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# Optimal sizing of residential PV-systems from a household and social cost perspective
## A case study in Austria

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ABSTRACT

In this paper we analyse optimal sizing of grid connected rooftop photovoltaic systems from a household's perspective. We estimate the profit maximizing size for more than 800 households in Austria for various electricity tariffs and subsidy schemes considering economies of scale related to the investment costs of photovoltaic systems in the size range of 1–20 kW of installed capacity. Size dependent investment costs are estimated from data on photovoltaic systems installed in Austria from 2008 to 2013. We then take a social cost perspective and relate the results to the total investment costs to install a certain amount of capacity in residential areas. We find that in the presence of economies of scale substantial cost inefficiencies can occur resulting from incentives to install relatively small systems. Depending on the compensation scheme the simulated optimal system size can be as low as 2 kW resulting in high costs per capacity. Subsidy design and tariff regulations can be adopted to incentivize larger photovoltaic systems in the residential sector which would reduce the costs of achieving a certain level of distributed PV generation. It is estimated that for a minimum system size of 5 kW total investment costs for subsidised residential photovoltaic systems in Austria from 2008 to 2013 could have been 2.2% lower for the same amount of installed capacity. We further argue that the strict focus on onsite use of electricity from photovoltaic systems in the residential area is not necessarily desirable from a social cost perspective because it can lead to small and therefore more expensive photovoltaic systems.



## 1. Introduction

Sizing of photovoltaic (PV) systems influences not only the profitability of individual investments, but also affects the total costs of reaching a certain PV penetration level in the residential sector. In this paper we focus on the optimal size of grid connected PV systems from a household perspective and its effects on the social costs of PV integration. In our definition the optimal size is the size that maximizes the internal rate of return of the investment in the PV system. While clearly meteorological and technical elements are important factors for the optimal size of a PV system, we will abstract from these parameters to emphasize economic drivers and incentives. These are partly subject to policy making and regulations and can therefore be adapted to incentivize more efficient investment decisions. The objective of this paper is to raise awareness on the importance of incentives resulting from policy making like subsidy schemes or tariff regulations to avoid potential cost inefficiencies in the process of integrating PV into the electricity system. We also discuss the widespread assumption that PV systems should be scaled to maximize on-site use of PV output.

Several studies have been conducted on optimal sizing of PV systems. Khatib et al. (2013) provide an overview of various system size optimization approaches for off-grid and grid connected systems with different emphasis on economic, environmental, and technical elements.

Notton et al. (2010) analyse the relationship between the PV array- and inverter size for different installation angles and module technologies. While they find that the inverter efficiency curve is crucial for the sizing of the PV system, technical issues are not the focus of our study. We assume the PV array/inverter size to be optimal for all PV array sizes in this study. Kornelakis (2010) applies a Multiobjective Partical Swarm optimization model with

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details on individual system components and their costs to determine the optimal design and size of PV systems. The modelling of individual components in this approach is suitable to account for economies of scale of PV systems, however the focus of the study is not on economic implications related to sizing but rather on detailed technical design issues for planning a PV system.

Hernández et al. (1998) and Mondol et al. (2009) point out that the optimal size of a grid connected PV system depends on the ratio of the buying and selling price of electricity and the share of the household's load met by PV generation. Obviously, when the selling price is higher than the buying price it is optimal to install the maximum size possible (see Liu et al. (2012) and Mondol et al. (2009)). However, if the selling or feed-in price is lower than the buying price, excess PV electricity production reduces the profitability of the PV system. Since subsidized feed-in tariffs are constantly decreasing (see Leepa and Unfried (2013)), we argue that this a much more likely scenario in the future and focus on tariff structures where the retail price is higher than the feed-in price ($p_r > p_f$).

The objective in all those studies is to optimize the size with respect to the profitability of the system from a private economics perspective using tariffs and prices in the residential sector. There are only a few studies that relate the private investment decisions to a public welfare perspective (see Borenstein (2012) or Bode and Groscurth (2013)). Also several studies deal with the benefits and limits of PV for the whole electricity system. Hirth et al. (2015) discuss the market value of PV and related integration costs from a system perspective, Denholm and Margolis (2007) study the limits of PV penetration levels in conventional electricity systems and show that marginal benefits tend to decline for very large shares of PV. Besides the market value of electricity from PV also effects on the total investment costs and benefits from residential PV systems matter from a social cost perspective. We argue that also potential economies of scale should be considered in such an evaluation.

It is clear that there are size-independent fixed costs related to the installation (e.g. planning costs, size independent labour and transport costs and other size independent costs)[1] and decreasing marginal costs for installing additional panels on a roof resulting in economies of scale for PV systems. Obviously these fixed costs are specifically relevant for small systems (up to 5 kW) installed capacity, which are common in the residential sector. Specific investment costs can therefore be significantly lower for larger PV systems. This also means that for a given budget the potential for installed PV capacity increases if average system sizes increase which affects total costs for the integration of residential PV systems. A study conducted by Lödl et al. (2010) on rooftop PV potentials in Germany shows that the average PV potential on residential buildings range from 8.7 kW in suburban regions to 13.7 kW in rural settlements. Comparing those figures to an average size below 5 kW for subsidised residential PV systems in Austria in the years from 2008 to 2013 reveals a certain potential for larger PV systems on residential building in Austria.

If the incentives from tariff regulations and subsidies lead to very small system sizes, the investment decisions taken by the households might be inefficient from a social or system perspective. Note that static retail and feed-in tariffs do not reflect the actual costs of providing electricity considering the variable nature of production costs throughout a day or season. In a study by Oliva and MacGill (2014b) on the net social value of PV, the wholesale market price and cost estimates for externalities are used to estimate the value of PV generation following the argument that residential electricity tariffs do not reflect the actual costs of production. We will address this issue with respect to incentives for the decision on the system size in the discussion of the results. The study focuses only on rooftop PV systems. We do not attempt to address the general discussion on rooftop versus large scale ground mounted PV systems. We also do not focus on distribution grid related issues and assume that the derived results are technically feasible. Grid related constraints which mainly depend on the cumulative installations in a particular locale are rather seen as the upper limit for the size of PV systems in the residential area but are not endogenous in our calculations.

