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Nomograms for de-complexing the dimensioning of off-grid PV systems

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ABSTRACT

There is a need to move the building stock towards a more energy self-sustained and self-reliant one. In most countries, photovoltaic installations have great potential to make dwellings energy-autonomous. To do so, the PV installation has to be coupled with a battery system capable of providing energy for periods no solar resource. Considering how many systems will need to be dimensioned and installed to achieve the objectives of reducing the carbon footprint of the built environment, sizing tools will have to be used by installers and other blue-collar specialists. This paper shows a methodology that uses modelling and simulation for the creation of dimensioning charts (nomograms), that could be used for sizing PV-systems. The method has been tested in two locations and it seems to be accurate and robust, despite uncertainty in demand profiles. Furthermore, a survey was conducted to evaluate users' response to the method. The results show that, although the tool may not be appealing to certain users, it achieves its goal fully: all participants managed to size the installation correctly in all cases, regardless of their level of training or expertise.

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1. Introduction

The integration of photovoltaic (PV) systems in the built environment is widely regarded as one of the key enabling technologies in the incumbent transition towards a society that runs on sustainable energy. PV has rapidly increased its market diffusion, owing largely to both technical advances that have resulted in continuously decreasing costs [1], and effective incentive schemes [2], which have brought new investments into the sector. Since the output of PV systems is primarily determined by highly intermittent solar radiation, it cannot be perfectly forecasted, and exhibits considerable temporal variability. Because of this, owners of photovoltaic systems can either self-consume the produced electricity by covering the building energy demand, or, in cases when supply exceeds energy demand, it can be injected into the grid, thereby using the electricity grid as an energy storage. In some countries, financial support schemes are in place to provide compensation for energy delivered to the grid, in the form of e.g.

net metering or feed-in tariffs [3]. However, driven by the decreasing levelized cost of energy (LCOE) of PV and the critical concentrations of intermittent decentralized energy in some areas, regulatory bodies are now contemplating to terminate or reform these incentive schemes for electricity prosumers [4,5]. This scenario will likely result in positive economic opportunities for PV-battery systems, keeping in mind that battery storage costs have also dropped significantly in recent years [6]. When PV is coupled with a battery system, the excess electricity during the sunny period is buffered to be later used during no/low-solar radiation periods, thus reducing the amount of energy drawn from the power grid and consequently increasing self-sufficiency of the system. Besides the grid-connected decentralized power generation units, the traditional application cases for PV-battery systems include standalone and hybrid installations in rural/remote areas, where system availability aspects are of the utmost importance.

To get an attractive value proposition for PV-battery systems, it is important to design them in such way that a good level of storage utilization is accomplished, in relation to the amount of renewable energy production and the corresponding demand side considerations. A PV-battery installation is characterized by a triangle of interrelationships: solar yield, accumulation capacity and energy

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demand are the components of the system and they depend on each other. The design of cost-effective PV-battery systems is a challenging task, because both meteorological parameters (i.e. weather/irradiance sequences) and load profiles are highly dynamic and stochastic, featuring both seasonal and diurnal variations.

In recent years, several studies have used building performance simulation (BPS) to assist in exploring trade-offs in battery sizing.

For example [7], carried out simulation of a residential building in Sweden served by a solar-assisted heat-pump system using TRNSYS, in order to investigate the impact of a storage system design on PV electricity self-consumption rate. A study on the assessment of the economic impact of demand-side management achieved by integrating of electrical batteries in positive energy buildings was done by Ref. [8]; who performed simulations in Dymola/Modelica environment [9]. Explored strategies for reducing the annual mismatch between the PV/micro-wind turbine production and demand from a detached house in Finland, with a particular focus on hybrid thermal-electrical storage analysis, with lead-acid batteries modelled by Type 47b in TRNSYS.

Albeit being very powerful, these detailed studies using BPS also reveal a number of drawbacks, in particular related to the high input requirements, the required level of expertise, and difficulties in generalizing findings to other application cases.

At the other end of the spectrum, one can find simple sizing methods relying on design days and average load profiles. Detailed analyses of the pros and cons of different sizing methods are presented in the review papers [10,11]. Essentially, most of these sizing procedures try to establish minimum required energy storage capacities for a certain PV system's nominal power, meeting a certain *reliability of supply* that is tolerated by the user (Zhu et al., 2016; Starke et al., 2017). The traditional performance indicator that is used for this characterization is loss of power probability (LPP) and the outcome of sizing procedures is often presented in the form of sizing curves. This type of simple-to-use tools have low input requirements and are designed to be intuitive to use by practitioners, but have as drawbacks that they do not take realistic weather sequences and demand patterns into account, and that they provide limited understanding of the underlying causal relationships between solar yield, storage capacity and energy demand for the specific case at hand.

