# Design rules for a PV-inverter in Belgium: evaluation of actual rules of thumb

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**Abstract:**
An optimized inverter sizing depends on the installed photovoltaic capacity, the azimuth and zenith of the panels, the latitude and the efficiency curve of the inverter. Simplified inverter sizing rules are generally used and can be narrowed to two rules of thumb. The first rule aims a maximum PV-production and uses an inverter according to the PV power, the second rule aims a maximum self-sufficiency and uses an inverter size ratio of 0.7. Simulations are performed to quantify the production loss or self-sufficiency loss when the rule of thumb is used instead of the optimized inverter power for a load profile with only household appliances. In a second part, the energy system is extended with a heat pump, a battery or both combined. This study checks if the refurbishment of residential PV systems with heat pump and/or battery still can use the same rules of thumb or is a new sizing method preferred to replace the inverter. Detailed models for load, PV-inverter, battery and battery-converter are developed. The PV-production and the self-sufficiency are determined for 6 azimuths and 7 zenith positions. A final evaluation of the rules of thumb is made.

**Keywords:**

Inverter, Photovoltaics, renewable energy, electrical storage, heat pump

## 1. Introduction

The energy transition is progressing and boosts the sales of photovoltaic solar systems (PV). Between 2015 and 2021, the installed PV capacity in Belgium is more than doubled[1]. The heat pump market grew with factor 10[2] and in 2021 the number of installed home batteries exceeded 11000 units where in 2020 hardly 337 units were installed[3].The inverter is an important component of the PV system. Since several years, the Flemish government advises to size the inverter power on 70% of the installed PV power at standard reference conditions to get a maximum self-sufficiency [4-6], the Walloon government advises 70 to 100%[7], the Brussels region advises 80% [8]. Belgium's neighbouring countries do not give an unambiguously advice. In France, the government advises 80% [9], in the Netherlands 90 to 110% [10] is advised to have a maximum production and in Germany [11] 100% for maximum production and 70% for maximum financial benefit. All those rules of thumb can be narrowed to two rules. When a maximum PV production is the target, the inverter is sized with an inverter ratio of 1[12]. When a maximum self-sufficiency or self-consumption is targeted, the inverter ratio is 0.7.The optimized inverter power to get a maximum PV production is described by Burger [13], Nofuentes[14] and Van Der Borg [15]. They investigated the inverter power for different zeniths and azimuths to maximize the PV production. Their results show that the ideal inverter power, for maximum PV production vary from 0.3 to 1.1. The rules of thumb give just one fixed figure, namely a ratio of 1. What is the production loss if the rule of thumb is used? Maximizing the self-sufficiency or self-consumption is another target to optimize the inverter power[4] .The previous target, maximizing the PV production, is maximizing the energy output of the inverter which is independent of the loads connected to the inverter. Once maximizing the self-sufficiency becomes the main objective, the load profile of the energy user becomes an extra parameter. Since every end user has a different consumption profile, different equipment, different PV technologies, orientations, inverters etc. it is impossible to state that there is one optimal inverter power. This includes that the resulting optimized inverter power in this case is indicative and can state a trend. Although the authors could not trace the original documents that formed the basis of the rule of thumb where 70 to 80% of the installed PV power is used, in each case this rule was made when heat pumps and batteries were not frequent applied [16], now they are. Adding a heat pump to a residential energy system will increase the energy use during the winter

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and mid-season, just in the period that less solar energy is available. The load profile of the heat pump is even the opposite of the PV production profile. It can be questioned if it is not better to optimize the inverter for the energy use during winter. A similar question can be asked in case of adding a battery to the residential energy system. The battery can take energy during the full period with daylight. As long as there is daylight a battery can charge energy. The battery can be considered as a load that can take energy during the moments with maximum solar radiation. Is a larger inverter power beneficial in that case? Optimized inverter sizing to maximize the PV production is described by different authors [13-15, 17] but optimized inverter sizing to maximize the self-sufficiency related to orientation and panel zenith or the impact of a heat pump, or battery, on the optimized inverter power is not yet described. In this study the different rules of thumb are investigated for residential buildings in the Belgian climate. Different scenarios are investigated starting with a reference case with only household appliances, called ‘appliances’ in this paper. Next, the energy system is extended with a heat pump and/or a battery. Evaluating the impact of the heat pump and the battery on the optimal sizing of the inverter compared to the rules of thumb is the main contribution of this research. The optimized inverter is determined for the full range of both, zenith and azimuth. For each case the maximum self-sufficiency, using the optimized inverter power, is compared to the self-sufficiency obtained by using the rules of thumb.