In summary, we contribute to the existing research in the following way:

– We assess the optimal size of grid connected PV systems from a household perspective in the presence of economies of scale for various cost and tariff assumptions for a large sample of measured household consumption data in Austria.
– We interpret the results from a social cost perspective and evaluate potential inefficiencies related to scaling of PV systems.
– Furthermore we discuss the effect of the Austrian subsidy design on the optimal size of PV systems and derive general suggestions for support schemes of PV in the residential sector.

The main research questions we address in this study are the following:

– Does the optimal size for PV systems from a household perspective lead to significant cost inefficiencies?
– In which way does the Austrian subsidy design influence the optimal PV system size?

The remainder of this paper is structured in the following way. In Section 2 we present the theoretical approach to assess an optimal size based on the internal rate of return of the investment and define the most relevant parameters and variables. In Section 3 the methodology and data used to assess the optimal PV system size for a sample of more than 800 households in Austria is presented. The simulation is done for various scenarios on prices, tariffs, cost curves, and subsidies. Results from this numerical analysis are shown in Section 4. We discuss the results and evaluate the efficiency of the investment incentives from a social costs perspective in Section 5. We also attempt to generalize the findings and derive policy suggestions in this section before we end this paper with conclusions in Section 6.

## 2. Theoretical approach and definitions

In this section we define our assumptions to estimate the optimal size of a PV-system from a household perspective. We assume that households will profit from savings on electricity bills and from feed-in of excess PV-production into the grid and that they aim to maximize its profits.[2] We use the internal rate of return (IRR) of the investment as a benchmark. We neglect storage facilities or demand response possibilities in this paper.

Under these assumptions the household is expected to choose the system size (x) that satisfies the following condition:

$$\max_x IRR(x) 0 = \sum_{t=0}^{T} \frac{R(x)_t - C(x)_t}{(1 + IRR)^t} \quad (1)$$

[1] In particular for small systems in the range of 1–20 kW which are analysed in this paper.

[2] This might not be the case for all households but the size in combination with the share of onsite consumption is likely to be considered in the investment decision when onsite consumption is priced higher than the feed-in of electricity from PV systems.

With

| | |
|---|---|
| x | PV system size [kW] |
| IRR | Internal rate of return [%] |
| R | Revenues and savings compared to a no investment case [€] |
| C | Costs compared to a no investment case [€] |
| t | Index for time period [–] |
| T | Total lifetime of the PV system [a] |

As indicated in (1) both the revenues (R) as well as the costs or spendings (C) of the project depend on the PV system size (x).

### 2.1. Revenues and system size

The development of revenues over the system size for a specific household depends on the retail price of electricity ($p_r$),[3] the price for excess electricity which is fed into the grid ($p_f$) and the household's consumption level and pattern. Considering these influences, the revenues ($R_t$) in one year can be written as:

$$R(x)_t = E(x)_t\theta(x)_t p_r + E(x)_t(1-\theta(x)_t)p_f \tag{2}$$

$$\theta(x)_t = \frac{O(x)_t}{E(x)_t} \tag{3}$$

With

| | |
|---|---|
| $E_t$ | Total annual electricity from PV [kW h/a] |
| $\theta_t$ | Share of electricity from PV consumed on site throughout one year [–] |
| $O_t$ | Onsite consumption – total annual output of PV system consumed on site throughout one year [kW h/a] |
| $p_r$ | Retail price of electricity for households [€/MW h] |
| $p_f$ | Price for feed in [€/MW h] |

Onsite consumption ($\theta_t$) in period $t$ is considered to be the amount of electricity consumed onsite in each period (e.g. year). In the simulation it is calculated for each 15 min interval and then summed up over the whole period.

The amount of electricity consumed by the household does not increase linearly with PV system size as at a certain point most of its additional output will exceed the household's load (see Fig. 1 – top left). Therefore the share of PV-output that is used by a typical household (θ) decreases rapidly with system size.[4]

The effect on the revenue (Fig. 1 – top right) depends on the tariffs or prices $p_r$ and $p_f$. Here we show a case where the variable part of the retail price ($p_r$) exceeds the feed-in price $p_f$ which leads to decreasing marginal revenues for larger PV systems. This causes incentives to install smaller systems.

In cases were $p_f \geqslant p_r$ (e.g. subsidised feed-in tariffs) or $p_r = p_f$ the revenues will increase disproportionately or linearly with the system size. In that case, assuming economies of scale for PV-systems, the household should seek to install a PV-system as large as possible. For the remainder of this paper we will focus on tariff structures where $p_r \geqslant p_f$ reflecting a situation in many European countries where the on-site use of decentralized generation is promoted.

### 2.2. Costs and system size

While decreasing marginal revenues would incentivize investments in small PV-systems, the cost structure of PV systems makes small systems relatively expensive due to economies of scale (e.g. see Feldman et al. (2013)). Planning, transport and the installation of the system include a significant share of fixed costs. To account for this we use a simple linear cost function for investment costs ($I_0$). That includes fixed costs ($c_{fix}$) independent of the system size and a variable part ($c_{var}$). We define $C$ as the sum of investment and operation costs and assume the operation costs ($Opex$) to be proportional to the system size.

$$I(x)_0 = c_{fix} + c_{var}x \tag{4}$$

Fig. 1 shows the assumed cost structure and resulting costs per installed capacity

$$i = \frac{c_{fix}}{x} + c_{var} \tag{5}$$

which decrease substantially for small systems as $\frac{\partial i}{\partial x} = -\frac{c_{fix}}{x^2}$.

### 2.3. Trade-off between costs and revenues

The trade-off between declining marginal revenues and economies of scale related to the investment costs defines the optimal size of a PV system in this paper.

Including a restriction on the size ($x_{max}$)[5] Eq. (1) can be rewritten as follows:

$$\max_x IRR(x)0 = -(c_{fix} + c_{var}x) + \sum_{t=1}^{T} \frac{E(x)_t\theta(x)_t p_r + E(x)_t(1-\theta(x)_t)p_f - Opex_t \cdot x}{(1+IRR)^t} \quad s.t.: 0 < x < x_{max} \tag{6}$$

The optimization problem can lead to two possible solutions.[6] In case 1 the optimal size is found at a point where the additional revenue is greater than the variable costs of an additional unit of installed capacity. As the additional revenues decline due to a decrease of the share of onsite use (θ), we observe a peak in the internal rate of return on investment. (see Fig. 1 – bottom right). In case 2θ and therefore the revenues decrease faster. The higher revenues due to the onsite use of PV output cannot offset the higher costs for small systems which is why we do not observe a peak in such cases. This can be observed for households with very low electricity consumption and low correlation between demand and PV production. Here the main part of revenues stems from electricity fed into the grid. In these cases the highest return on investment can be achieved with the maximum size ($x_{max}$) to exploit the economies of scale of the investment. Fig. 1 summarizes the influencing size dependent factors that determine the internal rate of return described above.

