The economic inefficiency of grid parity: The case of German photovoltaics in scenarios until 2030

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***Abstract*—Due to massive reductions in the price for photovoltaic (PV) systems, PV grid parity has recently been reached for German households. As PV system prices continue to decrease, the gap between the levelized costs of electricity (LCOE) of PV and the retail electricity tariff will grow and trigger investments in residential PV systems for captive electricity generation – even in the absence of any direct financial incentives such as solar power feed-in tariffs. However, while the single household can lower its annual electricity costs through investments in rooftop PV systems for captive electricity generation, the partial optimization of the single household is inefficient from an economic perspective. Households optimize their PV investment by comparing the LCOE of PV to the residential electricity tariff that includes network tariffs, taxes, levies and other surcharges that can be avoided when consuming self-produced PV electricity instead of purchasing electricity from the grid. Therefore, private investments in rooftop PV systems receive an indirect financial incentive in the current regulatory environment.**

This paper analyzes the consequences of PV grid parity in Germany until 2030 from both the single household and the wholesale market perspective. We find that exempting self-consumed PV electricity from all additional charges induces significant investments in rooftop PV systems and small scale storage systems, allowing for high shares of in-house PV electricity consumption. From the single household perspective, the optimal PV and storage system capacities increase with the number of residents living in the household, enabling households to cover on average 72 % of their annual electricity demand by self-produced PV electricity. The single household's optimization behavior entails direct consequences for the wholesale market, as it changes the residual load both in volume and structure. The inefficiency caused by the partial optimization of single households (induced by PV grid parity) leads to significant excess costs of 7.1 bn €$_{2011}$ compared to the cost-optimal solution achieved under a total system optimization which ensures the cost-efficient development of Germany's electricity generation mix up to 2030.

I. INTRODUCTION

The photovoltaic (PV) market in Germany has seen unprecedented growth over the last years. Since 2009, installed capacity rose by approximately 7.5 GW per year, reaching 25 GW at the end of 2011. This massive expansion was due to a combination of generous solar power feed-in tariffs – guaranteed to PV electricity producers by the German Renewable Energy Sources Act (EEG) – and decreasing PV system prices, which over the last 6 years have fallen at a faster rate than the solar power feed-in tariffs.[1]

[1]PV system prices have fallen by over 65 % from 2006 to 2012 [1].

In order to slow down the expansion of PV capacities and the associated costs of supporting PV electricity – which are added to the electricity price and hence passed on to the electricity consumers via the so called 'EEG' surcharge – the federal government agreed to further cut the feed-in tariffs for photovoltaics and to stop the direct financial incentives once a cumulative capacity of 52 GW is reached.[2] However, due to the fact that PV grid parity has recently been achieved for households in Germany [2], investments in rooftop PV systems are expected to become a compelling option for residential electricity consumers in the near future, even in the absence of any direct financial incentives such as solar power feed-in tariffs.

PV grid parity for households is defined as the threshold at which the levelised costs of electricity (LCOE) - including initial investment and operations and maintenance costs - of the PV system over its lifetime reach parity with the residential electricity tariff. Hence, PV grid parity marks the point in time at which households can lower their annual electricity costs by consuming self-produced PV electricity rather than purchasing electricity from the grid.

Due to the fact that households avoid network tariffs, taxes,

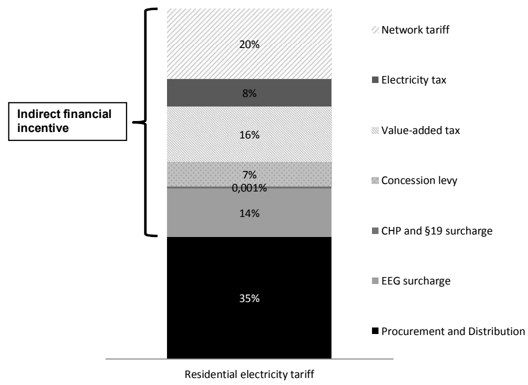

Fig. 1. Composition of Germany's residential electricity tariff in 2012 based on [3]

levies and other surcharges for the amount of PV electricity consumed in-house, the grid parity calculus depicts an indirect financial incentive for PV electricity generation granted to residential PV electricity consumers (see Figure 1). How-