# 2. Methodology

## 2.1. Residential energy system

The reference case (case 1) is a realistic example of a standard family in Belgium. The family counts 4persons. The energy system is used for a residential house where space heating and domestic hot water production is realized with fossil fuel combustion technology. The energy use for the appliances is 5000kWh/a. A PV system of 5 kWp is installed. The optimized inverter power is determined for this system as reference for a panel zenith of 0° to 90° in steps of 15° and 6 orientations are considered with steps of 60°. Case2 to case 4 are based on this reference case where the system is extended with a heat pump, a battery or the combination of the two. Case 5 is similar to case 1 but with an high efficiency inverter (Table 1). In each case, the PV production and self-sufficiency obtained with the optimized inverter power is compared to the one resulting with the rule of thumb inverter power.

## 2.2. Components overview

### 2.2.1. Photovoltaic panels

The power output of a PV area is simulated in Trnsys, using type 94. The simulations were performed with the technical specifications of the polycrystalline solar panel type Q.Plus-G4.1 275. The power $P_{pv}$ , in Watt is a function of:

$$P_{pv} = f(n, \mathrm{W}_p, \Phi_{solar}, T_{module}) \tag{1}$$

### 2.2.2. Inverter

The inverter transforms the DC-voltage coming from the PV panels to AC 230V which can be used by the appliances. The inverter efficiency varies with the load. Faranda [18] presented a few typical inverter curves. Two of them are used in this study (see Fig. 1). ’Inverter 1’ has a pronounced efficiency drop for low part loads. ‘Inverter 2’ has a significant higher efficiency in that part. The impact of a high efficient inverter will be evaluated. Each curve is characterized by two sections. A low part load ,below 10% of the nominal power, results in a low inverter efficiency due to the relative high self-consumption losses compared to the input. Once the load is above 10% of the nominal power, the efficiency reaches maximum values of up to 96%. The inverter efficiency curves presented in Fig. 1contain already the information to predict the trend which can be expected as end result:

- An inverter sized too small will have high part loads with high efficiency but the limited inverter power will not be able to handle the loads above the nominal inverter power. The load will be limited to the nominal inverter power and the overshoot becomes an extra production loss.
- An inverter sized too large will result in small part loads which gives a low inverter efficiency

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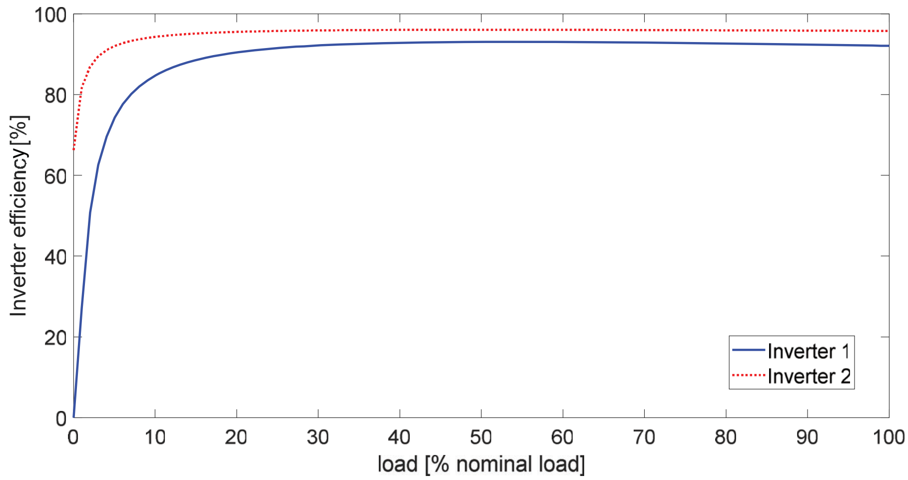


**Figure. 1.** Typical inverter efficiency curves from different manufacturers[18]

The presented inverters have a maximum efficiency between 90 and 96%. New technology is already available with 99% inverter efficiency [19, 20]. The simulations are made with inverter model 1. Inverter model 2 is used as alternative to check the influence of a high efficient inverter. Adding a heat pump to the system for space heating and domestic hot water makes that the winter period will have the highest energy use, just when the PV production is lower and where the efficiency of the inverter at low part load becomes more important. The results show the impact of the heat pump on the inverter selection.
The power of an inverter is therefore a function of:

$$P_{inverter} = f(\eta_{eff}, P_{pv}) \tag{2}$$

### 2.2.3. Heat pump

The heat pump is an air to water inverter system used for space heating and production of domestic hot water. The heat pump model calculates the needed energy input for the given outdoor temperature, heating curve and needed capacity for space heating. Manufacturer data is used to make the model. The start-up sequence and switch off sequence of the heat pump is integrated into the model to get realistic electric peak loads in the load profile. Each 3 minutes, the part load ratio can increase or decrease with 10% to get a balance with the energy demand. The minimum part load ratio is 30%. The production of domestic hot water always happens on full load.

$$P_{hp} = f(PLR_{HP}, T_{outdoor}, T_{lwt}) \tag{3}$$

### 2.2.4. Battery converter

The battery converter is characterized by its efficiency curve and its capacity. The same considerations as for the PV inverter are applied. The efficiency curve presented by Weniger [21] is used with a nominal capacity of 5kW. Previous simulations showed that the self-sufficiency achieved with a converter power of 5kW reaches an optimized point within the range of 0.5% loss due to not optimized battery converter for the considered load profiles, PV area and different PV panel positions.