Recently [12], have outlined the importance of using realistic load profiles instead of average/maximum energy consumption, for PV-battery system optimization, in particular for such criteria as system autonomy, self-consumption ratio and number of battery cycles. Moreover, in research by Ref. [13]; it was found that significant variations in battery system utilization are experienced from year to year, and that monthly averages do not provide enough information regarding extended day-to-day spells of low irradiance. For risk-informed sizing of PV-battery systems, it is therefore important that this kind of variability is also integrated in the relevant boundary conditions of sizing procedures.

The goal of this paper is to identify ways of developing sizing tools that focus on simplifying the work that needs to be done by the practitioner. With this in mind, graphical sizing charts (Nomograms) have been created. The charts can be an easy-to-use-tool that can be attached to professional guides and technician books so technicians can get an impression on what system to select with one glance. While developing these graphs, some interesting learnings have been obtained from this research exercise.

Also, to be able to consider the outcomes of this work to be valid, it was necessary to test if the nomograms were really understood by the lay person. For this purpose, a questionnaire was proposed to a varied group of professionals, both related to the field of renewable energy and unrelated to it. The survey had a dual scope: to

verify if the chart truly simplifies the sizing process and to evaluate if users are willing to introduce it in their professional activities.

2. Methodology

This work aims at developing a generic approach that can accommodate many combinations of energy demand patterns and storage systems in the context of renewable energy integration. Therefore, it is important to extract generally applicable parameters, and to perform a synthesis exercise for ensuring that the input parameters of the approach are widely available. With this, we are able to create a normalisation method that would allow the use of sizing chart for many different applications. This normalisation is explained in the following sub-sections.

2.1. Normalisation

The normalisation has to be such, that maintaining the real significance of the project, moves the numbers of relevant magnitudes to a normalised space that will extract all the relevant ratios and proportions, yet representing a variety of equivalent scenarios. This is similar to the normalisation carried out in Fluid Dynamics with dimensionless numbers such as Reynolds, Nusselt, or Prandtl numbers.

The production or yield provided by the PV panels will serve the demand, and for any deficit or surplus, interaction with the battery storage system has to take place. Sizes of PV installations are in the industry characterized using the nominal power in Wp, which represents the yield of the PV system under standard conditions of irradiance, which are fixed to 1000 W/m². This value of Wp can be considered as a good proxy of the potential yield of the installation. On the other hand, the energy demand of the dwelling is a key parameter for sizing the installation, and one can anticipate that the proportion between the two is an important figure. This ratio will provide an idea of the proportion between the energy that could be expected from the solar panels and the demand. This ratio is therefore fundamental for the understanding of the level of surplus that one may expect. It is for this reason that the first ratio we compute is the average electric demand, normalised with the nominal power of the PV installation, and we call it the Power Generation Ratio.

$$PGR = P \text{ average demand} / P \text{ PV watt-peak} \quad (1)$$

To allow the calculation of this ratio without a computer, an auxiliary graph has been created in order to make the solving simple and to suggest an alternative to digital calculation (Fig. 1). This new chart is a typical parallel-scale nomogram used in other applications for multiplications and divisions, but adapted for this case with power (watts) values. Although the calculation can be done with Eq. (1) we wanted to include this parallel-scale nomogram to create a full kit of graphical tools that make unnecessary even the use of a calculator.

This normalisation allowed us to use the same charts irrespective of the size of the installation/dwelling: its electrical requirements or the size of the installed PV systems. With this number we created and called PGR, we are taking only into account what is relevant for the problem at hand, which is the ratio between what is consumed and what is produced. Also, we see that for each case this ratio will have a turning point which is interesting for the sizing of the installations. If one imagines a PGR that is very small, then the PV installation will generate enough electricity for covering most of the time the power demand. If on the contrary, the PGR is very large, then one will see that even with batteries it will

Fig. 1. Parallel scale nomogram to obtain the PGR value.

not be possible to cover the demand of the house, as there will not be enough energy in absolute values in the yield of the generators to cover the demand.

After this normalisation, it is possible to continue evaluating the problem and normalising also the capacity of the battery system. The most commonly used unit for battery systems is the energy storage capacity in kWh. It is straightforward to add the same normalisation to this unit, so we obtain a ratio with dimensions of time, which is highly relevant for the dimensioning of the system as time of black out is one of the outputs of the nomograms that we want to design. As time is also the unit to measure potential black-outs, this is convenient. Because of this, we use the following normalisation for the capacity of the batteries:

$$C_{norm} = \text{Battery capacity} / P_{PV \text{ watt-peak}} \quad (2)$$

Also in this case, a suited nomogram is created to obtain the C_{norm} value without the use of digital calculation (Fig. 2). With these two normalised values it is possible to start defining ways in which the sizing charts could be developed.

