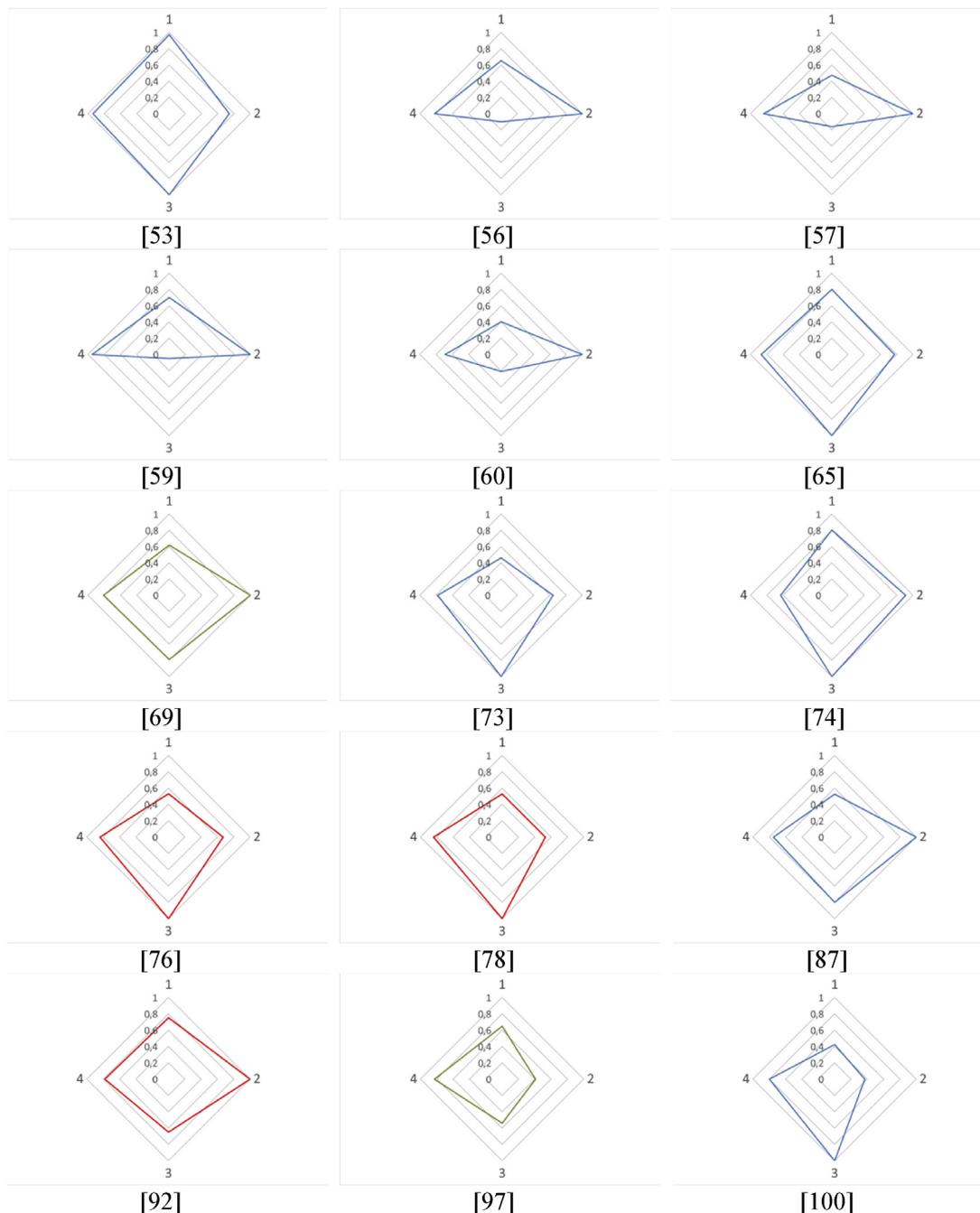


Fig. 5. Radar charts for the 15 studies included in this review that provided enough information to calculate SPF_{PV-HP} . Charts corresponding to hourly time spans (H) are in blue, to monthly time spans (M) in red and to a whole year (Y) in green. The 4 axis correspond to SPF (1), SCR (2), SF_{PV} (3) and PR (4).

Table 7

Values obtained with the SISIFO tool for PR, PR₂₅ and PR_{ref,25} and the corresponding SPF_{PV-HP,ref,25} for those studies that provided enough information.