[3] It should be noted that here we only refer to the variable part of the retail price which consists of energy costs, variable part of grid connected costs and taxes on those costs. The share of variable costs depends on the tariff structure and can vary significantly throughout countries or utilities.

[4] The decrease for a specific household depends on the load-production correlation and the level of electricity consumption. For a 5 kW system the share of onsite use is typically between 15% and 30% of total PV-output.

[5] The maximum system size for households is given by the available roof area if we ignore ground mounted systems. For this study we will set the maximum installed PV capacity to 20 kW which corresponds to a large roof with roughly 160 m$^2$ available for PV panels. This generally exceeds the average PV potential of single family houses (see introduction and Lödl et al. (2010)) but we chose to allow for very large sizes to analyse potential effects. If the model results shown in 4.1 exceed the available roof area of a household the maximum size that fits on the roof would yield the highest *IRR*.

[6] The focus of this study is to estimate an optimal system size and not necessarily to assess whether a PV-system is profitable. This is why the system size in the model is also restricted to be greater than zero. Of course for all negative IRR the optimal solution would be $x = 0$.

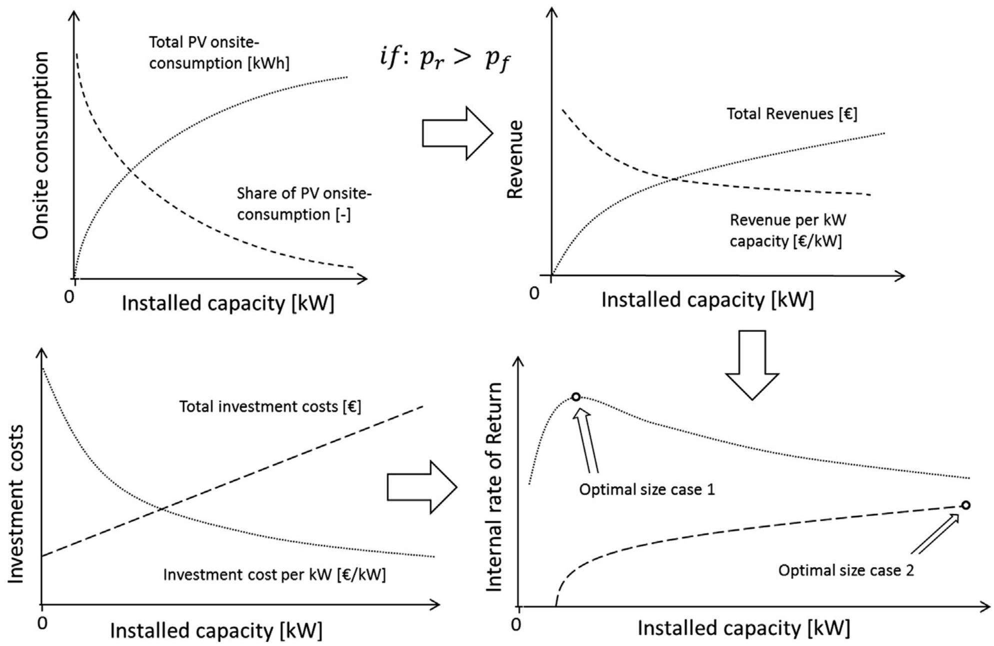


**Fig. 1.** Development of onsite consumption, revenues, investment costs and internal rate of return over PV system size for tariff structures where the value of onsite consumption is higher than the value of electricity fed into the grid.

The following parameter will influence the optimal size and the economic efficiency of a PV system in general:

- Location and solar irradiation
- Level of electricity consumption of a household
- Correlation between the household's load and the PV generation
- The difference in price levels: $\Delta p = p_r - p_f$.

These factors can vary significantly over time, different households and geographical regions. While quantitative results are therefore hard to generalize, relevant drivers and their impact on the optimal size are also valid for other regions and tariff schemes.

## 3. Methodology and data

In this section we briefly present the data and scenario based approach we apply for the numerical analyses in the case study for Austria.

### 3.1. Residential load data

We use load profiles of 821 households measured in 15 min time resolution. All households are located in Upper Austria within a relatively small radius of less than 100 km around the city of Linz which is located at 48°18′North 14°17′East. The time frame of the measured data is April 2010 to March 2011.

Fig. 2 shows the distribution of important factors influencing the optimal size. (a) Shows a boxplot of the total electricity consumption within the time frame. The median (red line) is around 3000 kW h/a and 75% of households consume between 2000 and 4500 kW h/a. Extreme values range from just 100 kW h/a up to a maximum of 10,000 kW h/a. (b) Shows load profiles expressed as boxplots of the average hourly load for all households. While the average of all households reflects the standard household load profile, the consumption patterns of individual households deviate significantly from standard load patterns which are shown for two households in (b). This influences the economic efficiency of a PV system. High positive correlation between load and generation increases onsite use for a given PV system size which increases the revenue per $kW_{peak}$ installed.[7] (c) Illustrates the wide range of correlation (Pearson correlation coefficient between load and PV electricity production from −0.32 to 0.34).

### 3.2. PV model

PV generation is modelled in a PV simulation tool developed at the Institute of Energy Systems and Electrical Drives, TU Vienna. It includes the simulation of the position of the sun (see Eicker (2012)), the calculation of solar radiation on an inclined surface for diffuse and direct irradiation. The data for solar radiation is derived from satellite measurements provided by the HelioClim database[8] (15 min time resolution). The simulated PV system generates at a maximum of 1050 full load hours for an optimal tilt angle of ~30° and an azimuth of 180° (=south). The model allows for any combination of installation angles to be simulated and installation angles have been included in the optimization algorithm.

### 3.3. PV system cost scenarios

As described in Section 2.2 we use a linear cost curve (Eq. (4)) with a fixed and variable cost component. It is clear that PV system prices decreased significantly in recent years which will affect the choice for an optimal system size. Even though price decreases independent of the system size are very well documented, no reliable studies on the development of the composition of the system price (fixed vs. variable costs) and their development over time could be found. Thus we decided to fit the parameters of the cost curves ($c_{fix}$, $c_{var}$) directly from available price data on more than

[7] Assuming that $p_r > p_f$.