2.2. Nomogram design

Sizing an off-grid system, several variables have to be included. The idea behind this method is to simplify the process allowing the user to consider the minimum number of parameters, while the others are already included in the chart itself. The rationale behind this work, despite the fact that one can find calculation engines for dimensioning PV-Battery installations, was that we believe that the fact of having a sizing chart provides more information at a glance, which provides an educational component to its use, at the same

time that it minimises iterations in the evaluation of options.

The aim is to create a graphic that can contain information about the two normalised values discussed above, the PGR and the C_{norm} , and a third value, the number of blackout days, which describes the condition with a lack of electricity in the off-grid system. Through these three parameters, the simplified sizing process of the off-grid system will be considered complete. Fixing two of the values, the chart will give the third one as output. For instance, knowing the PGR value and the C_{norm} value, it will be possible to know for how many days out of a year the off-grid system will be enough for that specific demand. Likewise, fixing how many days of blackout one is willing to face and the PGR, it will be possible to have an idea of which kind of battery would be more appropriate, and so on.

As mentioned, the other values will not be neglected, but they will be incorporated in the chart itself. Among others, battery efficiency, losses and above all users' profiles play a fundamental role in the whole sizing procedure. This is why the nomogram will be composed of bands of values, to include the variability of the different parameters. Moreover, a significant difference among values will depend on geographical position, i.e. on the weather files. For this reason, every weather file will correspond to a different chart. With this method it will be able to tap into the capillarity that one gets with the fact that each single location can have its chart, and all people in that place will use that graph and be capable of dimensioning a PV off-grid installation. From that level, the users will not see the fact that the graph is not usable for other locations, but considering the philosophy of the tool, they will not need to use it in other locations, as the principle of this is to make everyone capable of dimensioning their own installation.

In the following chapters, the whole process to obtain the final

Fig. 3. Daily profiles used in the simulations.

nomograms will be analysed.

2.3. Simulation

The idea of this work is to perform as much pre-processing as possible to the weather data, so the work that needs to be done at the practitioner's side is reduced to a minimum. For this, we took advantage of a series of parameters of PV installations that are seen to be the norm in most cases within small ranges and used those for pre-processing of the data. With this, we developed a full framework in Octave (Matlab's GNU counterpart) for the simulation of PV-off-grid systems. The code includes the solar PV generators with a given efficiency, the storage, and the demand. The performance of charging and discharging is also included in the code, and the control logic is such to use electricity primarily from the panels and if they do not deliver enough (or any) to consume the energy stored within the batteries.

With respect to the generation of power, the code takes the normal and the diffuse radiation from any. Epw weather file, and using the latitude of the panels, the area, and their optimal orientation, a series of the irradiation reaching the panels is calculated. As the input used is the nominal power of the installation (watt-peak) there is no need to define the efficiency of the solar panels. However, losses in generation has been taken into consideration and have been included in the code. After this, an ideal battery is modelled, the input here is the capacity of the battery normalised with the nominal power of the PV plant. The battery has been assumed to have losses in charging and discharging.

One of the parameters that are included in the simulator is the performance of the batteries. Electric batteries use different technologies. However, due to their different characteristics (mainly volume and weight) some technologies are more popular than others for domestic applications.

The fact that a value of performance for charging and discharging is available and holds true for most devices allows to develop a simulation framework that would evaluate the suitability of different systems depending on the size of the storage system and the ratio of demand/yield (Eq. (1)). Although these two seem to be available, the third component of the system, the actual demand, holds unknown, and it will be unrealistic to assume that there will only be one type of demand profile.

The demand will therefore be variable depending on the users. Nevertheless, the batteries will smoothen this demand, so there is

Fig. 4. Example of simulation for Murcia with a mean PGR of 0.08 W/Wp, a profile 3 and a storage of 5 Wh/Wp during 5 days.

room for investigation in this aspect. In this work we have considered 4 different profiles of electricity demand, to evaluate if it is really possible to use the average power demand as an entry for the sizing charts and still get good results, or in opposition there are better options.

2.4. Electricity profiles

Battery banks cover mostly oscillations in the solar resource that correspond to time periods close to the days or few weeks' length [14]. Considering this, one can anticipate that the daily profiles of consumption are going to have an effect on the sizing of the battery banks, and so has been seen in the literature [12,15]. To take this into consideration four different electricity profiles were used to evaluate their impact in the nomograms created. With this, we were able to make a sensitivity analysis that would check the validity of the sizing charts at the same time that a confidence interval or estimation error will be provided. It should be mentioned that all these time series were normalised by the nominal power of the PV system and will have units W/Wp, following the normalisation explained above. The four profiles are shown in Fig. 3.

The first profile in blue is a standard load profile from real data taken from Refs. [16], it is rather smooth as it represents the profile that one may expect from a multifamily building. The second profile in green was extracted from the VDI, which is a reference load profile of single-family and multi-family houses for the use of CHP systems (VDI Guideline 4655). It is sharper than the former profile, showing larger skewness towards the evening.

The third profile in red was chosen from Ref. [17] and it represents an extreme case of peaks during the evening.