Ref.	PR	PR ₂₅	PR _{ref,25}	SPF _{PV-HP,ref,25}
[57]	0,83	0,84	0,89	-
[68]	0,81	0,82	0,87	7,14
[73]	0,78	0,78	0,85	4,89
[76]	0,84	0,86	0,90	5,84
[78]	0,84	0,86	0,90	5,34
[80]	0,80	0,83	0,88	-
[87]	0,75	0,76	0,89	6,16
[90]	0,80	0,84	0,91	-
[92]	0,78	0,84	0,91	6,34
[94]	0,80	0,82	0,86	-
[96]	0,83	0,87	0,94	-
[99]	0,80	0,81	0,85	3,81
[100]	0,86	0,88	0,93	-

technologies and system applications. This is one possible classification of both, but others could be defined.

When analyzing the results shown in Table 4, it can be observed that it is actually very difficult to compare PV-HP systems as reported, as they are very heterogeneous. The majority of the systems use A-W HPs, but there are also many that use W-W, A-A and even some combinations of these. In very general terms, A-W and W-W systems are used for water heating applications and A-A systems, for space heating or cooling, but there are exceptions like [66] (W-W system for S-H) or [71] (A-A system for W-H). It can be seen that grid-connected systems have been widely explored, while stand-alone configurations are less frequent. In particular, there are very few examples of OPV stand-alone systems. It is also remarkable that most studies are for heating applications and very few for cooling. This is probably due to the fact that many of these studies have been developed in the colder regions of the planet and because PVT systems, which are the most abundant, are better suited for heating applications than for cooling. As for the time span and the test conditions, there is also a very high variability among the studies here included. Most PVT systems report hourly results, which have little representativity of the long-term performance of the system, while OPV systems generally report a whole year of operation (although many of them are simulations). Finally, these studies were performed in different regions of the planet, covering a wide range of climatic zones: irradiances vary from 261 to 837 W/m², ambient temperatures from 3.7 to 37 °C and cell temperatures from 19.7 to 57.1 °C.

For example, references [90] and [97] report a whole year of operation in two regions of the planet with similar climatic conditions (Naples and Alicante) and both of the systems described are OPV, grid-connected and for space heating and cooling. However, they are only completely comparable if we disregard the HP technology, because one of them uses an A-W HP while the other uses an A-A. A similar analysis must be performed for any couple of studies before making any comparison.

Table 6 presents the values of the traditional and new performance indicators obtained for all of the HP studies included in Table 4, together with the ratio between the nominal power of the PV generator and the nominal power of the HP system. The cells with '-' mean that there was not enough information to calculate the performance indicators proposed here. As some studies reported the nominal COP or EER, and some the average values along the test period, the distinction between both has been made in this table. For heating applications, EER is Not Applicable (NA), as well as COP for cooling applications – they are marked with '.' in Table 6-. SPF and SPF_{PV-HP} values are given together with the time span for which they were calculated -hourly (H), monthly (M) or yearly (Y). As mentioned in section 4.1, the PR values are given in DC terms for this review, as the studies included do not report AC PV energies. There is only one case -reference [69]- where it was not specified (NS) whether the PV energy was given in AC or DC terms. Finally, it is indicated which studies consider only the electricity consumption of the compressor (super index a), which studies define COP and EER in terms of energy

instead of in terms of power and therefore have been considered as SPF values (super index b) and which PR values have been obtained using the simulation tool SISIFO (super index c), under the same conditions described for calculating the ambient conditions in Table 4.

There is a lot of diversity in the results shown in Table 6, not only in the values obtained for the KPIs but also in what KPIs are reported or can be calculated from the given information. In fact, there are up to 7 references ([8, 51, 58, 75, 86, 89, 94]) that do not permit to obtain any of the KPIs for different reasons: only minimum and maximum values are reported but not the average ones, only the thermal energies are given, the system has been designed but not tested...

COP, EER and SPF values are not reported for many of the analyzed studies, and for most of the cases only the nominal or the average values are given, but not both. The ranges of values are (2.88–6.50) for the COP, (3.10–4.10) for the EER -which is only given for 5 OPV systems- and (2.77–6.86) for the SPF. In addition, some studies define COP and EER in terms of energy instead of in terms of power. According to equations given in section 4.1, these COP and EER values have been considered as SPF values. This different criterion when defining these KPIs can create confusion when comparing different studies, so it is important to report exactly how they are defined in each case.