[8] "HelioClim database" accessed October 10, 2014, http://www.soda-is.com/eng/services/services_radiation_pay_eng.phpFor the simulation we use irradiation data for just one location. We consider this to be a justified simplification, as the measured load profiles are within a small radius in which the irradiation does not differ substantially. It is clear that the irradiation is a main driver for the economic efficiency of PV-systems but this has been shown in several other studies and is common sense. Here we focus on the load pattern and consumption level.

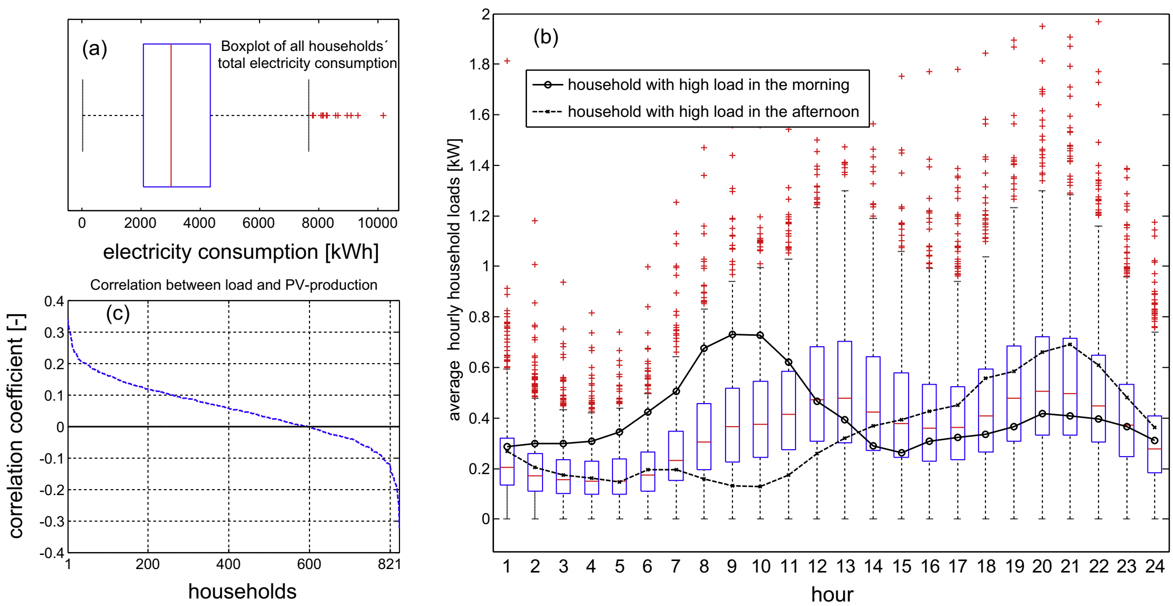


**Fig. 2.** Residential load data: Boxplot of total electricity consumption (a), boxplot of average hourly load over one year of all households and average load of two households with deviating patterns. The blue boxes indicate the 25th and 75th percentiles and the red line indicates the median value. The black whiskers indicate extreme values while the red markers are households who are considered to be outliers in the sample (b), distribution of correlation coefficient between load and PV-generation for all households (c). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

10,000 PV systems installed in the residential sector of Austria between 2008 and 2013 (system sizes between 1 and 10 kW). We estimate the parameters with an ordinary least square approach for each year separately. Although the prices within similar size ranges vary substantially (see Fig. 3) the influence of the size is highly significant for prices per installed capacity in each year. The estimated parameters can be seen in Table 1. We treat each year as a separate scenario in the simulation runs.

In the period of observation households could apply for subsidies designed as a non-refundable investment grant for each kW of installed capacity up to 5 kW.[9] The grant was adjusted each year to account for decreasing PV system prices. Subsidy levels for each year are shown in Table 1. For each year and corresponding cost curve we run the model with and without subsidies to assess the influence of the subsidy on the optimal system size. The average system size increased from 4.4 kW in 2008 to around 5.3 kW in the year 2013.

Similar to Cucchiella et al. (2014) we assume constant operation and maintenance costs (*Opex*) of 1% of investment costs per anno throughout the whole life time of the PV-system in all scenarios. We assume the life time of the system to be 25 years with a degradation of the efficiency of 0.5% p.a. (Branker et al., 2011).

### 3.4. Electricity price and feed-in scenarios

Additionally to the cost-curve-scenarios with and without subsidies for different years, we distinguish between three scenarios for the price of electricity fed into the grid ($p_f$). In the first scenario "High FIT" it is assumed that households are granted a high feed-in tariff (FIT) by utilities. In Austria, several utilities offer to pay a higher price for PV generation. We assume a relatively high tariff of 10 cent/kW h for this scenario. In a second scenario "Base-FIT" we assume a lower constant feed-in tariff of 4 cent/kW h which reflects a constant tariff at the base load price for electricity on the wholesale electricity market.

[9] Until 2010 the size was strictly restricted to 5 kW. In the following year households aiming at installing larger systems where allowed to apply as well, but only up to 5 kW where subsidized. Additional subsidies were granted by local authorities in most regions in Austria which is not considered in this study.

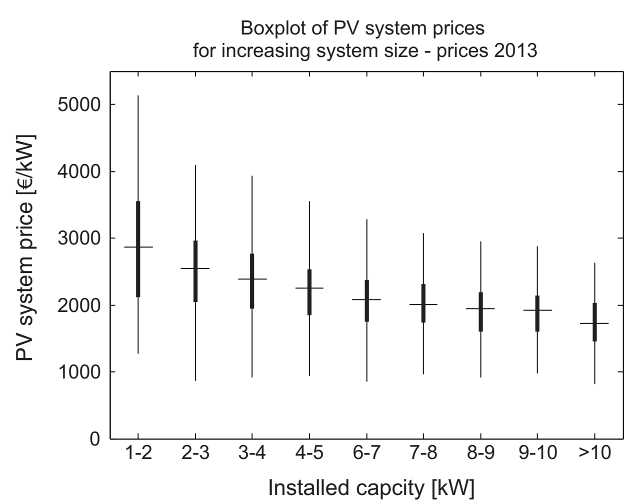


**Fig. 3.** Boxplot of PV system prices over system size in year 2013.

**Table 1**
Cost and price parameters for scenario runs.

| Scenario parameters | | | |
|---|---|---|---|
| Cost curves | Fix costs - $c_{fix}$ | Variable costs – $c_{var}$ | Subsidy |
| 2008 | 4510€ | 4671€/kW | 2400€/kW |
| 2009 | 3910€ | 4359€/kW | 2000€/kW |
| 2010 | 4043€ | 3511€/kW | 1300€/kW |
| 2011 | 3595€ | 3026€/kW | 1100€/kW |
| 2012 | 3750€ | 1705€/kW | 800€/kW |
| 2013 | 3410€ | 1456€/kW | 300€/kW |
| Electricity prices | Feed-in – $p_f$ | On-site use – $p_r$ | |
| High FIT | 10 cent/kW h | 16.5 cent/kW h | |
| Base FIT | 4 cent/kW h | 16.5 cent/kW h | |
| Spot | Hourly spot prices | 16.5 cent/kW h | |