The last and simplest electricity profile in turquoise is a constant demand with the average of the power consumption of the dwelling. The profiles represent the power distribution for 24 h, to convert this into year demands the profiles were concatenated 365 times. No seasonal or weekly variations of the data have been considered in this work. However, a detailed study about the effect of the seasonality of conditioning loads could be interesting for further work. Examples of simulation results using the profiles can be seen in Fig. 4 and Fig. 5. One should note that there are not peaks of power consumption in this profiles except for the peaks in profile 2. This means that a user of the chart who is expecting not-normal profiles with extra-large peaks should complement the use of the charts with detailed dynamic simulators of PV installations.

It should be taken into consideration that seasonal or weekly

Fig. 5. Example of simulation for Murcia with a mean PGR of 0.15 W/Wp, a profile 2 and a storage of 5 Wh/Wp during 5 days.

validations have not been taken into account in this test. However, as the profiles are substantially different, we expect that some of the changes that one could expect from seasonal and weekly variation will be within the bands of probable results result of the different profiles. Nevertheless, it is recommended further evaluation in further work.

2.5. Weather data

There are several sources of weather information that contain solar irradiance. In our case, we have used EnergyPlus weather files (.epw) obtained from enrgyplus.net. Two weather files were used as examples, the weather file from Beek, in The Netherlands which is an IVEC file, and the weather file from Murcia which is a SWEC¹ file.

3. Results

Several results were obtained from the work here explained. Although the main aim was to develop a sizing tool that can be used with almost no expertise and that can help to size PV-battery systems, substantial learnings have been obtained thanks to the evaluations performed.

3.1. Standard parameters graphs

As the methodology was later validated with the widely-used sizing tool EU PVGIS, the parameters of the simulations were chosen based on common cases and these assumptions will be evaluated along the research. The performance of the batteries for charging and discharging was fixed at 80%, and the overall losses of generation were fixed at 28% as an educated guess from engineering books. Although these figures were rather approximate, they were a starting point to evaluate the results that one may find when generating the graphs searched in this research.

The charts obtained with these parameters for the locations at hand are shown in Fig. 6 and Fig. 7. The reader is reminded that blackouts are days in which the energy in the battery has run out and there is no solar resource to guarantee the electric power demanded by the user, causing a lack of electricity in the off-grid

Fig. 6. Sizing chart with standard parameters for the weather file of Murcia.

Fig. 7. Sizing chart with standard parameters for the weather file of Beek.

system. The graphs should be interpreted in the following way:

- At first, one has to find which PGR represents their installation. For this, as mentioned before, one has to divide the average power consumption by the photovoltaic installed power using the graph in Fig. 1.
- In the main nomogram (Figs. 6 and 7), each PGR is represented with one line (with different colours). One should use the corresponding one to evaluate to what extent a battery ratio would be capable of balancing consumption and demand in a way in which blackouts will be smaller than desired.
- Seeing the curve that represents the balance for that installation between generation and demand, and considering the acceptable number of days in which the battery can be emptied, one can see the battery size that is needed in absolute values using the auxiliary chart in Fig. 2.

It is worth mentioning that this method considers effective battery capacity, so if the batteries used can only be discharged up to e.g. 50%, then one has to multiply by two the number found in this graph.

¹ The weather files were synthetically generated using Climed (Portuguese software developed by Ricardo Aguiar) from mean monthly data coming from the Spanish Meteorological National Institute by Prof Perez-Lombard.

Fig. 8. Outlining of the singular point on the PGRs curves that separates short term (days) storage from long-term (months) storage.

3.2. Identification of daily and seasonal storage

The creation of these sizing graphs with standard parameters allowed to see the first finding of the investigation. Figs. 6 and 7 confirm the rationale of this work, expressed in section **Error! Reference source not found.**, i.e. having more information about all the components of the system at a glance.

Having a look at the graph with a given PGR, the user can see the situation the building is in, and to what extent it makes sense to make more or less investment in storage, or instead if it is worth “jumping” to another PGR, e.g. by installing more PV panels.

In addition to that, an interesting feature has been seen in the sizing curves. For each one of the PGR values, it has been seen that two clear tendencies exist in the graphs. Taking for example the $PGR = 0.04 \text{ W/Wp}$ for Beek, one can see that the curve from 0.1 Wh/Wp to 0.6 Wh/Wp maintains a constant curvature. From 0.6 Wh/Wp to 20 Wh/Wp the curvature changes, and although the convexity is still the same, a small inflexion point around the value 0.6 Wh/Wp is seen here. This turning point at 0.6 Wh/Wp for this PGR occurs because before this point, the batteries can cover the gaps produced by nights and sporadic low-irradiance days. As these represent the majority of the periods that need to be covered with the battery storage, the curve decreases quickly. After this point, further reduction of the blackout periods need a substantial increase in the battery size as one is getting into the zone of seasonal storage.