SCR and SF_{PV} are the most reported KPIs among the studies included in this review. However, it is remarkable that, especially for PVT systems, these KPIs are not always given together with the ratio of the nominal power of the PV generator and the HP. The values of SCR and SF_{PV} are by definition dependent on this ratio of powers, which should be one of the key design parameters of the system. In general terms, higher power ratios lead to lower SCR and higher SF_{PV}, although other aspects are also significant (for example, if the HP unit operates only during daily hours or also at night). As expected, SF_{PV} = 1 for all stand-alone systems.

PR values were not directly reported for the great majority of the studies, but in many cases they could be calculated from given information or simulated with the SISIFO tool. As mentioned in section 4.1, the PR is defined in terms of DC energy in this review, although it is traditionally defined in terms of AC energy, so the obtained values will be slightly higher than expected if comparing them to traditional grid-connected systems. Even though, it is surprising to observe 3 studies with PR values higher than 0.9:

1. Reference [53] (PR = 0.94): this study has a short time span of only 7h, which is favorable for obtaining a high PR as it is easier to match the generation to the demand. Also, it is not specified if the reported solar irradiance was measured in the horizontal or in the plane of the generator. If the first, it could also explain the high PR obtained.
2. Reference [60] (PR = 0.95): this study has the shortest time span reported (only 1h). Moreover, the solar irradiance was simulated with a set of tungsten halogen floodlights, which has a spectral behavior different to the real Sun.
3. Reference [70] (PR = 0.99): as well as reference [50], this study reports a short time span of only 8h and it is not specified how the irradiance was measured. Furthermore, the ambient temperature conditions along the experiment were not given.

Finally, SPF_{PV-HP} could only be obtained for 15 out of the 53 studies included in the review, because the rest did not report all the information needed, even if using the SISIFO tool. From these 15 studies, only 4 correspond to OPV systems because they do not usually report the traditional SPF. The range of values is (3.18–11.34), but is important to highlight that they are not comparable. As previously discussed in this section, the conditions under which these studies were performed are different, as well as the HP technology used and the application of the system. Following the example used for the discussion of Table 4, we are going to discuss the KPIs obtained for references [90] and [97]. Both systems are used for space heating and cooling and they report the nominal values of COP and EER, but such values are higher for the reference [97] (corresponding to an A-A HP) than for [90] (which is

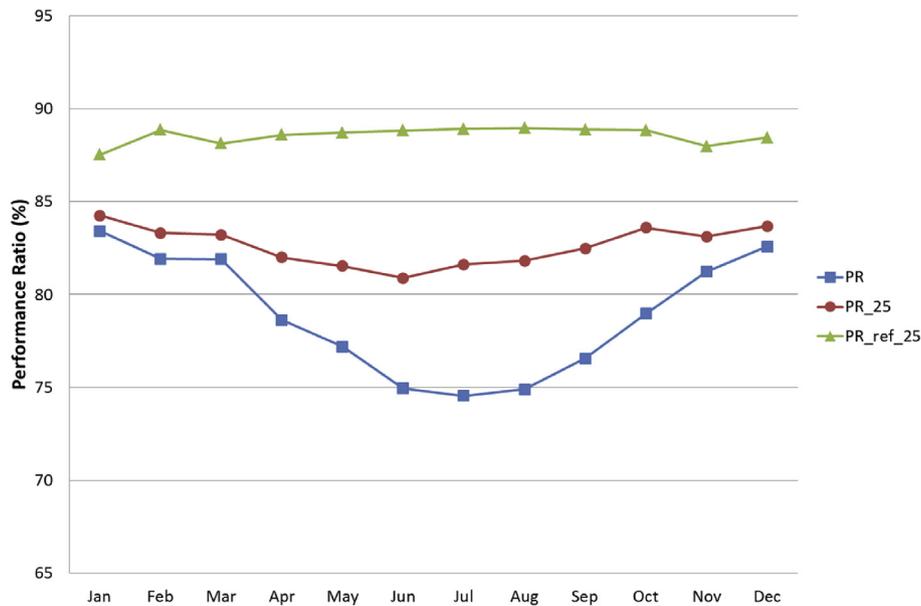


Fig. 6. Monthly values for the PR, PR₂₅ and PR_{ref,25} obtained with the SISIFO tool for a system located in Naples [90].