[2]Germany's National Renewable Energy Action Plan forsees a target value of 52 GW for PV in 2020

ever, the expenditure savings on the side of the residential PV electricity consumers go along with revenue shortfalls on the side of the government, municipalities and system operators, which will need to be somehow compensated. For example, the costs for operating, maintaining and upgrading the grid do not decrease with the amount of PV electricity consumed in-house but rather increase due to necessary investments in the distribution grid. Hence, system operators will need to either increase the network tariffs or change the tariff structure - e.g. from energy-related to capacity-related tariffs - to be able to cover the costs. Moreover, households save electricity tax payments for the share of in-house PV electricity consumption, which contribute to public funds (e.g. pension funds) in Germany. Hence, an increased share of in-house PV electricity consumption induced by PV grid parity results in a reallocation of financial resources: it lowers the burden to be borne by households that consume a part of their PV electricity generation and increases the burden to all other electricity consumers. Moreover, society is faced with significant excess costs under such a scenario, due to the fact that investments in rooftop PV and small scale storage capacities do not depict a cost-efficient investment option in Germany before 2030. Specifically, the partial optimization on the household level leads to an inefficient electricity generation mix from the total system perspective.

The potential cost savings from the single household perspective correspond to the difference between the residential electricity tariff and the LCOE of PV. The greater the difference between the residential electricity tariff and the LCOE of PV increases, the larger the potential cost savings achievable by households become, as shown in Figure 2.[3] However, potential cost savings are limited to the amount of PV electricity that is consumed by the residents.

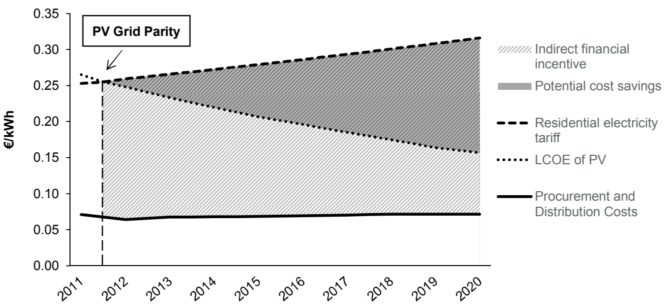

Fig. 2. Potential costs savings from the single household perspective induced by PV grid parity

The rapidly growing gap between the residential electricity tariff and the LCOE of PV is expected to lead to considerable investments in rooftop PV systems for in-house electricity consumption in the near future.[4] However, given the prevalent mismatch of sunshine hours and residential electricity consumption behavior, supplementary investments in storage capacities could increase the potential cost savings, allowing for higher shares of in-house PV electricity consumption.

At present, studies have primarily focused on the identification of the point in time at which PV grid parity will be reached ([4], [2]) as well as on the analysis of factors influencing this point of time ([5],[6],[7]). The potential consequences of PV grid parity, in contrast, have hardly been analyzed.

An adequate assessment of the potential impact of PV grid parity on the total electricity system requires a profound analysis of the single household's cost minimization behavior. In the absence of any direct financial incentive such as solar power feed-in tariffs, the single household's decision concerning the installation and the dimensioning of a PV and storage system depends on the gap between the residential electricity tariff and the LCOE of PV, the household's electricity consumption profile and the market value of the non-consumed PV electricity that is fed into the grid. The single household's cost minimization behavior entails direct consequences for the wholesale market. This is because increased shares of in-house PV electricity consumption cause changes in the residual load, both in volume and structure, and in turn effect the provision and operation of power plants.[5]

In this paper, we analyze the consequences of PV grid parity in Germany after 2020 - both from the single household and the wholesale market perspective – by iterating a household optimization model with an electricity system optimization model. Within this framework, the following questions will be answered:

- What are the optimal PV and storage system capacities – from the single household perspective – induced by PV grid parity?
- What is the share of total PV electricity generation that can be consumed in-house by a single household (given the optimal dimensioning of PV and storage system capacities)?
- What is the share of a single household's annual electricity demand that can be supplied by self-produced PV electricity (given the optimal dimensioning of PV and storage system capacities)?
- What are the consequences for the wholesale market?
- What are the excess costs induced by PV grid parity?