In a third scenario "Spot" it is assumed that PV feed-in is priced at the spot market price of the respective hour, representing a real time price scenario for feed-in. For the simulation we keep all variables constant assuming no significant changes in real terms.

For the savings related to the onsite use of generated electricity we use a standard tariff structure in Austria with a constant retail tariff ($p_r$) of 16.5 cent/kW h, which is applied in all scenarios. In Table 1 the parameters for the cost curves, feed-in tariffs and retail prices are summarized for all scenarios.

### 3.5. Simulation and optimization

For each household the simulation was conducted individually for all six cost-curve scenarios and three price scenarios with and without subsidies which results in 36 scenarios per household. We assume an investment horizon of $T = 25$ years and restrict the system size to be greater than 0 kW to force an investment (which also allows for negative rates of return) and less than 20 kW. Additionally to the size, the tilt angle (β) and the azimuth (α) of the PV-system were implemented as decision variables for the optimisation.[10]

The objective function for each household is as follows:

$$\max_{x,\alpha,\beta} IRR(x,\alpha,\beta) 0 = -(c_{fix} + c_{var}x) + \sum_{t=1}^{T} \frac{E(x,\alpha,\beta)_t \theta(x,\alpha,\beta)_t p_r + E(x,\alpha,\beta)_t (1-\theta(x,\alpha,\beta)_t) p_f - Opex_t \cdot x}{(1+IRR)^t} \quad (7)$$

$$s.t.: \quad 0 < x < 20$$
$$0 < \alpha < 360$$
$$0 < \beta < 90$$

The function "*fmincon*" available in Matlab© is applied for this nonlinear constrained optimization problem with multiple decision variables.

## 4. Results

### 4.1. Optimal system size

The results for all 821 households are illustrated in Fig. 4 for the three price and feed-in scenarios and for each estimated cost-curve from 2008 to 2013. The top three figures show the results for optimal system sizes without subsidies and the bottom three figures illustrate the optimal size considering the federal subsidies in each year. The boxplots indicate the medians (red) the 25% and 75% quantiles (blue box) and extreme values.

#### 4.1.1. General observations

In the scenarios with no subsidies the optimal system size tends to increase in all scenarios because the estimated variable costs decrease more than the fix costs. It is also evident that the solution for the optimal size heavily depends on the difference between $p_r$ and $p_f$. The subsidies (investment grants) lead to incentives for larger systems. The modelled optimal sizes are likely to be below the average maximum PV potential per residential building for the scenarios with low feed-in tariffs.

#### 4.1.2. Comparing the scenarios

In the "High FIT" scenario the optimal size tends to be significantly higher than in the "Base FIT" and "Spot" scenarios. Including federal subsidies, the optimal size is the maximum size allowed in the model for all years in the "High FIT" scenario.[11] Without any subsidy, we observe smaller optimal system sizes with medians ranging from 6.9 kW to 20 kW in the "High FIT" scenario. Still, in all years more than 25% of the analysed households would be best off with the maximum system size. For the cost structure of 2012 and 2013 the model suggests the maximum size for all households even without subsidies. This is because of a relatively high fix vs. variable costs ratio in those years.

The "Base FIT" and "Spot" scenarios show much smaller optimal sizes with slightly larger system sizes for the years 2012 and 2013 in the "Spot" scenarios without subsidies. The median is between 2 kW and 3 kW for the years 2008 to 2011. Here the majority of the revenue stems from savings in electricity bills with shares of onsite use between 20% and 50% for the majority of households. (see Fig. 5) In the years 2012 and 2013 the median optimal system size increases to more than 4 kW in the base price scenario and to more than 6 kW in the "Spot" scenario. The increase in the optimal size in those years is again due to higher fixed vs. variable cost ratios in the calculations (see Table 1). A possible explanation could be that module costs decreased faster than installation and planning costs.[12] The slightly larger optimal system sizes in the "Spot" scenario are due to higher prices in the hours around noon (peak time in Austria). This increases the value of the excess electricity compared to a fixed base price. Note that for the years 2012 and 2013 in both price scenarios the median share of onsite use is below 20% indicating that most of the generated electricity is fed into the grid.

The results of the two low price scenarios with subsidies do not show clear trends. This is due to the fact that the subsidy level in each year did not necessarily reflect the decrease in PV system costs. In effect, the variable investment costs for a household did not decrease monotonically. E.g. the variable costs in 2012 amounted to $1705-800€/\text{kW} = 905€/\text{kW}$ compared to $1456-300€/\text{kW} = 1156€/\text{kW}$ in 2013. Irrespective of the time trend, there is a clear tendency for larger systems compared to no subsidy scenarios. The median size rises from around 2 kW to around 4 kW to 6 kW for the years 2008 to 2011. In the year 2012 the median size is at the maximum size of 20 kW compared to 6 kW without subsidies. For the year 2013 the median value is around 12 kW compared to 7 kW without subsidies (the role of subsidies will be discussed in Section 5).

The results show, that the decision for an optimal system size from a household perspective is significantly affected by the parameters used in the model. It is clear that the level of feed-in compensation and the tariff structure directly affects the optimal size of a household's PV-system.

### 4.2. Onsite use of PV electricity at optimal system size

Fig. 5 shows the share of on-site consumption ($\theta$) and total PV output for the optimal system sizes presented in the previous section. We only show the results without subsidies.[13] It can be seen that the median for on-site consumption shares is below 10% in the "High FIT" case. Median values for the "Base FIT" and the "SPOT" scenario are between 28% and 40% for the years 2008 to 2011 and below 20% for the years 2012 and 2013 due to larger optimal system sizes. This means that even with relatively small system sizes below 5 kW, the majority of the output is fed into the grid and not consumed by the households itself. Implications of those findings will be discussed in Section 5.