$$P_{batt\ conv} = f(E_{bat\ conv}, PLR_{bat\ conv}) \tag{4}$$

### 2.2.5. Battery

A battery model described by Brivio [22] is modelled in Matlab to calculate the battery performance. The model is represented by a RC circuit. The R and C value is related to the state of charge. The model calculates the available charge or discharge capacity which is function of the C-rate. The battery is determined by its nominal capacity, the maximum depth of discharge (80%), maximum state of charge90%, self-discharge 3%/month, charge capacity factor 0.5kW/kWh and discharge capacity factor0.55kW/kWh.

$$P_{batt} = f(E_{bat}, C_{bat}, C_{dr}, R_f, SOC, E_{loss}) \tag{5}$$

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#### 2.2.6. Grid

The generated PV energy is converted by the inverter to be used by the appliances and/or the battery system. The surplus of energy is supplied to the grid. In case the PV system nor the battery can deliver enough energy, the deficit is supplied by the grid. It is assumed that there is no feed-in limitation.

$$\frac{d\,E_{bat}}{dt} = P_{inverter} + P_{grid} - P_{appliances} - P_{hp} \quad (6)$$

## 2.3. Load profiles

### 2.3.1. Appliances

A synthetic load profile is developed for a household of four persons, one full time working parent, apart-time working parent, a student and a young child. The load profile of the base case only contains appliances, assuming that space heating and DHW is done with fossil fuels. A probability curve is used to identify the start of use of 19 different appliances [23] [24]. Reinhardt measured the energy use of different appliances , for several actions, on a 1 second timestep [25]. His results are the building blocks of the synthetic profile. The energy use profiles are composed out of appliances with different measured performances to get a load profile of 5000kWh/a. The synthetic load profile is generated with a 1 sec time step and rescheduled to a 3 minute time step. The synthetic profile is verified with the results of measured data. Fig. 2 shows 4 load duration curves of load profiles of 5000kWh/a. All curves are presented on a 3 minute time step. One measured profile is a similar household measured in the Lineas project[26] with time step 15 minutes. The second verification is the average of 50 load profiles of 5000kWh/a from the distribution network operator Fluvius. The synthetic profile is presented with a time step of 15 minutes and also with a time step of 3 minutes. The different curves show that the 15 minute time step synthetic profile matches the average values. The 3 minutes time step synthetic profile shows more peak loads. The larger the time step the more that peak loads disappear in the average values.

### 2.3.2. Domestic hot water

The daily DHW-profile of the European Directive EU813/2013 is used (Medium user profile - 3XS user profile Ecodesign) ) [27]. To use a maximum of solar energy, the charging of the DHW buffer is programmed to start at 14h00.

### 2.3.3. Heating demand

An archetypical Belgium dwelling[28] is used to calculate the heating demand. The heating demand is simulated in Trnsys[29] for a south oriented building. The air infiltration is simulated with Trnflow[30].The resulting heating demand includes the inertia of the building mass and the under floor heating. The appliances and the persons (presence is coupled with the probability determination used for the load profile) are considered as an internal heat gain and are assigned to a specific room. A predefined heat gain factor is used per appliance to deduct the not used energy such as the hot water drain of a laundry machine.

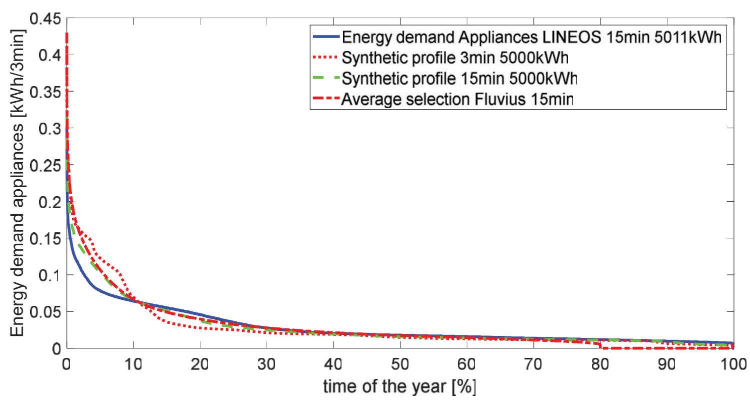


**Figure. 2.** Load duration curves of different load profiles

## 2.4. Climate data

The Meteonorm climate data of the reference year of Uccle (Belgium), time step 1 hour, is used to simulate the PV performance and the heating demand. The PV generation and the heat demand is simulated in Trnsys using the Meteonorm data using interpolated time steps of 3 minutes. To check the impact of 3 minute interpolated time steps using 1 hour data compared to 3 minute time step, measured data with time step 1 minute is used. The self-sufficiency calculated with the interpolated data had a maximum difference of 0.6% compared to the self-sufficiency calculated with 3 minute data. Using the 3minute interpolated hourly climate data gives no significant difference when 3 minute appliance data is used.