The remainder of the paper is structured as follows: Section II presents the scenario definition and the methodology developed to analyze the consequences of indirect financial incentives for PV electricity generation – induced by PV grid parity in Germany until 2030. Section III summarizes the model results and analyzes their implications for Germany's power sector up to 2030. Section IV concludes and provides an outlook on further possible research.

II. METHODOLOGY

In this section, the scenarios are defined and the models are presented that are used to analyze the effects of indirect

[3]The residential electricity tariff is assumed to increase by 3 % per year and PV system prices to decrease by approximately 3.3 % per year until 2020.

[4]The greater the gap between residential electricity tariffs and LCOE of PV, the higher the return on investment. To depict a compelling investment option, the return on investment will at least need to exceed the capital market interest rates for fiscal investments with a comparable investment risk.

[5]In the analysis, the residual load corresponds to Germany's total electricity demand (load) without the accumulated in-house PV electricity consumption of the single households.

financial incentives – induced by PV grid parity – both from the single household and the wholesale market perspective.

A. Scenario definition

For the analysis of the grid parity effects, two scenarios are defined. As seen in Table I, which lists the main settings of the scenario simulations, the difference between the scenarios refers to the deployment of PV systems in Germany after 2020. While in scenario A the expansion of PV systems is based on the single household's optimization behavior (induced by PV grid parity), scenario B simulates a cost-efficient development of Germany's electricity generation mix up to 2030. All other assumptions regarding political targets or the expansion of interconnector capacities are identical in both scenarios. Germany (and its neighboring countries) are assumed to achieve their national renewable energy targets stated in the National Renewable Energy Action Plans (NREAP's) by 2020 and the European CO_2 reduction target, which increase linearly up to 60 % until 2030 (compared to 1990 levels). Moreover, the interconnector capacities between Germany and its neighboring countries are assumed to be expanded according to planned projects according to the ENTSO-E's 10-Year Network Development Plan 2012 (TYNDP) [8].
The scenarios described above are simulated with two optimization models: a household optimization model and an electricity system optimization model. The following sections introduce these two models and describe the iterative approach used in the analysis to quantify the effects of PV grid parity from the single household and the wholesale market perspective in scenario A.[6]

TABLE I
SCENARIO DEFINITION

	A	B
Deployment of PV systems after 2020	Household optimization	System optimization
Expansion of renewables until 2020	Realization of NREAP targets	
Expansion of interconnector capacities until 2030	Realization of TYNDP projects	
Reduction of CO_2 emissions until 2030	60 % (compared to 1990)	

B. Household optimization model

In the first step, a linear optimization model is developed to minimize the annual electricity costs of households, given yearly solar irradiance and electricity consumption profiles, PV and storage system investment costs, residential electricity tariffs and hourly market values of PV electricity generation. The model in turn determines the optimal PV and storage system capacities from the single household perspective – depending on the number of residents living in the house (i) and the location of the house (r) – as well as hourly system performance statistics, including hourly PV electricity self-consumption and grid feed-in profiles.
The annual electricity costs of a household are defined as the sum of the annualized PV system investment costs ($C_{i,r}^{PV}$), the annualized storage system investment costs ($C_{i,r}^{ST}$), the annual operation and maintenance costs ($M_{i,r}$) and the annual costs for the amount of electricity purchased from the electricity grid ($P_{i,r}$). In addition, annual electricity costs are decreased by the revenue acquired from selling PV electricity to the grid ($R_{i,r}$), which is assumed to be remunerated by the market value of PV electricity in the specific hour (p_h^W). The annual electricity costs are minimized subject to several techno-economic constraints. Equation (7) depicts the power balance of supply and demand that needs to be achieved for each point in time. The electricity generation of the household's PV system in a specific hour and region ($G_{h,i,r}^{PV}$) can either be directly consumed by the household ($E_{h,i,r}^{PV}$), sold to the electricity grid ($E_{h,i,r}^{SA}$) or stored in the battery system ($S_{h,i,r}$). At the same time, however, the household's electricity demand in a specific hour and region ($d_{h,i,r}$) needs to be met by electricity supplied by the PV system ($E_{h,i,r}^{PV}$), the storage system ($E_{h,i,r}^{ST}$) or the electricity grid ($E_{h,i,r}^{PU}$) (Eq. (8)). As stated in Equation (9), the power output of a household's PV system in a specific hour and region ($G_{h,i,r}^{PV}$) depends on the solar irradiance on the tilted PV cells in

[6]Note that the cost-efficient development of Germany's electricity generation mix in scenario B is simulated by using the electricity system optimization model. In specific, no iteration with the household optimization model is conducted.