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[10] Results for optimal tilt angles are not shown in this paper.

[11] Note that the subsidy was limited to 5 kW installed capacity. From a household perspective it was therefore preferable to build a 5 kW system, which is the most common size in the data set.

[12] In those two years the modelled optimal sizes for the scenarios including subsidies are more likely to be close the maximum PV capacity that fits on an average single family house. In those cases the tariff schemes are not a limiting factor to fully exploit the economies of scale.

[13] On-site consumption ratios for the subsidy scenario are generally lower as the subsidy scheme leads to larger optimal system sizes.

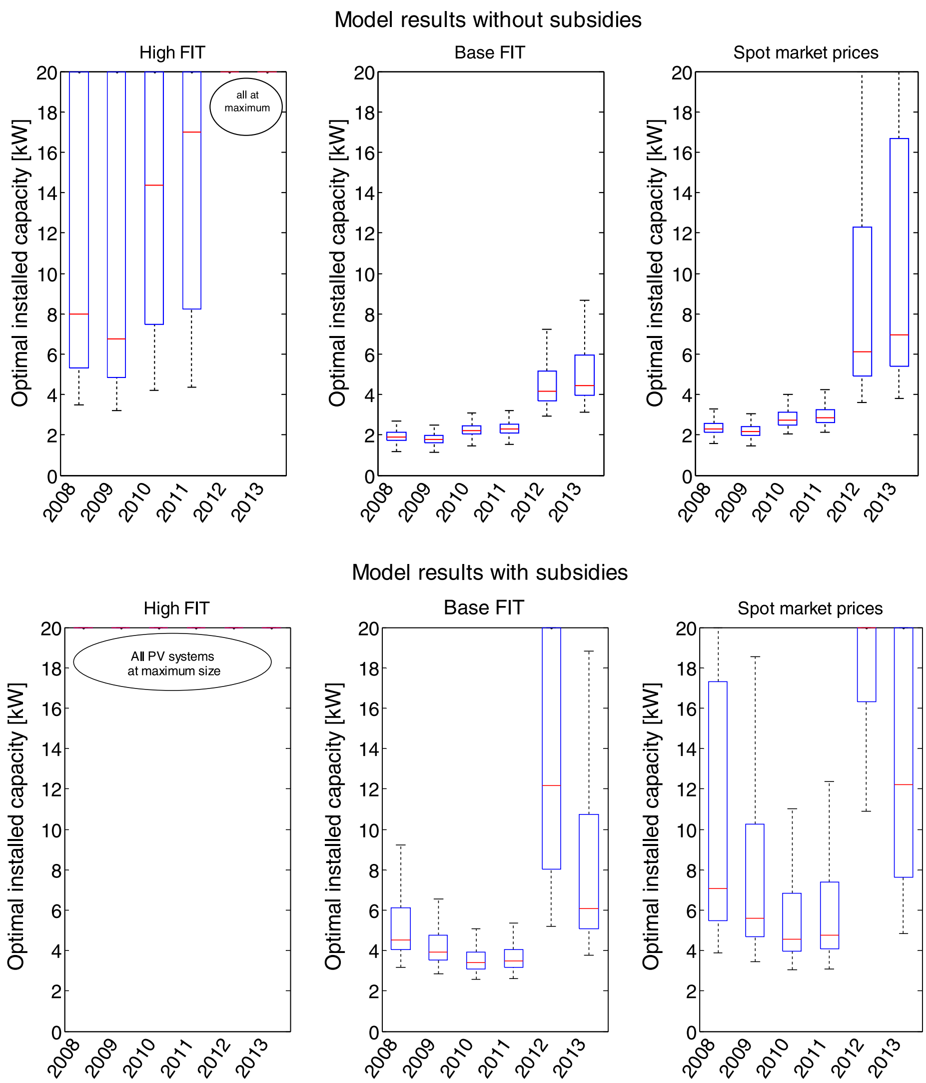


**Fig. 4.** Boxplot of optimal system size for all scenarios.

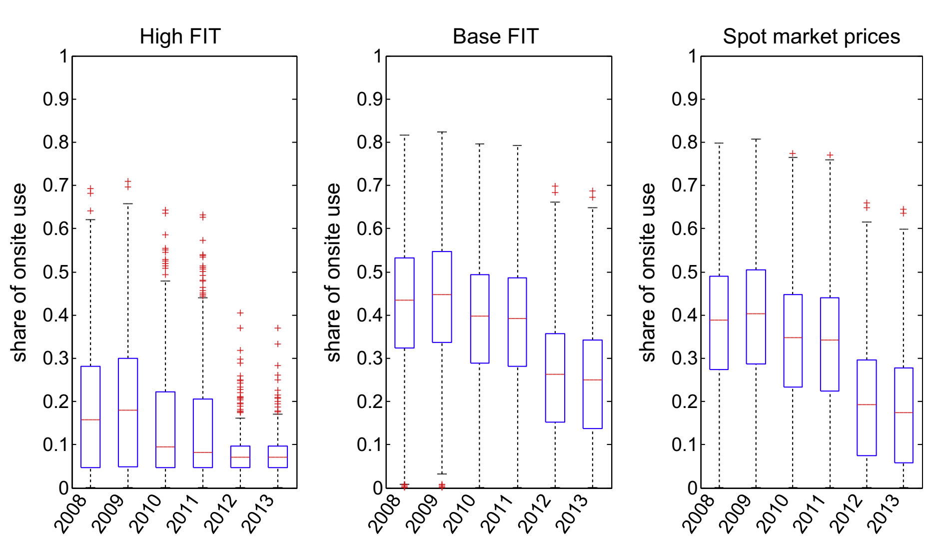


**Fig. 5.** Share of onsite use (θ) for the optimal system size in all scenarios.

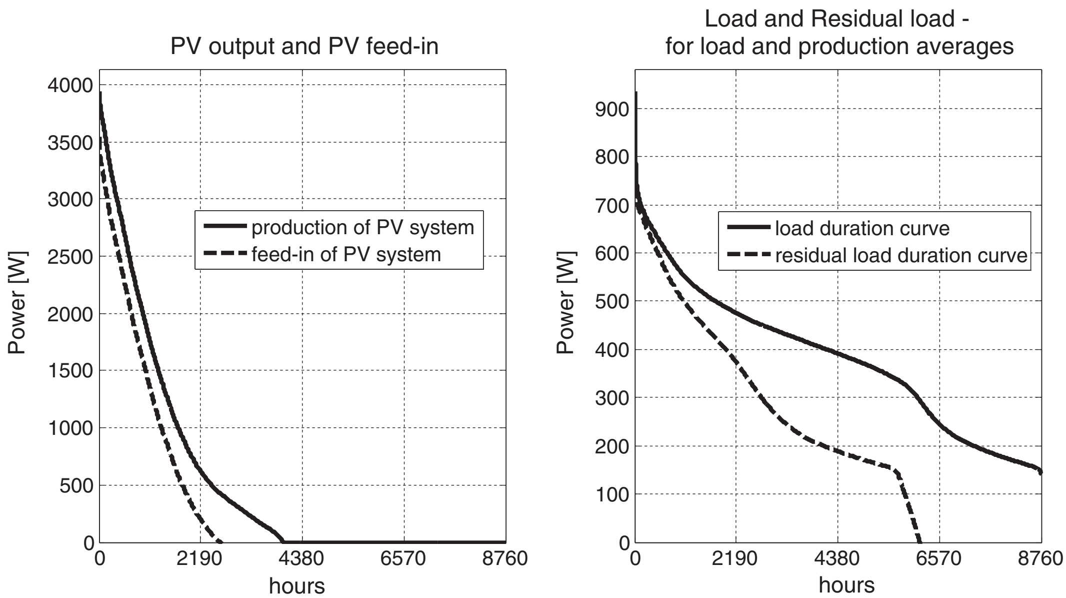


**Fig. 6.** Duration curves for PV production and household loads.

We also analysed the effects of PV production peaks and their correlation with households' consumption patterns with respect to concerns of grid capacity restrictions. Fig. 6(a) shows the duration curve of PV production for an average system size in the low feed-in tariff scenario in the year 2011.[14] We show an average load over all households here for illustration reasons. It can be seen that feed-in peaks are only reduced by 12% through on-site consumption for average figures. We also analysed the 100 highest values of PV output within a year and the corresponding consumption data of each household at these points in time. We find that the average consumption of a household at these PV peak times is around 500 W. We conclude that it is therefore not likely that on-site consumption will significantly reduce PV feed-in peaks and does not solve the problem of high PV feed-in peaks.

Similarly, we analysed whether consumption of electricity from the grid at peak times would be reduced by onsite consumption of electricity from PV. Fig. 6(b) shows the load duration curve for average household loads and the residual load resulting from on-site consumption of electricity from PV (negative residual load is not shown here). Again it can be seen that PV systems do not significantly reduce the peaks as residential peak load in Austria usually occurs in the evening hours of winter month.

From those findings we conclude that in the absence of on-site storage facilities or demand side management (1) the majority of the produced electricity will be fed into the grid even for relatively small system sizes (e.g. around 3 kW), (2) the installation of PV systems does not reduce residential peak loads and (3) on-site consumption does not significantly affect peaks of PV feed-in into the grid. Implications of these findings will be discussed in Section 5.

## 5. Discussion

In this section we will discuss the implications of the presented findings from a system perspective and for policy making with respect to PV.