## 2.5. Simulation method

The simulations of the energy flows between the different components are performed in Matlab. Several authors investigated the impact of the time step [31] [32] [33] [34] and conclude that a time step of less than 5 minutes reduces the error to 2% and even less than 1% in case a battery is used. All inputs (PV production, electrical load, heating demand, domestic hot water production) are on a 3 minute time step. All simulations are done for a full year. To investigate one case, 7 inverter powers are simulated for 7 zeniths and 6 orientations. The load is determined by the sum of the energy use of the appliances and the energy use of the heat pump if available. If there is renewable energy available, it is first used to compensate the energy demand of the appliances and the heat pump, a shortage is supplied from the grid, a surplus is supplied to the battery (if available) as far as the battery can take the surplus in quantity and power. The leftover is supplied to the grid. All efficiencies (inverter, converter, battery) are calculated per time step.

### 2.6. Case study selection

The 5 selected cases could be a timeline of one residential energy system starting with a PV system that can cover the energy use of the appliances. The following cases could be the refurbishment of the energy system, namely adding or a heat pump, or a battery, or both. For each case the results are checked to see if the inverter has a different power as in the reference case. The reference case is an energy system with only appliances (5000kWh/a) with 5kWp PV, no heat pump, no battery. The optimized inverter is calculated for the targets of the two main rules of thumb, namely maximum PV production and maximum self-sufficiency. The results are compared with the rules of thumb.

**Table 1.** Overview cases

| Case | Appliances | Heat pump | Battery | Inverter model |
|---|---|---|---|---|
| 1 | 5000 kWh/a | no | 0 kWh | 1 |
| 2 | 5000 kWh/a | no | 8 kWh | 1 |
| 3 | 5000kWh/a | yes | 0 kWh | 1 |
| 4 | 5000 kWh/a | yes | 8kWh | 1 |
| 5 | 5000 kWh/a | no | 0 kWh | 2 |

Two solar panel positions are picked out to follow up each case, respectively due south (azimuth 0° ) and azimuth -120° .

# 3. Results

## 3.1. Case 1

### 3.1.1. Maximum PV production

To maximize the PV production, the rule of thumb advises to use an inverter ratio of 1. The maximum PV production is evaluated at the output of the inverter. This is the sum of used PV energy in the residential energy system and the energy supplied to the grid.

$$0 = P_{inverter} + P_{grid} - P_{appliances} \quad (7)$$

This is only evaluated for case 1 but is equal for all other cases. Fig. 3 gives the resulting inverter output in kWh/a in relation to the inverter power for different zeniths with 0° azimuth and a PV area of 5kWp. Each curve is characterized by a fast decreasing inverter output for an inverter power lower than 4 kW and a slightly decreasing efficiency above an inverter power of 4 kW. The fast inverter output decrease in the left side of the curve is caused by the peak shaving due to the limited inverter power. All produced energy above the nominal capacity of the inverter is a loss. The slow decreasing right part of the curve is caused by the low efficiencies during small part loads. The larger the inverter power the more the inverter will operate in the region of the low part loads which results in low inverter efficiency. The 90° zenith has less high irradiation than the 0° zenith. The lower irradiation is a lower part load of the inverter and results in a lower inverter efficiency. Over-sizing the inverter power is less critical than under-sizing. The best performing PV panel position (due south, zenith

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between 30 and 60° ) gives an ideal inverter ratio of 0.99 and 1.01. For this positions, the rule of thumb is perfect. The 90° zenith gives an optimized inverter ratio of 0.81. Using the rule of thumb is a 19% oversizing but results in a loss of 0.6% of the yearly production.

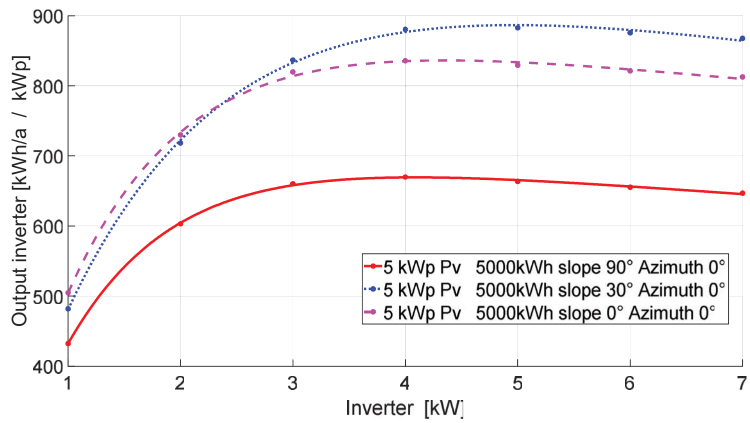


**Figure. 3.** Output inverter for inverter model 1, 5kWp PV, no heat pump, no battery, azimuth 0°

Table 2 gives the optimized inverter power per kWp installed PV at reference conditions to get the maximum yearly production. In case of azimuth -120° and a 90° zenith, the optimized inverter power is0.54kW/kWp instead of 1kW/kWp (rule of thumb). The optimized inverter ratio 0.54, results in 3.7%more PV production. Due to the lower irradiation, a smaller inverter is needed.

