On the development of dimensioning charts for small size PV-battery system

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Abstract
Several initiatives have started to move the building stock towards a more self-sustained and self-reliant one, with respect to energy use. In most countries, photovoltaic installations have great potential to make a dwelling energy-autonomous. To do so, the PV installation has to be coupled with a battery bank that will be capable of storing enough energy in the periods with large solar resource so it can be delivered to the periods with little or no resource. Several tools are available to investigate what capacity is needed in terms of storage to optimise the PV+batteries installation and to minimise the time that the user may suffer a black-out, without unnecessarily increasing the battery size and therefore its price. These tools are rather accurate, however, their use tends to be limited to technical professionals such as engineering firms or academia. A tool that is simple enough to be used by anybody involved and that is accurate enough to give similar answers to those obtained with complex dynamic simulators, would be of great value, and will promote the deployment of such solutions. This paper shows a methodology that uses modelling and simulation for the creation of dimensioning charts, that could be use with this purpose. The method has been tested in two locations and it seems to be robust despite the demand profiles; and also, it seems to give accurate answers for dimensioning battery systems.

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 (Barbose and Darghouth, 2015), and effective incentive schemes (Bertsch, Geldermann, & Lühn, 2017), 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, can inject it 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 (Ossenbrink, 2017). 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 (Huijben and Verbong, 2013; Comello and Reichelstein, 2017). 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 (Vieira, Moura, & Almeida, 2017). 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 is such a way that a good level of storage utilisation is accomplished, in relation to the amount renewable energy production and the corresponding demand side considerations. This 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, Thygesen and Karlsson (2014) 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. Assessment of the economic impact of demand-side management achieved by integrating of electrical batteries in positive energy buildings was done by Dumont et al. (2017), who performed simulations in Dymola/Modelica environment. Cao, Hasan, and Siren (2013) 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, whereas lead-acid battery is modelled by Type 47b in TRNSYS.

Albeit being very powerful, these detailed studies using BPS also have 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.

On the other end of the spectrum are 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 (Khatib, Ibrahim, & Mohamed, 2016; Rawat, Kaushik, & Lamba, 2016). Essentially, most of these sizing procedures try to establish relationships between the PV system’s nominal power and energy storage capacity, meeting a certain reliability of supply that is tolerated by the user. 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 form of sizing curves.

Recently, Meunier et al. (2015) 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 Fragaki and Markvart (2008), 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 they can get an impression on what system to select with one glance. It was interesting to see that although the aim of this wok was the development of this graphs, some learnings have been obtained from this research exercise.

**Methodology**

This work aims at developing a generic approach that can accommodate many combinations of demand patterns and storage systems. It is therefore important to extract generally applicable parameters, and to perform a synthesis exercise to ensure that the input parameters of the approach are widely available. With this, we are able to create a normalisation method that would allow to use the sizing chart for many different applications.

**Normalisation**

The normalisation has to be such, that maintaining the real significance of the project, moved the numbers to a normalised space that will extract all the relevant ratios and proportions.

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 characterized using the nominal power in Wp, which represents the yield of the PV system under standard conditions of irradiance, which are fixed to 1000W/m². This value of Wp can be considered as a good proxy of the potential yield of the installation. Also, the power demand of the dwelling is a key parameter, 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 compared to 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.

\[
PGR = \frac{P \text{ average demand}}{P \text{ PV watt-peak}}
\]  

This normalisation allowed us to use the same charts irrespective of the size of the dwelling, its electrical requirements or the size or the installed PV systems. With this number, we are taking only into account what is relevant for the problem at hand, which is the ratio between what is produced and what is consumed. Also, we see that for each location 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 not be possible to cover the demand of the house, as there will be not enough energy in absolute values in the yield of the generators to cover demand.

There will be then a set of PGRs in which the batteries will be highly relevant and will bring the installation into optimal utilisation. This ratio will depend on the location at hand, and will go from the PGR that makes the annual
yield equal to the annual demand (larger PGRs will have black outs despite of the battery size), we call that the critical PGR (PGRCrit).

After this normalisation, it is possible to continue evaluating the problem and normalise also the capacity of the battery system. The most common unit used 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. Time is also the unit to measure potential black-outs which is convenient. Because of this, we use the following normalisation for the capacity of the batteries:

\[ C_{\text{norm}} = \frac{\text{Battery capacity}}{\text{P PV watt-peak}} \]  

(2)

With these two normalised values it is possible to start defining ways in which the sizing charts could be developed. The objective figure for the sizing was chosen to be days of black out.

Simulation

The idea of this work is to perform as much pre-processing as possible and as general as possible with 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 in most cases within small ranges and use those for pre-processing the data. Our assumptions were that these ranges will not add much error to the dimensioning charts. The parameters are explained in the following.

One of these parameters was the performance of the batteries. Electric batteries have 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 yield/demand (Eq. 1). Although these two seem to be available, the third component of the system that is in Figure 1, 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 smooth by definition this demand, so there is 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.

Electricity profiles

Four different electricity profiles were used to evaluate how much the curves obtained would differ. 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 is provided.