This effect has been explained in Fig. 8. We consider that these points that separate short-term storage from long-term storage have a substantial importance, and it was significant to see that they can be accurately represented with a second order polynomial. More research about this singularity is recommended for further work. Although this could be identified with seasonal storage, there are many factors that would affect that kind of storage, and due to the aim of this paper, that focusses in small off-grid installations, the identification of this part of the chart is provided only for illustrative purposes (see Fig. 9).

3.3. Effect of battery charging/discharging performance

After this satisfactory test of a dimensioning chart, we evaluated the effect that the preliminary parameters that we have chosen may have on the final result. For this, one curve of PGR was plotted

Fig. 9. Effect of different battery efficiencies in the sizing curves.

Fig. 10. Effect of production losses on the sizing charts.

on its own with three different values of charging/discharging performances. This has been shown in **Error! Reference source not found.** It was seen that the efficiency of the batteries for charging and discharging has an important effect on the sizing curves. This suggests that different technologies may need different graphs. However, the new Ion-Lithium batteries seem to have a rather high and consistent performance, which opens the way for unitary graphs. This is particularly relevant as it also seems like this technology is becoming more popular in domestic installations.

3.4. Effect of production losses

There are several factors that make generation not maximum in photovoltaic installations. Examples of these are temperature of the cells, transmission losses, converters losses, maintenance of the panels and several others.

It is because of this that a correction factor is needed when calculating the yield of a PV installation, failure to apply this will lead to over-optimistic results. It is understood by the authors that this parameter can change substantially depending on the installation at hand, so it was important to evaluate the effect that the

Fig. 11. Different curves using different demand profiles. Diagram for Murcia. Profiles 1, 2, 3 and 4, are represented respectively with '-', 'x', 'o' and '+',.

losses will have in the dimensioning graphs, so they can be compared with other parameters which are a source of uncertainty. This is shown in Fig. 10.

The evaluation of the effect of the production losses in the graphs has shown that although these have less impact on the geometry of the curves than the variation due to battery performance, they can as well be a source of discrepancies between graphs. It is worth noting that although the changes in efficiency in battery were changing the overall slope of the sizing curves, the changes in production have shown to shift the curves as well.

3.5. Variation with respect to users' profiles

One important factor for the operation of an off-grid PV installation is the daily profile of the electricity consumption. Depending on when most of the demands are occurring, one can expect the installation to be more or less strained. In addition to that, one can expect that the effect of daily profiles of consumption in the performance will be larger as the battery size is smaller. Once the installation has batteries large enough so one can tap into seasonal storage, the daily profiles should have less effect on the system.

To evaluate the effect of the daily profiles in the sizing charts, the profiles described in the methodology section were used to generate different curves. The results can be seen in Fig. 11.

The evaluation of the black-out times in Fig. 11 shows the variability that one finds in the results when using the four different profiles (that has been marked respectively with '-', 'x', 'o' '+'). Although the number of profiles that were evaluated do not represent all options, due to their differences, they provide a good picture of the variability that one can find in real installations.

The generation of this figure helped to understand how the profiles have significant influence in all cases, and only when one sizes the battery system to ensure that no black-outs will occur one can see that the curves from different profiles tend to converge.

After seeing these graphs, it was possible to see that the variability depending on the user profile could be an added value to the graph. This is because the new trend to install smart meters and other home automation devices that can optimise the load profiles may open a door to the user towards investing in home automation devices instead of purchasing a more expensive battery pack.

The variability between profiles was plotted as areas in the chart, each one corresponding to a given PGR, as show in Fig. 12 and **Error! Reference source not found..** In this way, the nomogram user

Fig. 12. Sizing chart for Murcia, Spain including the variability given by the profiles.

can observe how sensitive their installation is to different behaviours of users.

In addition to that, the chart can be used not only for selecting the battery size, but also the PV installation size. By looking at the charts, one can see the level of PGR that one may need, to make an installation self-sustained with batteries, or in case of going for a combined solution of PV and other on demand generating systems such as fuel generators, then one can see the optimal PGR considering the investment.

3.6. Validation

The graphs created here add, to our believe, more than simple calculation tools as they allow to visualise in one glance the effect that a change in the design may have. However, it is important that the graphs that we show here are in accordance with well proven tools, so practitioners in the field are not taking mistaken assumptions. It is for this reason that we used the tool: *Photovoltaic geographical information system*² developed for the European Commission and available in the previous footnote to validate the graphs. The indicator that we have chosen to evaluate the accuracy of the methods is the percentage of days with charge in batteries smaller than 10% at the end of the day, which is an indicator given by the PVGIS application and makes the comparison seamless.