**Table 2.** Optimized inverter power kW/kWp for maximum energy production, inverter model 1, 5kWp PV, no heat pump, no battery

| azimuth | -180 | -120 | -60 | 0 | 60 | 120 | 180 |
|---|---|---|---|---|---|---|---|
| zenith | | | | | | | |
| 90 | 0,30 | 0,54 | 0,78 | 0,81 | 0,78 | 0,54 | 0,30 |
| 75 | 0,35 | 0,61 | 0,89 | 0,93 | 0,88 | 0,61 | 0,35 |
| 60 | 0,38 | 0,67 | 0,94 | 0,99 | 0,93 | 0,67 | 0,38 |
| 45 | 0,41 | 0,72 | 0,96 | 1,01 | 0,95 | 0,71 | 0,41 |
| 30 | 0,56 | 0,77 | 0,95 | 0,99 | 0,94 | 0,76 | 0,56 |
| 15 | 0,74 | 0,82 | 0,92 | 0,95 | 0,91 | 0,81 | 0,74 |
| 0 | 0,87 | 0,87 | 0,87 | 0,87 | 0,87 | 0,87 | 0,87 |

Most rules of thumb advice 1kW inverter power/kWp to get the highest production. The results show that the rule of thumb fits for a south orientation. Deviating from the best zenith decreases the inverter power for the south direction up to 20%, changing the azimuth to east or west can decrease the inverter power up to 50%. The mentioned design rules can be considered as a good first estimation. Using the simulated optimum as design criteria can bring an extra production up to 3.7% (azimuth between 120° and -120° )and gives an additional saving due to the lower inverter power to be installed. A pure north orientation, zenith 90° , results in a loss of 8.8%. North facing solar panels are rare but there is a growing interest, especially for building integrated PV panels [35] [36] [37].

### 3.1.2. Maximum self-sufficiency

To maximize the self-sufficiency, the advised inverter ratio is 0.7. Fig. 4 show the self-sufficiency for different inverter powers and zeniths for azimuth 0. The optimized values are listed in Table 3. If the aim of the PV system is to maximize the self-sufficiency, an optimized inverter size ratio of 0.7 to 0.77is calculated for azimuth 0° . The azimuth -120° has enough with an inverter size ratio down to 0.33.A higher self-sufficiency for the same PV capacity means that the energy production is better fitting with the energy demand. The chosen load profile is for a standard family with standard behaviour. This means an average daily energy demand profile is characterized by a peak in the morning and a peak in the evening. The PV production peak at noon happens most of the time during a low energy demand which makes that the high inverter power is not needed for the high peaks at noon. In contrary the high inverter power makes that the low PV generation in the morning and the evening is transformed at a lower inverter efficiency. A lower inverter power brings the average inverter efficiency to a higher level when the solar energy can be used. In case an inverter ratio of 1 is used (gives the maximum PV production) when a maximum self-sufficiency is targeted, less PV energy can be used. The maximum extra loss is 6.2% when the inverter ratio 1 is used and the 0.7 inverter ratio gives a maximum extra loss of 3% (see Table 4).

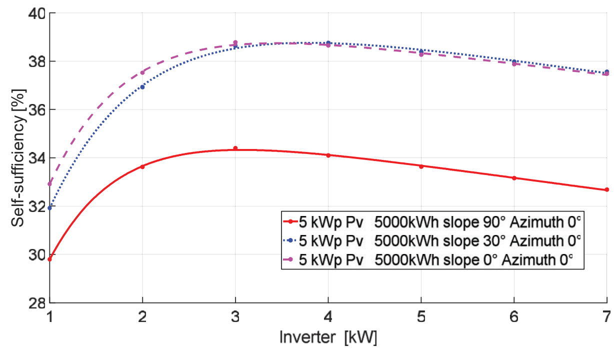


**Figure. 4.** Self-sufficiency load inverter 5000kWh/a, inverter model 1, 5kWp PV, no heat pump, no battery, azimuth 0°

As long as the azimuth is between -60° and 60° , the loss in self-sufficiency remains smaller than 1%using the 0.7 inverter ratio.