TABLE II
MODEL SETS, PARAMETERS AND VARIABLES

Sets	
$h \in H$	Hour of the year
$i \in I$	Number of residents living in the household
$r \in R$	Region
Parameters	
$a_{h,r}$	Solar irradiance on tilted PV cell [W/m^2]
c^{PV}	PV investment costs [€/kW]
c^{ST}	Storage investment costs [€/kW]
$d_{h,i,r}$	Electricity demand [kWh]
η	Efficiency of the storage [%]
m^{ST}	PV O&M costs [€/kW]
m^{ST}	Storage O&M costs [€/kWh]
p^R	residential electricity tariff [€/kWh]
p_h^W	Market value of PV electricity [€/kWh]
u	Discount rate [%]
ω	PV Performance ratio [%]
$\overline{a}$	Solar irradiance under STC [W/m^2]
t^{PV}	PV lifetime [years]
t^{ST}	Storage lifetime [years]
Variables	
$C_{i,r}$	Total costs [€]
$C_{i,r}^{PV}$	Annualized PV investment costs [€]
$C_{i,r}^{ST}$	Annualized storage investment costs [€]
$E_{h,i,r}^{PU}$	Electricity purchased from the grid [kWh]
$E_{h,i,r}^{PV}$	Electricity supplied by PV system [kWh]
$E_{h,i,r}^{SA}$	Electricity sold to the grid [kWh]
$E_{h,i,r}^{ST}$	Electricity supplied by storage system [kWh]
$G_{h,i,r}^{PV}$	Total PV electricity generation [kW]
$K_{i,r}^{PV}$	Capacity of PV system [kW]
$K_{i,r}^{ST}$	Capacity of storage system [kWh]
$L_{h,i,r}^{ST}$	Storage level [kWh]
$M_{i,r}$	O&M cost [€]
$P_{i,r}$	Costs of purchasing electricity [€]
$R_{i,r}$	Revenue from selling electricity [€]
$S_{h,i,r}$	Storage input [kWh]

the specific hour and region ($a_{h,r}$) and on the performance ratio of the PV cells (ω). The maximum storage level of a household's battery system ($L^{ST}_{h,i,r}$) is determined by the storage capacity ($K^{ST}_{i,r}$) (Eq. (10)), while the hourly change in the storage level of a household's battery system depends on the storage operation in the specific hour and the losses during the charging process (Eq. (11)).

$$\min C_{i,r} = C^{PV}_{i,r} + C^{ST}_{i,r} + M_{i,r} + P_{i,r} - R_{i,r} \quad (1)$$

s.t.

$$C^{PV}_{i,r} = c^{PV} \cdot K^{PV}_{i,r} \cdot \left[1 - \frac{1}{(1+u)^{t^{PV}}}\right] \quad (2)$$

$$C^{ST}_{i,r} = c^{ST} \cdot K^{ST}_{i,r} \cdot \left[1 - \frac{1}{(1+u)^{t^{ST}}}\right] \quad (3)$$

$$M_{i,r} = m^{PV} \cdot K^{PV}_{i,r} + m^{ST} \cdot K^{ST}_{i,r} \quad (4)$$

$$P_{i,r} = \sum_{h \in H} \left[p^R \cdot E^{PU}_{h,i,r}\right] \quad (5)$$

$$R_{i,r} = \sum_{h \in H} \left[p^W_h \cdot E^{SA}_{h,i,r}\right] \quad (6)$$

$$G^{PV}_{h,i,r} = E^{PV}_{h,i,r} + E^{SA}_{h,i,r} + S_{h,i,r} \quad (7)$$

$$d_{h,i,r} = E^{PV}_{h,i,r} + E^{ST}_{h,i,r} + E^{PU}_{h,i,r} \quad (8)$$

$$G^{PV}_{h,i,r} = K^{PV}_{i,r} \cdot \omega \cdot \left[\frac{a_{h,r}}{\overline{a}}\right] \quad (9)$$

$$L^{ST}_{h,i,r} \leq K^{ST}_{i,r} \quad (10)$$

$$L^{ST}_{h+1,i,r} - L^{ST}_{h,i,r} = \left[S_{h,i,r} \cdot \omega\right] - E^{ST}_{h,i,r} \quad (11)$$