For the validation, a full dynamic simulation has been performed using the widely used software EnergyPlus. The software only allows to model photovoltaic systems connected to the utility, i.e. grid-connected or hybrid systems. An off-grid system and a hybrid system are both composed by the solar panels, the battery bank and the inverter. The two systems have a similar distribution structure: the electrical power is generated by the solar panels in order to meet the energy demand and the excess of power is stored in the battery bank for future use. When the energy demand is higher than the energy produced by the generator, for instance in winter or in cloudy and rainy days, the power stored by the battery bank is used. The main difference between the two systems is that, when the battery discharges, the hybrid system can take power from the grid, while the off-grid system presents a blackout day.

Hence, the off-grid system has been simulated in EnergyPlus as a hybrid system in which the days with no charge stored are

² http://re.jrc.ec.europa.eu/pvg_tools/en/tools.html#PVP.

Table 1

Validation based on the comparison with the European Commission's tool. Each line represents a potential scenario based on differences in installed power, battery size and average energy use. Case of Murcia.

Installed power [Wp]	Average demand [W]	Daily Energy [Wh/day]	PGR [W/Wp]	Battery size [Wh]	Battery size [Ah]	Battery ratio [Wh/Wp]	E+	Charts	EU PVGIS
5000	500	12000	0.10	10000	800	2.00	10.1%	9.0%	7.0%
5000	500	12000	0.10	8000	640	1.60	11.5%	11.2%	9.0%
3000	300	7200	0.10	2500	200	0.83	41.1%	30.1%	45.0%
5000	700	16800	0.14	10000	800	2.00	18.4%	17.8%	18.0%
2000	300	7200	0.15	8000	640	4.00	17.0%	14.0%	16.0%
3000	180	4320	0.06	3000	240	1.00	3.3%	3.0%	4.0%
8000	400	9600	0.05	1000	80	0.13	100.0%	100.0%	49.0%
8000	600	14400	0.08	8000	640	1.00	8.2%	8.2%	10.0%
7000	600	14400	0.09	9000	720	1.29	9.3%	9.3%	9.0%
3000	120	2880	0.04	5000	400	1.67	0.0%	0.0%	0.0%

considered as blackouts days. The generator has been modelled through its performance, specifying the PV cells area and the efficiency of the surface. The battery bank has been modelled as a storage system with 10 modules in parallel and 10 modules in series, with a circuit voltage of 12.5 V. Charging and discharging curves have been designed and the maximum module capacity have been defined for different case scenarios. The inverter has been modelled through the definition of its efficiency curve. All the components are connected in EnergyPlus through a distribution system, that links the PV system with the rest of the building. Furthermore, an electric equipment has been defined, using the same demand profiles considered for the charts. The design level varied depending on the energy demand considered for each case.

In order to compare the results of the dynamic simulation with those from PVGIS and the charts, the output considered for the validation was the percentage of days with charge in batteries smaller than 10% at the end of the day. As the output were calculated with an hourly frequency, the value at 23:00 h of each day has been considered. Several simulations have been run to reproduce each scenario considered, with variations in design level of the electric equipment, cell efficiency value and maximum module capacity of the storage system.

For the validation, we run different cases in the two cities. The values can be seen in [Tables 1 and 2](#).

The results of this validation are also shown in [Fig. 13](#). Here we have shown how the graphs have good accuracy when compared with the PVGIS. Although an error can be found between the outputs of the sizing chart presented here and the results from the PVGIS tool, we can see how those errors are smaller than the inevitable variability of the weather (from year to year). Predictions of the source of the errors could be the efficiencies and losses that have been considered in the PVGIS simulation. No information on the website has been found that shows this information, so no further investigation has been done to identify this error (see [Fig. 14](#)).

4. Survey

The second part of this research consisted of the development of a survey that was later completed by a cohort of people of diverse backgrounds. The survey was developed based on published and tested questionnaires, and they were designed to evaluate the ease of dimensioning PV-battery systems by the general public with the nomograms, and the satisfaction of users that used the graphs.

To evaluate the results of the survey, statistic tests have been done following standard statistical methods.

4.1. The questionnaire

The test is composed of five main parts, and it is included in the

Appendix. The first one points out the demographic profile of each respondent, including mainly age range, gender, and his/her professional sector, level of education and knowledge about photovoltaic systems. For professionals of the energetic fields, a few questions about the sizing system they use were also included.

The second part has the purpose of understanding the candidate's approach to use a chart rather than the computer when sizing PV systems through the use of the Likert scale, i.e. scoring from strongly disagree to strongly agree. This section also refers to psychometric chart, an example of easy-to-use-tool, making something complex understandable even to a student. Also, other scenarios are proposed in this section, as facing a client, being in the worksite or simply having an alternative to the computer calculation.