**Table 3.** Optimized inverter power kW/kWp in function of azimuth and panel zenith for maximum self-sufficiency, load 5000kWh/a, inverter model 1, 5kWp PV, no heat pump, no battery

| azimuth | -180 | -120 | -60 | 0 | 60 | 120 | 180 |
|---|---|---|---|---|---|---|---|
| zenith | | | | | | | |
| 90 | 0,23 | 0,33 | 0,49 | 0,61 | 0,54 | 0,32 | 0,23 |
| 75 | 0,29 | 0,38 | 0,56 | 0,70 | 0,62 | 0,38 | 0,29 |
| 60 | 0,32 | 0,42 | 0,62 | 0,75 | 0,68 | 0,44 | 0,32 |
| 45 | 0,36 | 0,48 | 0,66 | 0,77 | 0,71 | 0,50 | 0,36 |
| 30 | 0,46 | 0,55 | 0,69 | 0,77 | 0,72 | 0,58 | 0,46 |
| 15 | 0,59 | 0,63 | 0,70 | 0,74 | 0,72 | 0,64 | 0,59 |
| 0 | 0,69 | 0,69 | 0,69 | 0,69 | 0,69 | 0,69 | 0,69 |

**Table 4.** Evaluation loss caused by rules of thumb

| sizing method | | ideal inverter | inverter ratio 0,7 | | inverter ratio 1 | |
|---|---|---|---|---|---|---|
| Azimuth | zenith | Self-sufficiency [%] | | | | |
| | | Result | Result | % Loss | Result | % Loss |
| -120° | 0° | 38,7 | 38,7 | 0,0 | 38,3 | 1,1 |
| | 30° | 31,6 | 31,1 | 1,6 | 30,3 | 4,2 |
| | 90° | 27,9 | 27,0 | 3,0 | 26,1 | 6,2 |
| 0° | 0° | 38,7 | 38,7 | 0,0 | 38,3 | 1,1 |
| | 30° | 38,8 | 38,7 | 0,0 | 38,5 | 0,7 |
| | 90° | 34,4 | 34,3 | 0,3 | 33,7 | 2,1 |


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Considering each target, the rule of thumb is in both cases a good robust sizing method for a load profile with only residential appliances.

## 3.2. Case 2

Case 2 is the energy system of case 1 with an extra battery of 8kWh useful battery capacity. The nominal battery capacity is 11.4kWh with a maximum state of charge of 90% and maximum depth of discharge of 80%. Adding a battery will not change the maximum PV production but will increase the self-sufficiency from 40% to 68% for azimuth 0° zenith 30° . Table 5 gives the optimized inverter ratio for the this extended energy system.

$$\frac{d\,E_{bat}}{dt} = P_{inverter} + P_{grid} - P_{appliances} - 0 \quad (8)$$

Table 5 shows that the optimized inverter power to maximize the self-sufficiency is between 0.5 and 0.77 for the values of azimuth -120° to +120° . This brings the average inverter power value on 0.64 instead of 0.6 for the values of azimuth -120° to +120° , so 6% closer to the rule of thumb of 0.7.

**Table 5.** Optimized inverter power kW/kWp in function of azimuth and panel zenith for maximum self-sufficiency, load 5000kWh/a appliances, inverter model 1, 5kWp PV, heat pump 1691 kWh/a, 8kWh battery

| azimuth | -180° | -120° | -60° | 0° | 60° | 120° | 180° |
|---|---|---|---|---|---|---|---|
| zenith | | | | | | | |
| 90° | 0,30 | 0,50 | 0,65 | 0,68 | 0,68 | 0,49 | 0,30 |
| 75° | 0,35 | 0,51 | 0,67 | 0,71 | 0,70 | 0,51 | 0,35 |
| 60° | 0,38 | 0,51 | 0,66 | 0,69 | 0,69 | 0,52 | 0,38 |
| 45° | 0,40 | 0,51 | 0,64 | 0,68 | 0,67 | 0,53 | 0,40 |
| 30° | 0,42 | 0,52 | 0,62 | 0,65 | 0,63 | 0,52 | 0,42 |
| 15° | 0,49 | 0,54 | 0,59 | 0,60 | 0,60 | 0,54 | 0,49 |
| 0° | 0,57 | 0,57 | 0,57 | 0,57 | 0,57 | 0,57 | 0,57 |

Table 6 gives the relative increase of the optimized inverter power of case 2 compared to case 1. Zeniths above 45° have a significant increase of the inverter power up to 53%, zeniths below 45° have a smaller inverter power up to 19% smaller. The vertical installed panels have the largest increase. Without battery, the inverter is determined by the match between solar production and energy demand. Using a large battery, produced energy can be used as long as the battery is not full charged. This means that the vertical panel has only a short period of the day that beam irradiation can be captured. The lower the zenith the larger the period of the day that beam irradiation can be captured which can even result in a smaller optimized inverter power.