Given that the focus of the analysis is on the German electricity market, all country-specific input parameters of the household optimization model – such as the residential electricity tariff, the household's electricity consumption profile and the solar irradiance profile – have been defined according to German levels.

The single households' electricity consumption profiles were derived with the model of domestic electricity use developed in [9], which creates synthetic electricity demand data for 24 hours (with one-minute resolution) through the simulation of domestic appliance use – depending on the number of residents living in the house, the day of the week and the month of the year.[7] The domestic electricity demand model was configured to the use of domestic appliances in Germany based on data from [10], [11], [12] and [13] and run for 8760 hours of the year. Overall, 250 annual electricity consumption profiles were simulated, each differing with regard to the number of residents living in the dwelling (1-5) and the amount of domestic appliances.

The hourly solar irradiance profiles for three different regions in Germany were taken from [14] and converted from a horizontal to a tilted surface.

All other input parameters of the household optimization model are listed in Table III. The input parameters are set to the expected values achievable between the years 2025

TABLE III
ASSUMPTIONS OF THE HOUSEHOLD OPTIMIZATION MODEL IN SCENARIO A

Parameter	
$\overline{a}$	1000 [W/m^2]
c^{PV}	1250 [€$_{2011}$/kWp]
c^{ST}	500 [€$_{2011}$/kWh]
η	95 [%]
m^{PV}	11 [€$_{2011}$/kWp p.a.]
m^{ST}	7.5 [€$_{2011}$/kWh p.a.]
p^R	0.378 [€$_{2011}$/kWh]
t^{PV}	30 [years]
t^{ST}	15 [years]
u^R	3 [%]
ω	75 [%]

and 2030, at which time any direct financial incentives such as solar power feed-in tariffs are assumed to be abolished. However, at this time, the gap between the residential electricity tariff and the LCOE of PV is assumed to have increased to a level resulting in an attractive rate of return from investments in PV and storage system capacities. In specific, PV system investment costs (c^{PV}) are assumed to amount to 1,250 €$_{2011}$/kWp (incl. VAT of 19 %) and the technical lifetime of PV systems (t^{PV}) is assumed to amount to 30 years. Moreover, storage systems are assumed to exhibit investment costs (c^{ST}) of 500 €$_{2011}$/kWh and to have a technical lifetime (t^{ST}) of 15 years.[8] In contrast to the residential electricity tariff (p^R), which is derived by linear extrapolation of current values and assumed to amount to 0.378 €$_{2011}$/kWh,[9] the market value of PV electricity (p^W_h) is endogeneously determined with the electricity system optimization model, which is presented in the next section.

C. Iteration with an electricity system optimization model

From a wholesale market perspective, a large PV penetration and a high share of self-consumed PV electricity generation on the household level causes changes in the load and the provision and operation of power plants. As a result, there is a change in the marginal value of excess (not self-consumed) PV electricity that is fed into the electricity grid. To account for this interdependent relationship, the household optimization model is iterated with an electricity system optimization model.

The electricity system optimization model used in this analysis is an extended version of the long-term investment and dispatch model for conventional, renewable, storage and transmission technologies as presented in [15]. It covers 29 countries (EU27 plus Norway and Switzerland), which can be aggregated to larger market regions to reduce the computational time. The model determines the cost-efficient development of generation and storage capacities and their operation for the time period up to 2030. The objective of the model is to minimize accumulated discounted total system costs while being subject to several techno-economic restrictions, such as the hourly matching of supply and demand, fuel availabilities and potential space for renewable

[7] The domestic electricity demand model is distributed under http://hdl.handle.net/2134/5786 and documented in [9].