A-W). As for the ratio of the nominal power of the PV generator and the HP, it is higher for reference [90], which also has a higher SF_{PV} as expected. However, its SCR is surprisingly higher than the one of reference [97], which seems contradictory with the higher power ratio. It is probably due to a different use of the HP (the set temperature in the room and the occupation hours). Regarding the PR, both studies present similar values of 0.8 and 0.83, as expected for similar climatic zones (which would be Naples and Alicante) and time spans (1 year). It was not possible to compare the SPF nor the SPF_{PV-HP} values, as the first was not reported for reference [90].

In the light of the results here discussed, we suggest that future works include the following information for obtaining and analyzing their KPIs and to know if they are comparable or not:

- HP technology, application, whether it is experimental or simulated, the time span, the location and the ambient conditions (G, T_{amb}). Also, it should be indicated how those ambient conditions were measured/estimated.
- Moreover, we recommend yearly time spans to mitigate the influence of particular operating conditions. If other different time spans are used, they should be clearly indicated.
- The values of P*_{PV}/P_{HP}, SPF, SCR, SF_{PV} and PR (or all necessary data for calculating them). It is important to know if the PR is given in terms of DC or AC energy, although we recommend using AC energy to consider the inverter efficiency and the losses in the AC wiring.
- It should be clearly indicated if the work reports rated COP/EER, average COP/EER or SPF.

2.4.2. Usefulness of the new KPIs proposed

Fig. 4 present the SPF_{PV-HP} values obtained for the 15 studies that provided enough information. Only 3 of them correspond to time spans of several months -in red- and only one is reported for a whole year of operation -in green-. The remaining values are only for some hours of operation -in blue-. In order to show the usefulness of the new KPIs proposed for designers, Fig. 5 presents the radar charts of these 15 studies, considering the 4 KPIs that compose the SPF_{PV-HP} (i.e. SPF, SCR, SF_{PV} and PR). The SPF axis has been normalized to the maximum obtained for these studies (which is 6.86). Fig. 4 allows evaluating which study presents higher SPF_{PV-HP} and Fig. 5, to assess why. For example, the highest SPF_{PV-HP} corresponds to radar chart 1, with high SPF, SF_{PV} and PR; the lowest SPF_{PV-HP} corresponds to radar chart 5, with low SPF, SF_{PV}

and PR. If the needed information was provided, similar radar charts could be done with the different factors of PR to evaluate the causes of hypothetical low values. We must insist that no conclusions about which system performs better can be drawn, as they are not comparable. However, this could serve as an example of how to visually evaluate the performance of one system along different periods of operation, or of several studies if they are comparable.

Table 7 Presents the values obtained for PR, PR₂₅ and PR_{ref,25} for those studies that provided enough information to simulate the PR with SISIFO (the same ones as indicated in Tables 4 and 6), as well as the corresponding SPF_{PV-HP,ref,25}. It can be observed that the difference between the PR and the PR₂₅ is bigger than 3% for those systems operating in warm regions of the planet, as they suffer higher thermal losses. They are highlighted in grey and they correspond to systems located in Serbia, Italy and Spain. As for the PR_{ref,25}, it is the highest one for all the cases, as a reference PV module always measures a smaller irradiance than a pyrometer. This is precisely the indicator that is independent from the climatic conditions and the time span of the measurement, and that makes PV systems actually comparable. Be aware that this does not mean that PV-HP systems are comparable through the SPF_{PV-HP,ref,25}, as the boundaries associated to the SPF are still present.

To show that PR_{ref,25} is more stable than the others, Fig. 6 presents the monthly values obtained for these three indicators for the reference [90], located in Naples. It is easy to observe how the variability along the year is reduced with the PR₂₅ and practically eliminated with the PR_{ref,25}.

In the light of the discussion of the new KPIs here proposed, we suggest that future works follow the following practices for obtaining SPF_{PV-HP} and SPF_{PV-HP,ref,25}:

- To use a reference PV module to measure G and T_c and to provide the time series, instead of just average values, in order to calculate PR_{ref,25}.
- When analyzing the G time series, to distinguish between G_{HP,c}, G_{useful} and G_{used} in order to obtain the URs defined in Table 3.