Table 6. Increase of inverter power in percentage case 2 compared to case 1

| azimuth | -180° | -120° | -60° | 0° | 60° | 120° | 180° |
|---|---|---|---|---|---|---|---|
| zenith | | | | | | | |
| 90° | 33 | 53 | 33 | 12 | 26 | 51 | 33 |
| 75° | 20 | 36 | 19 | 1 | 13 | 34 | 20 |
| 60° | 17 | 22 | 7 | -8 | 2 | 20 | 17 |
| 45° | 11 | 7 | -3 | -13 | -6 | 4 | 11 |
| 30° | -9 | -6 | -11 | -16 | -12 | -11 | -9 |
| 15° | -17 | -14 | -16 | -19 | -17 | -16 | -17 |
| 0° | -17 | -17 | -17 | -17 | -17 | -17 | -17 |

Adding a battery to the energy system brings for most positions the optimized inverter power closer to the inverter ratio of the rule of thumb. The energy loss due to a not optimized inverter power is even smaller.

## 3.3. Case 3

Case 3 is case 1 extended with a heat pump. Table 7 shows the percentage increase of the inverter power compared to the base case.

$$0 = P_{inverter} + P_{grid} - P_{appliances} - P_{hp} \quad (9)$$

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The orientations influenced by the rising sun have a small increase of inverter power, the orientations influenced by the sunset have a small decrease of inverter power. The morning has the coldest temperature of the day and will make that the heat pump is more activated which makes that the resulting load during the morning will be higher. When the solar panels are oriented to the west makes that they only have diffuse irradiation during the morning. A smaller inverter power will increase the efficiency of the small part loads that occur in the morning. On the level of sizing can be concluded that the extra load of the heat pump does not influence the optimized inverter power significant. For example azimuth -60° , zenith 75° , brings the optimized inverter from 0.56kW/kWp to0.62kW/kWp. Adding a heat pump makes the loss smaller when the rule of thumb is used.

**Table 7.** Percentage increase of inverter power, case 2 compared to case 1

| azimuth | -180° | -120° | -60° | 0° | 60° | 120° | 180° |
|---|---|---|---|---|---|---|---|
| zenith | | | | | | | |
| 90° | 1 | 5 | 11 | 2 | 1 | 1 | 1 |
| 75° | 0 | 7 | 9 | 0 | 0 | 1 | 0 |
| 60° | 0 | 9 | 7 | 0 | 0 | -1 | 0 |
| 45° | 1 | 8 | 5 | 0 | -1 | -1 | 1 |
| 30° | 0 | 4 | 3 | 0 | -2 | -1 | 0 |
| 15° | 0 | 2 | 2 | -1 | -1 | -1 | 0 |
| 0° | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

## 3.4. Case 4

In case 4 the energy system is extended with a heat pump and a battery.

$$\frac{d\,E_{bat}}{dt} = P_{inverter} + P_{grid} - P_{appliances} - P_{hp} \quad (10)$$

Table 8 shows the optimal inverter for maximum self-sufficiency for the reference system extended with a heat pump and a battery. Most values come even closer to the rule of thumb value of 0.7.
Table 9 gives the relative increase of the optimized inverter power of case 4 compared to case 1 in percentage. The increased load due to the added heat pump and the extra battery that charges the surplus makes that a larger inverter power can be used for zeniths which have a limited time to capture beam irradiation. The orientations having larger periods access to beam radiation have more time to charge the battery resulting in a smaller inverter power. Case 4 combines the effects of case 2 and case 4: decrease for zeniths below 45° and increase for zeniths above 45° , increase for sunrise sensible positions and decrease for sunset sensible positions. The statements are mentioned in case 2 and case 3.

**Table 8.** Optimized inverter power kW/kWp in function of azimuth and panel zenith for maximum self-sufficiency, load 5000kWh/a appliances, inverter model 1, 5kWp PV, heat pump 1691 kWh/a, 8kWh battery

| azimuth | -180° | -120° | -60° | 0° | 60° | 120° | 180° |
|---|---|---|---|---|---|---|---|
| zenith | | | | | | | |
| 90° | 0,30 | 0,52 | 0,69 | 0,72 | 0,69 | 0,50 | 0,30 |
| 75° | 0,35 | 0,56 | 0,72 | 0,77 | 0,73 | 0,53 | 0,35 |
| 60° | 0,38 | 0,56 | 0,72 | 0,76 | 0,73 | 0,55 | 0,38 |
| 45° | 0,41 | 0,56 | 0,71 | 0,75 | 0,71 | 0,57 | 0,41 |
| 30° | 0,44 | 0,56 | 0,68 | 0,71 | 0,68 | 0,56 | 0,44 |
| 15° | 0,52 | 0,57 | 0,65 | 0,66 | 0,64 | 0,56 | 0,52 |
| 0° | 0,61 | 0,61 | 0,61 | 0,61 | 0,61 | 0,61 | 0,61 |