[8] The assumptions regarding the storage system reflect expectations for Lithium-Ion batteries.

[9] The residential electricity tariff is assumed to increase by 3 % per year until 2025.

energies as well as politically implemented restrictions such as EU-wide CO_2 emission reduction targets and limited nuclear power deployment.[10]
The simulation of the European electricity markets is carried out as a two-stage process: In the first step, investments in generation and storage capacities are simulated in 5-year time steps until 2030. For each of the years, the model determines both investments in new capacities and decommissionings of existing capacities.[11] The dispatch of capacities is calculated for eight typical days per year on an hourly basis (scaled to 8760 hours), representing variations in electricity demand as well as in solar and wind resources along with their multivariate interdependencies. In the second step, the capacity mix in 2030 is fixed and a high-resolution dispatch is simulated. Instead of typedays, the dispatch is simulated on the basis of hourly load profiles as well as hourly electricity generation profiles of wind and solar power technologies for 8760 hours of the year (based on historical hourly wind and solar radiation data from [14]). Due to computational time constrainst the simulation is run for 9 European market regions, which are considered most relevant for dispatch and investment decisions in Germany. The simulated market regions are depicted in Figure 3.

The results of the electricity system optimization model

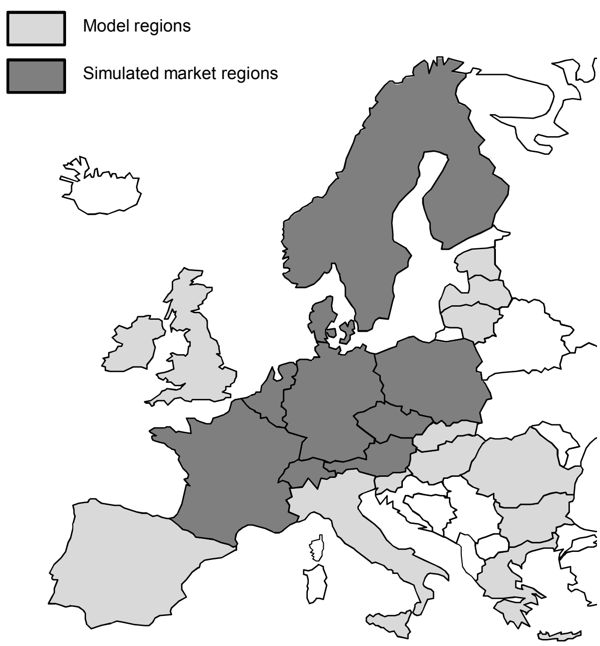

Fig. 3. Simulated model regions

encompass the commissioning and decommissioning of conventional, renewable and storage capacities until 2030, the electricity generation of all technologies and the marginal costs of electricity generation in each hour of the year 2030.

Since the optimal PV and storage system capacities from the single household perspective directly depend on the

[10]Total system costs are defined by investment costs, fixed operation and maintenance costs, variable production costs and costs due to ramping thermal power plants.

[11]All assumptions regarding techno-economic parameters, fossil fuel prices and investment costs of conventional, storage and renewable technologies are based on [16].