In the third part, a simple comprehension test is proposed: candidates are requested to solve a sizing exercise using the nomograms of the city of Murcia. Three questions are about the numeric calculation of PGR, Cnorm and capacity respectively. To solve them, the auxiliary nomograms ([Figs. 1 and 2](#)) can be used. The last question, that could be considered more complex, proposes a *what if* scenario to capture if candidates get the potentiality of the chart. Its aim was to suggest that, through the nomogram, at a glance one can obtain more than a numerical result, allowing a global vision in the research of the optimized sizing. In particular, in the example presented, increasing the battery capacity of a small quantity will lead to a significant reduction of blackouts, a conclusion difficult to get with other sizing methods. The fifth part uses a System Usability Scale (SUS) test [[18](#)] to measure the usability of the nomograms. The SUS test involves ten predetermined questions with five answer options, from strongly disagree to strongly agree (Likert scale). The scoring system is not trivial, changing according to even or odd items, and it returns a score of 0–100, that is not a percentage. Summarizing the result's interpretation, scores above 68 are considered satisfactory, otherwise the usability of the system is evaluated as inadequate. The last part gathers the candidate's final considerations after employing the method, through ten items based on Likert scale. Objects of evaluation are, among others, the understanding speed, the graphical effectiveness and the possibility of use comparing to other techniques. Three versions of the questionnaire have been elaborated, to increase its diffusion: the English version, the Spanish version and the Italian version. Most of the candidates received all versions to choose which one they felt most comfortable with.

4.2. The pilot test

To evaluate the questionnaire, a beta version of the survey has been proposed to a group of students and researchers that do not have any knowledge about photovoltaic systems. Observing their questions and their comments, it was possible to improve the

Table 2
Validation based on the comparison with the European Commission's tool. Each line represents a potential scenario based on differences in installed power, battery size and average energy use. Case of Beek.

Installed power [Wp]	Average demand [W]	Daily Energy [Wh/day]	PGR [W/Wp]	Battery size [Wh]	Battery size [Ah]	Battery ratio [Wh/Wp]	E+ (23:00)	Charts	EU PVGIS
5000	500	12000	0.1	10000	800	2	35.6%	37.3%	37.0%
5000	500	12000	0.1	8000	640	40	37.8%	38.6%	36.0%
3000	300	7200	0.1	15000	1200	10	29.6%	29.9%	33.0%
5000	300	7200	0.06	10000	800	2	20.6%	20.3%	20.0%
5000	300	7200	0.06	8000	640	40	22.2%	21.6%	21.0%
3000	180	4320	0.06	3000	240	10	25.2%	26.6%	29.0%
8000	400	9600	0.05	1000	80	1	100.0%	100.0%	53.0%
10000	800	19200	0.08	8000	640	0.4	41.1%	37.0%	53.0%
7000	600	14400	0.085	9000	720	2	33.4%	34.5%	44.0%
3000	120	2880	0.04	5000	400	10	11.5%	12.9%	11.0%

Fig. 13. Representation of the validation points when comparing results obtained with full dynamic simulation performed with EnergyPlus, and with the nomograms.

Fig. 14. Representation of the validation points when comparing results obtained with PVGIS, and with the nomograms. One can see that if the installations are adequately sized and do not have large periods with empty batteries, the nomograms are highly accurate.

comprehensibility of the whole test, in particular for what concerns the exercise in the third part of the questionnaire. The changes affect both the way of writing the questions and the numerical example, so it was possible to reach an optimized test. The first suggestions were about a better explanations of technical terms: concept as blackouts were totally new for users that do not deal with photovoltaic systems. Moreover, the pointed out it was not that clear the parameters were referring to a whole year. Other propositions were about simplifying the calculations, through adding more numbers to the logarithmic graphs and choosing a simpler numerical sample.

4.3. Data collection

About 160 questionnaires have been sent to a quite varied group of professionals, with differences both in working sector's and geographical terms. A total of 42 respondents filled the test, of which five contain at least one blank question, while the others have been completed in all their parts. Short interviews have been conducted with some of the respondents as well to get the most of the impressions that the tool had caused in the participants. As a result, one of the questionnaires has been classified as unusable because some answers were copied from another candidate. Consequently, 41 questionnaires have been considered for the results, four of which contain at least one blank question. Among the interviewed people that do not work in the energy sector, someone criticized the focus strictly related to the photovoltaic topic. They pointed out the lack of further explanations about basic concepts and the difficulty to answer to questions as "*I would like to use this system in my professional activity*", maybe failing to grasp the interpretation effort they were supposed to do. Other respondents,

in particular people that studied photovoltaic systems but did not use them in their professional activity, declared contrariwise that they enjoyed the questionnaire and that it could be safely used in an introduction course for students.

4.4. Survey's results

The demographic results of the first part of the survey show that the 70% of respondents are men and the 30% are women. 85% of candidates can be included in the age range 26–40 years old and hold a degree. Most of them (90%) have a technical professional profile, but just 58% of the respondents deal with photovoltaic systems in their professional activity, while the 39% have studied them during their academic career.