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**Table 9.** Increase inverter power in percentage case 4 versus case 1

| azimuth | -180° | -120° | -60° | 0° | 60° | 120° | 180° |
|---|---|---|---|---|---|---|---|
| zenith | | | | | | | |
| 90° | 32 | 58 | 41 | 17 | 28 | 55 | 32 |
| 75° | 21 | 48 | 28 | 9 | 17 | 38 | 21 |
| 60° | 17 | 33 | 17 | 2 | 7 | 26 | 17 |
| 45° | 13 | 18 | 6 | -4 | -1 | 13 | 13 |
| 30° | -4 | 3 | -2 | -7 | -7 | -3 | -4 |
| 15° | -11 | -8 | -7 | -11 | -11 | -12 | -11 |
| 0° | -12 | -12 | -12 | -12 | -12 | -12 | -12 |

### 3.5. Case 5

Case 5 is equal to case 1 but using a more energy efficient inverter (see Fig.1). Inverter model 1 has an EU-efficiency of 91.1%, where inverter model 2 has an EU-efficiency of 95.6%. Table 10 shows the optimized inverter power for inverter model 2 to maximize the self-sufficiency. In the previous cases the inverter power is often reduced to limit the inverter losses during low part loads. The higher the inverter efficiency during low part load the less there is a need to reduce the inverter power. The rule of thumb is in this case an under-sizing for the south orientation. The loss in self-sufficiency is maximum0.2%.

**Table 10.** Optimized inverter power kW/kWp in function of azimuth and panel zenith for maximum self-sufficiency, load 5000kWh/a appliances, inverter model 5, 5kWp PV, no heat pump , no battery

| azimuth | -180° | -120° | -60° | 0° | 60° | 120° | 180° |
|---|---|---|---|---|---|---|---|
| zenith | | | | | | | |
| 90° | 0,32 | 0,43 | 0,63 | 0,77 | 0,70 | 0,43 | 0,32 |
| 75° | 0,35 | 0,48 | 0,72 | 0,86 | 0,79 | 0,49 | 0,35 |
| 60° | 0,37 | 0,52 | 0,78 | 0,90 | 0,84 | 0,56 | 0,37 |
| 45° | 0,39 | 0,60 | 0,82 | 0,92 | 0,87 | 0,65 | 0,39 |
| 30° | 0,57 | 0,69 | 0,84 | 0,91 | 0,88 | 0,73 | 0,57 |
| 15° | 0,73 | 0,78 | 0,85 | 0,89 | 0,87 | 0,80 | 0,73 |
| 0° | 0,83 | 0,83 | 0,83 | 0,83 | 0,83 | 0,83 | 0,83 |

## 4. Conclusion

The optimized inverter power is determined for a reference system without battery or heat pump, as well as for the extended systems with heat pump and battery. Adding a battery, or adding a heat pump, or both, results in a different optimized inverter power but the gains compared to the inverter power determined by the rule of thumb are small.

Two rules of thumb to select the inverter power are used by contractors in Belgium, namely 70% and100% of the installed PV power expressed in kWp regarding the standard conditions. The 70% rule aims a maximum self-sufficiency, the 100% rule aims a maximum PV production. The results show that the rules of thumb are valid for the ‘best’ orientation in Belgium, namely due south and 30° zenith. A deviation of this position results in an extra loss of self-sufficiency or extra loss in production. Those losses are smaller than 1%. Adding a heat pump, a battery or both gives a small shift to a larger or smaller inverter power depending the orientation and zenith. Even with a changing load profile by adding heat pump and/or battery, the rule of thumb remains a good selection method of the inverter power. For an azimuth out of the range [-60°,60°] the optimized inverter will have a smaller power as the one determined by the rule of thumb and will reduce the investment with a better performance on top.

## Nomenclature

| | |
|---|---|
| $C_{bat}$ | charge/discharge rate of the battery [ $h^{-1}$] |
| $C_{dr}$ | Capacitance of the battery cell in function of the open circuit voltage [F] |
| $E_{bat}$ | Nominal capacity battery [kWh] |
| $E_{loss}$ | Capacity loss of the battery in function of the SOC [kWh] |
| n | number of solar panels |
| $P_{appliances}$ | Power of all appliances [W] |
| $P_{batt}$ | Power charge/discharge battery [W] |
| $P_{batt\ conv}$ | Power battery converter [W] |
| $P_{grid}$ | Power supplied by the grid [W] |
| $P_{hp}$ | Heating power heat pump [W] |
| $P_{inverter}$ | Power output of the inverter [W] |
| $P_{pv}$ | Power generated by the solar panels [W] |
| $PLR_{bat\ conv}$ | Part load ratio battery converter [%] |
| $PLR_{HP}$ | part load ratio heat pump [%] |
| $R_f$ | Resistance of the battery cell in function of the open circuit voltage [mOhm] |
| $SOC$ | State of charge of the battery [%] |
| $T_{lwt}$ | Leaving water temperature heat pump [K] |
| $T_{module}$ | Temperature of the solar panel [K] |
| $T_{outdoor}$ | Outdoor temperature [K] |
| $W_p$ | peak power of the solar panel at standard conditions [W/panel] |
| $\Phi_{solar}$ | Solar irradiation [W/m²] |
| $\eta_{eff}$ | Efficiency of inverter [%] |

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