### 5.1. Important factors for PV sizing from a regulatory perspective

We have shown that the optimal size of PV-systems from a household perspective is sensitive to various influencing factors. While the consumption patterns are more or less static[15] the compensation scheme and the investment costs are determined through tariff regulation and subsidy schemes. Therefore the authorities and regulators directly influence the investment decision with respect to the PV system size.

#### 5.1.1. Compensation scheme and savings in electricity bills

As already discussed in Section 2, the optimal size is influenced by the difference between the variable part of the retail price $p_r$ (savings through onsite consumption) and the price for feed-in $p_f$. Assuming $p_r > p_f$, the bigger the difference, the smaller the optimal size will be. Both prices are partly influenced by regulators and authorities. Besides energy costs, a significant share of the retail price includes grid related costs, taxes including additional payments for financing support schemes for renewables, and other costs. The savings in electricity bills through on-site use of PV-generation depend on whether these parts of the bill are paid as variable costs per kW h consumed or whether they are to be paid as a lump sum over a certain period e.g. as a capacity charge for a month.

Also feed-in tariffs are regularly determined by some sort of regulation. Authorities can therefore shape incentives for sizing of PV systems to a large extend. If a certain size-range is preferred by a central planner (e.g. TSO, authorities) these effects have to be taken into account.

#### 5.1.2. Investment support

Besides prices and compensation schemes also subsidies on the investment of PV systems significantly influence the choice for a certain system size. The effect of an investment grant on the optimal size of a PV system depends on the specific support design. Investment grants independent of the size of the system will lower

[14] The average system size shifts the curves up and down but the absolute difference between production and feed-in stays constant independent of the average system size as consumption does not change.

[15] In the short term the consumption levels and patterns are more or less given as exogenous parameters if we neglect the option of demand side management or consumer behaviour adjustments. See e.g. Oliva and MacGill (2014a).

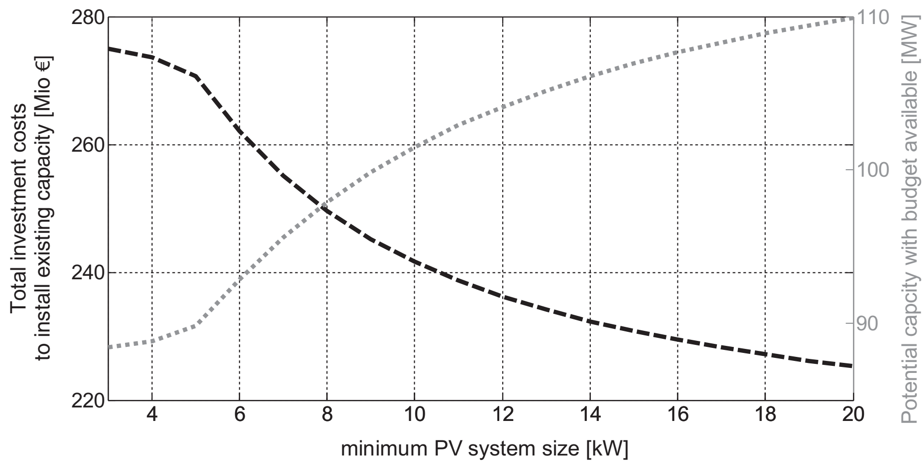


**Fig. 7.** Minimum PV system size and cost efficiency.

the fixed part of the investment costs which would provide an incentive for smaller PV systems. Investment grants per installed capacity like a constant payment per kW installed lower the variable part of the investment and will therefore promote comparatively larger PV-systems. Options like granting subsidies decreasing with the size of the system would allow for some flexibility if a certain range of system sizes was desired.