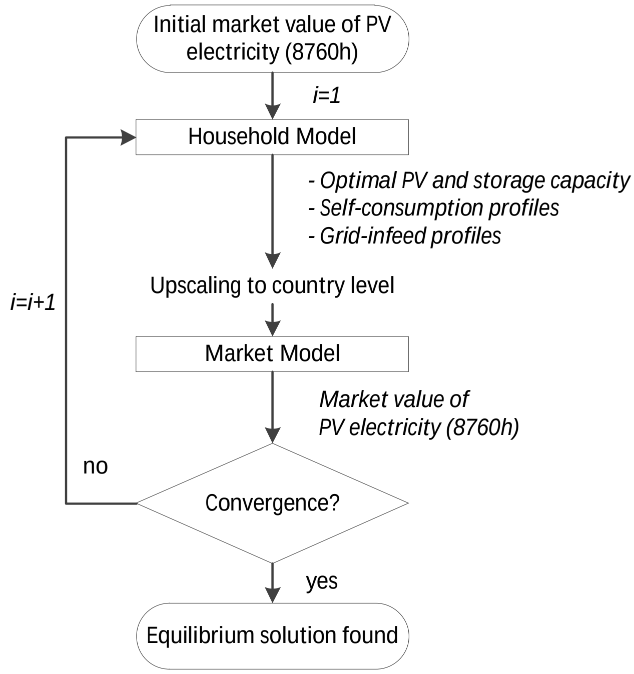

Fig. 4. Schematic representation of the iterative process

marginal value of excess (not self-consumed) PV electricity, the results of the household optimization model are iterated with the results of the electricity system optimization model. Figure 4 shows a schematic representation of the iterative process. Based on an initial market value of PV electricity in 2030 (which was assumed to amount to 0.055 €/kWh in all hours of the year) the household optimization model determines the optimal PV and storage capacities (depending on the number of residents living in the house and the location in Germany), as well as hourly system performance statistics, including the single household's hourly electricity self-consumption and grid feed-in profiles.
To analyze the impact of the single household's optimization behavior on the German electricity market, the results are scaled up to the country level by multiplying the model results with the number of one- and two-family-houses located in Germany (differentiated by the number of residents and the location of the houses). The procedure assumes complete rational behavior and abstracts from the so-called 'landlord-tenant' problem ([17]). Hence, scenario A can be said to depict a situation of 'unconstrained grid parity' in Germany up until 2030.
The upscaled results of the household optimization model – i.e. the household's optimal PV and storage capacities, self-consumption and grid-infeed profiles – serve as input parameters for the electricity system optimization model, which in turn determines the marginal costs of electricity generation in each hour of the year 2030. Given the fact that the marginal costs of electricity generation reflect the market value of excess (not self-consumed) PV electricity generation, the marginal costs of electricity generation are in turn taken as an input parameter for the household optimization model. Specifically, the household's PV electricity generation that is not self-consumed, but rather fed into the electricity

grid, is assumed to be remunerated by the marginal costs of electricity generation – which are determined by the electricity system optimization model.
Based on the new marginal costs of electricity generation – which reflect the market value of PV electricity – the household optimization model determines the optimal PV and storage capacities from the single household perspective. This iterative process is continued until the convergence of results is achieved.

III. Results

Figure 5 presents the development of optimal PV capacities during the iterative process in scenario A, depending on the numbers of residents (1-5) and the location (Southern, Central, Northern Germany) of the household. Optimal PV capacities reach stable levels after only three iteration steps. On average, optimal PV capacities change by less than 1 % in the last iteration step. Other quantities that are subject to change while iterating the two models – such as the optimal storage capacities and the market value of PV electricity – show the same convergent behavior.

Table IV shows the optimal PV and storage system capacities, the share of the household's annual PV electricity generation that is consumed in-house and the share of the household's annual electricity demand that is covered by self-produced PV electricity in scenario A after convergence has been reached (i.e. for iteration step 6). Both optimal PV and storage system capacities increase with the number of residents living in the household. However, the shares of in-house PV electricity consumption (i.e. the share of the household's annual PV electricity generation that is consumed in-house and not fed into the electricity grid) lie within a relatively low and narrow range between 43 % and 46 % for all configurations. Interestingly, households are able to cover 67 % to 77 % of their annual electricity demand by self-produced PV electricity in scenario A, given the optimized PV and storage capacities.