In the second section, it is interesting to focus on a few questions in particular. In fact, as the aim of the test was to evaluate the ease of use of the system and its effectivity, it is important to highlight the percentage of respondents that agrees with the affirmations "*I would like to have a chart to size photovoltaic system as well*" (66%) and "*I think that simplified photovoltaic system calculations could encourage their diffusion*" (68%).

For what concerns the four-items comprehension test of the third part of the questionnaire, results are shown in Fig. 15.

No candidate was unable to answer at least one question, and just three candidates responded correctly to only one question. Breaking down by professional sectors, all the three respondents that collected only one correct answer deal with architecture. To better understand this result, the reader is reminded that, in the comprehension test of the questionnaire, respondents had to

Fig. 15. Percentage of correct answers collected out of the four questions relative to efficiency of sizing tool.

Fig. 16. Results of the SUS test.

actually use the charts to size the battery in a specific scenario where user's energy use profile and photovoltaic system's power are given. With a score of three correct questions, the battery is considered correctly sized, as the fourth one is a theoretical question. We can conclude that the 93% of respondents (included people that have no practice in photovoltaic installations) managed to use the chart to size the optimized battery for the PV system considered.

Maybe the most important result of the questionnaire is the response to the usability test, the fourth part of the survey. As mentioned before, this test intends to estimate the accessibility of the method. The predefined scoring evaluation divides scores in four ranges of usability: awful (<51), poor (51–68), good (68–80.3) and excellent (>80.3). Fig. 16 shows how the candidates reacted to the test. To better understand the results, SUS scores have been grouped by professional sector (Fig. 17) and by level of study (Fig. 18).

Evaluating the last part of the questionnaire, among others, an observation considered noteworthy is the discrepancy between what people perceived about their comprehension of the sizing method and the real understanding obtained by the efficiency test. This lack of correspondence is evident focusing on respondents that gave at least three correct answers, i.e. that in the opinion of the

Fig. 17. Results of the SUS test grouped by professional sector.

Fig. 18. Results of the SUS test grouped by level of study.

authors understood the whole method. More than 45% of the aforementioned group of candidates scored less than 68 in the SUS test, which contains items such as “*I thought the sizing system was easy to use*”, but 79% of them agree or strongly agree with the statement “*I think that this system could be used also by people without a lot of experience with photovoltaic installation*” and 59% with the statement “*I would like to use this system in my professional activity*”.

5. Conclusion

This work shows how simulation has been used to perform a dimensionless analysis of PV installations with batteries, as input for the development of a graphical sizing chart. The information that the sizing charts can provide include the blackout periods that an installation may have, but also the error that may be induced due to epistemic uncertainties such as battery performance or generator losses and also aleatory uncertainties such as user's behaviour.

It has been seen that, unlike a one-point evaluation tool, the sizing charts can provide a good impression of the effect that selecting a system with variations in nominal generating power, or with variation in storage capacity may have. So much is so, that a breaking point on the curves selected has been identified, and it has been seen to follow clearly a mathematical expression. This is relevant, as these breaking points are relative only to a given weather profile, and it can provide with information about how PV installations unplugged from the grid should be considered in specific locations.

The effect of battery performance and losses of the generating system have been evaluated, and it has been seen that these parameters do not substantially change the shape of the curves, but the way in which they are modified when modifying this parameter has been found. As one could expect, the performance of the battery affects the results in a larger manner when installations with large levels of battery storage are selected; whereas the effect of the performance of the generator affects installations with all sizes of batteries as one also may expect.

The paper also shows the elaboration of a survey, that is based on proven methodologies to measure usability and satisfaction. The aim of the survey was to evaluate if the nomograms really are a tool that can cover the gap discovered between complex tools to size PV off-grid systems and the large need of technical assessment. The survey was completed by a heterogeneous cohort of respondents with diverse backgrounds, and the results were good with respect to the usability and practicality of the tool. This conclusion was confirmed by the survey, inasmuch as most of the respondents were of this same opinion. In particular, although the usability level was not that high, it was totally clear that the great majority of candidates, including the ones that never studied PV systems, solved correctly the sizing exercise and evaluated that anybody could use such a method. Consequently, the purpose of de-complexing the sizing system could be considered achieved, and this may be an important next step for off-grid PV systems' diffusion.

Overall, the graphical tool for sizing seems to perform as well as a standard calculation method but it provides extra information about *what if* scenarios that can be highly valuable for a practitioner taking decisions about the size of the installation and with higher-level knowledge about price of modifications or limitations of the site. It is firmly believed that these graphs could also contribute also to the large-scale proliferation of PV systems with storage for off-grid self-sufficient homes.

Author statement

I, Alfonso P. Ramallo-González am the main author of the paper, developer of the research and the original idea.

Valentina Tomat has been in charge of the usability survey under the supervision of myself for its design.

The rest of the authors have supported the work with contextualisation, support, and supervision.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.renene.2020.06.103>.

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