Finally, it would be very interesting for future works to define the equivalent of the PR_{ref,25} for the SPF. That way, all the SPF_{PV-HP,ref,25} calculated from this standardized indicators would be comparable independently of time span and climatic conditions.

3. Conclusions

This paper presents a review of the historic and most recent studies into PV heat pump systems, both Photovoltaic-Thermal (PVT) and Photovoltaic-Only (OPV). An analysis of the traditional KPIs used for this type of systems (COP, EER, SPF, SCR, SF_{PV} and PR) has been performed. The boundaries of these indicators were identified and new KPIs (PR₂₅, PR_{ref,25}, SPF_{PV-HP} and SPF_{PV-HP,ref,25}) were proposed for trying to mitigate such limitations, as well as for evaluating not only the quality of the HP and the PV generator, but also the quality of their integration and the renewable character of the whole system. The following conclusions could be drawn from this analysis:

- It was not possible to obtain all the KPIs for all the studies included in this review, because the necessary information was not always reported. The simulation tool SISIFO was used in some cases to estimate the climatic conditions and the PR. The indicators that are more frequently reported are the SCR and the SF_{PV}, while the least frequently reported is the SPF.
 - The traditional KPIs used for PV-HP systems are highly dependent on the climatic conditions and the time span for which those indicators are reported. This makes it very difficult to establish comparisons among different studies, only possible when they have been performed under similar condition, during a similar time span and when they use the same HP technology for the same application.
 - A factorization of the PR indicator is proposed, defining PR_{PV} and the utilization ratios UR_{HCP}, UR_{PV-HP}, and UR_{EF}. This way, in case of an unexpected value of the PR it is easier to identify the causes. However, the information required to calculate these utilization ratios was not available for any of the studies analyzed.
 - A new KPI (SPF_{PV-HP}) composed of 4 or 7 factors (depending on whether we can calculate the utilization ratios of the PR) is proposed. This indicator considers the performance of the HP system, of the PV generator and how well they are integrated, so in case of unexpected values it is easier to identify the causes. It was possible to calculate SPF_{PV-HP} only for 15 studies, and they are not comparable because of the diversity of technologies, applications, climatic zones and time spans.
 - In order to make studies more comparable, it is proposed to use the PR₂₅ and, especially, the PR_{ref,25} instead of the traditional PR, leading to the new SPF_{PV-HP,ref,25}. This reduces the effect of different climatic conditions and time spans, but implies that the irradiance and the cell temperature must be measured with a reference PV module in the same plane of the generator. It would be very useful to define some similar correction for the SPF, but the diversity of HP technologies, models and applications make it very difficult to find a general equation.
- This paper is aimed to be framed in the common effort of the PV-HP research community to reach a set of KPIs that allow comparing the different future works. Experimental or simulation studies should follow common criteria when characterizing the PV-HP systems; our contributions for achieving these common criteria are the following recommendations and future research lines:
- For knowing if systems are comparable or not, it has to be specified the HP technology, the application, whether it is experimental or simulated, the time span, and the climatic zone of the system. Yearly time spans are preferable.
 - The values of P*_{PV}/P_{HP}, SPF, SCR, SF_{PV} and PR (or all necessary data for calculating them) should be reported for calculating SPF_{PV-HP}. Values of AC energy for calculating the PR are recommended.
 - Common definitions of COP, EER and SPC must be adopted. We suggest that future works clearly distinguish between rated COP, average COP and SPF (or EER for cooling applications).

- We recommend measuring the time series of G, T_{amb} and T_c with a reference PV module installed in the same plane as the generator. With them it is possible to calculate the PR_{ref,25} and mitigate the effect of different climatic conditions and time spans.
- If the PR_{ref,25} is factorized into the URs proposed in Table 3, it is possible to evaluate the causes of hypothetical low values, which is especially useful for commissioning procedures. For PR_{ref,25} calculation, it is necessary to split the irradiance data (G) into G_{HCP}, G_{useful} and G_{used}.
- For the SPF_{PV-HP,ref,25} to be comparable among different studies, it is necessary to propose equivalent modifications of the SPF to the ones applied to the PR for obtaining the index PR_{ref,25}. These modifications are proposed as a future research line that would allow making SPF independent of the operating conditions and time span.

Declarations

Author contribution statement

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The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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