The first and simplest electricity profile was a constant demand with the average of the power consumption of the dwelling. As mentioned before, it should be considered that all these time series of power were normalised by the nominal power of the PV system and have units W/Wp.

The second profile is a standard load profile taken from (Linssen et al. 2017).

The third profile was extracted from the VDL Reference load profiles of single-family and multi-family houses for the use of CHP systems (VDI Guideline 4655).

The fourth profile was chosen from (Pflugradt 2014) and it represents an extreme case of peaks during the evening.

The four profiles are shown in Figure 2. The first profile in blue is rather smooth as it represents the profile that one may expect for a multifamily building. Profiles 2 and 3 in green and red respectively are sharper and show larger skewness of the profile towards the evening.

The profiles represent the power distribution for 24 hours, to convert this into year demands the profiles were concatenated 365 times. No seasonal variations of the data have been considered in this work. However, a detailed study about the effect of the seasonality of conditioning loads in poorly insulated buildings could be interesting for further work.

\[ \text{Figure 2. Daily profiles used in the simulations.} \]

Examples of simulation results can be seen in Figure 3 and Figure 4.

Weather data

There are several sources of weather information that contain solar irradiance. In our case, we have used energy plus weather files (.epw) obtained from eneryplus.net. Two weather files were used as examples, the weather file from Beek, in The Nederland which is an IWEC file, and the weather file from Murcia which is a SWEC\(^1\) file.

\(^1\) The weather files were synthetically generated using Climed (Portuguese software developed by Ricardo Aguiar) from mean
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 sizing PV-battery systems, substantial learnings have been obtained thanks to the evaluations performed.

Standard parameters graphs
As the methodology was later validated with the formal sizing tool PGIS, the parameters of the simulations were chosen based on common cases and as an assumption that will be later evaluated. The performance of the batteries for charging and discharging was fixed at 80%, and the overall losses of generation were fixed at 28%. Although these figures were rather approximated 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 Figure 5 and Figure 6. The graphs should be interpreted in the following way:

- At first, one has to evaluate what PGR represents monthly data coming from the Spanish Meteorological National Institute by Prof Perez-Lombard.
- Each PGR is represented with one line (with different colours) in the chart. One should use this to evaluate to what extent a battery 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.

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.

Identification of daily and seasonal storage
The creation of these sizing graphs with standard parameters allowed to see the first finding of the Institute by Prof Perez-Lombard.
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, what provides an educational component to its use, at the same time that it minimises iterations in the evaluation of options.

Having a look at the graph with a given PGR one can see immediately the situation at which the building is, and to what extent it makes sense to make more or less investment on storage, or 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 we see two clear tendencies in the graphs. Taking for example the PGR = 0.04 W/Wp for Beek, one can see that the curve from 0.1 kWh/kWp to 0.6 kWh/kWp maintains a constant curvature. From 0.6 kWh/kWp to 20kWh/kWp the curvature changes, and although the convexity is still the same, a small derivative is seen here. This turning point at 0.6kWh/kWp 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 Figure 7. 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.

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 on its own with three different values of charging discharging performances. This has been shown in Figure 8.

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 what opens the way for a unitary graph. This is particularly relevant as it also seems like this technology is becoming more popular in domestic installations.

Effect of production losses

There are several factors that make generation not perfect in photovoltaic installations. Examples of this are high atmospheric factors, temperature, transmission losses, converters losses, maintenance of the panels and many 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 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 Figure 9.

![Figure 7. Outlining of the singular point on the PGRs curves that separates short term (days) storage from long-term (months) storage.](image)

![Figure 8. Effect of different battery efficiencies in the sizing curves.](image)

![Figure 9. Effect of production losses on the sizing charts.](image)
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.

**Variation with respect to profiles**

One important factor for the performance 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 lager 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 Figure 10.

![Figure 10. Different curves using different demand profiles. Diagram for Murcia.](image)

The evaluation of the black-out times with different Figure 10 shows this 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.

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.

![Figure 11. Sizing chart for Murcia, Spain including the variability given by the profiles.](image)

![Figure 12. Sizing chart for Beek, Netherlands including the variability given by the profiles.](image)

**Validation with EU PGIS**

The graphs created here add, to our believe, more than simple calculation tools that allow to visualise in one glance the effect that a change in the design may have.

It is important that the graphs that we show here are in accordance with well proven tools, so we are not misleading practitioners in the field. It is for this reason that we used the tool: Photovoltaic geographical
information system developed for the European Commission and available in the previous footnote.

For the validation, we run different cases in the two cities chosen for the work i.e. Murcia and Beek. The values can be seen in Tables 1 and 2.

The results of this validation are also shown in Figure 13. Here we have shown how the tool has a good accuracy when compared with the PGIS. Although an error can be found between the outputs of the sizing chart presented here and the results from the PGIS 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 PGIS simulation. No information on the website has been found that shows this information, so no further investigation has been done to identify this error.

Table 1: Validation points for Beek.

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Table 2: Validation points for Murcia.

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Conclusion

This work shows how simulation has been used to perform a dimensionless analysis of PV installations with batteries that leads to a graphical sizing chart. The results that the sizing charts provide does 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.

Figure 13. Representation of the validation points.

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 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.

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.

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