### *5.2. Does the simulated household optimum correspond to a system cost optimum?*

While we showed that incentives can be shaped by regulators the question remains whether this is relevant from an efficiency point of view. We argue that from a strict cost perspective and if grid restrictions and grid expansion costs are neglected, a social planner (authorities/administration) should be in favour of large PV-systems in order to exploit economies of scale. However, it is often argued that a high share of on-site use is preferable due to limited distribution grid capacities. Thus, from a system perspective, two opposing effects influence the optimal size of PV systems. From this point of view the different pricing of on-site use and feed-in ($p_r$ and $p_f$) is a way to provide incentives towards a decentralized integration strategy. The crucial question here is whether the cost and benefits reflect the real costs and benefits for the electricity system as a whole.

Taking a closer look at the savings in the electricity bill we argue that they do not necessarily reflect the resulting cost savings for the whole electricity system. For a discussion on this issue see Bode and Groscurth (2013). While the value of reduced fuel costs is more or less represented in the energy price component of the electricity bill[16], other bill components cannot be associated with reductions on a system cost side or they may overvalue the cost reductions for the whole electricity system.

It is doubtful that the high share of variable costs in the grid component reflects a cost-by-cause allocation as (in the absence of storage) a household with a grid connected PV-system still relies on the grid. So the household's cost saving is overvalued compared to savings in system costs. Similar arguments can be found with respect to charges related to financing RES support (like the "EEG-Umlage" in Germany) if designed as variable components of the electricity bill. With a higher penetration of PV-systems in the residential area these contributions to finance support schemes and grid costs could decrease to a degree where changes in the tariff structure of the retail prices are very likely.

In general we argue that from a system perspective large PV-systems (e.g. covering the whole roof pointing south) are a more cost effective way to reach a certain share of PV-generation as long as no additional investments in the distribution grid are needed to cope with high feed-in peaks compared to a highly decentralized case (e.g. small PV-systems on many roofs in an area). While we will further need to investigate the maximum size of PV systems from a distribution grid perspective in detail, first simulation runs show a restriction to 10–15 kW of installed capacity for a household in a standard distribution grid in Austria which is way above the observed average system sizes. However, there might be additional objectives or effects (e.g. distribution of support budget over many households, positive behavioural effects of households with PV-systems, social acceptance, etc.) which could make small PV-systems more desirable than in the strictly monetary perspective we applied in this paper. While those benefits are hard to quantify and will also depend on personal preferences of households, the negative side of this trade-off can be estimated. Fig. 7 illustrates expected costs (black dashed line) for an assumed minimum size of a PV system. All smaller systems of our sample of 10,000 households where substituted with the minimum size and the total installed capacity was held constant. It can be seen that with a minimum system size of 5 kW total investment costs would have been 2.2% lower. An increase of minimum system sizes in the residential sector to 10 kW would have reduced total investment costs by around 10% compared to historic investment costs. The grey dotted line in Fig. 7 shows the increase of installed capacity for increasing minimum system sizes at constant investment budgets: for a constant investment budget, the installed capacity can be increased significantly for higher average system sizes.[17]

These cost differences should be considered when designing compensation and support schemes for PV systems and in the absence of contradicting arguments households should be incentivized to install larger PV systems. We argue that under the assumed circumstances and PV system costs, support systems that heavily incentivize very small grid connected PV systems with less than 2 kW of installed capacity should be avoided from a total cost efficiency perspective.

[16] Note that even the energy value is not correctly reflected in the bill savings if there are no spot price dependent tariffs in place because the system costs of a generated kW h depends on changing demand and supply situations.

[17] Note however that the minimum size is restricted by the available roof area of a household which on average limits the maximum size of PV systems. Larger systems between 10 kW and 20 kW could only be achieved in rather large houses. Efficiency gains over 10 kW shown in Fig. 7 are therefore likely to be overestimated.

## 6. Conclusion

In this paper we analysed the optimal size of a PV system from a household perspective considering economies of scale related to investment costs. The optimal size based on maximizing the internal rate of return was simulated for various compensation and PV cost scenarios for 821 households whose electricity consumption was measured. We showed that the decision for an optimal size of a PV-system depends on a variety of factors related to investment costs, consumption patterns and price or tariff schemes. Some of these factors can be influenced by regulators and authorities who therefore can shape the incentives for households to install PV systems of a certain size range.

Following our results we argue that regulation can lead to situations where households have incentives to invest in rather small PV systems (<5 kW). Especially a large positive delta between the value of onsite consumption and feed-in can lead to very small sizes as the share of on-site use decreases dramatically for most households for system sizes up to 5 kW. Considering that smaller systems are usually more expensive this causes total costs of PV in the residential sector to be higher. In other words, compensation schemes and subsidies that promote larger system sizes per household would be more cost efficient. Of course the size is limited by the capacity of the distribution grid but that incentives in Austria result in much lower PV system sizes compared to a technically feasible maximum size.

We also argued that typically existing tariff schemes do not fully reflect the actual costs and benefits related to PV-generation in the residential area. If no other arguments like distribution grid restrictions or additional benefits of smaller PV systems justify restricting the size per household we conclude that the current regulations with a strong focus on on-site use of electricity from PV do not provide the right incentives with respect to cost efficient sizing of PV systems from a social cost perspective.

Policy makers and regulators should therefore consider the implications on incentives related with subsidies or imposed tariff structures to increase the cost efficiency of PV integration in the residential sector in Austria.

Again, we want to point out that the focus of this study is on residential rooftop systems and not a comparison between large-scale ground-mounted systems and small scale residential PV systems. To address this topic, apart from economies of scale, more factors (especially land use issues) would have to be considered.

Further research will focus on distribution grid limitations on PV system size and on suitable tariff structures and regulations to incentivize a cost efficient integration of PV systems in the residential sector.

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