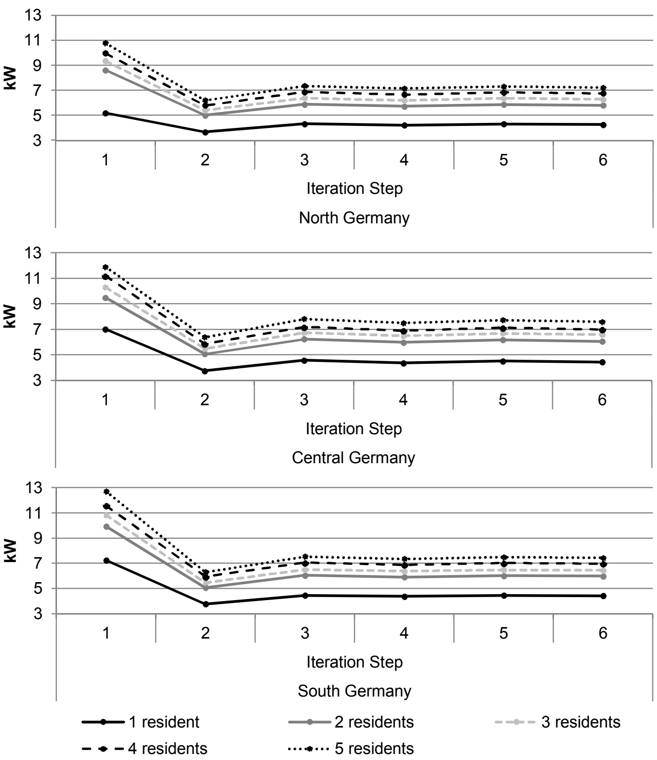

Fig. 5. Development of optimal PV capacities during the iteration in scenario A

Figure 6 shows the average share of the (daily) household electricity demand that can be covered by self-produced PV electricity during summer and winter in scenario A. On average, households are able to cover up to 96 % of their daily electricity demand by self-produced PV electricity in the summer, and up to 80 % in the winter. After having determined the optimal PV and storage system capacities for each single household, results are scaled to the country level by multiplying the optimal residential capacities with the number of one- and two-family-houses located in Germany, differentiated by the number of residents and the location of the houses (Table V) – based on data from [18] and [19].[12] In total, 82 GW of rooftop PV capacities are installed by 2030 in scenario A – in addition to the 52 GW of PV capacities foreseen in 2020 by Germany's NREAP.

TABLE IV
Overview of model results

	North Germany	Central Germany	South Germany
	Optimal PV capacity [kW]		
1 Resident	4.2	4.4	4.4
2 Residents	5.8	6.1	6.0
3 Residents	6.3	6.6	6.4
4 Residents	6.8	7.0	7.0
5 Residents	7.2	7.6	7.4
	Optimal storage capacity [kWh]		
1 Resident	3.3	3.4	3.9
2 Residents	4.4	4.5	5.1
3 Residents	4.9	5.1	5.7
4 Residents	5.2	5.5	6.1
5 Residents	5.5	5.7	6.4
	Share of in-house PV electricity consumption [%]		
1 Resident	45%	43%	45%
2 Residents	45%	43%	45%
3 Residents	45%	43%	45%
4 Residents	45%	44%	45%
5 Residents	46%	44%	45%
	Household demand coverage by PV electricity [%]		
1 Resident	67%	71%	75%
2 Residents	67%	71%	76%
3 Residents	68%	72%	76%
4 Resdients	68%	72%	77%
5 Residents	68%	73%	77%

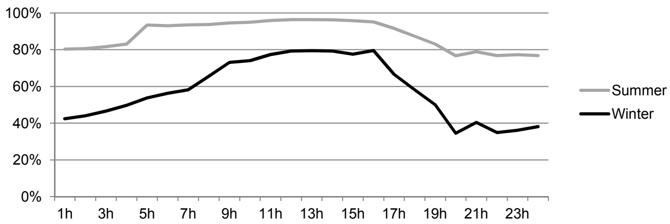

Fig. 6. Average daily residential electricity demand coverage by self-produced PV electricity in Germany in 2030

[12] To account for the fact that part of the rooftop potential of one- and two-family-houses will already be used to achieve commitment with Germany's NREAP target for photovoltaic in 2020 (52 GW) only 90 % of the one- and two-family-houses have been used for the upscaling.

TABLE V
NUMBER OF ONE- AND TWO-FAMILY-HOUSES LOCATED IN GERMANY

	North Germany	Central Germany	South Germany
1 Resident	927,873	2,019,445	130,7012
2 Residents	1,401,861	2,736,602	1,736,486
3 Residents	587,329	1,129,975	714,979
4 Residents	545,935	1,047,263	662,260
5 Residents	190,168	362,654	229,064

Storage capacities built in combination with these rooftop PV facilities amount to 65 GWh, corresponding to 160 % of currently installed pump storage capacities in Germany (40 GWh in the year 2010).

As shown in Figure 7 and Figure 8, high shares of in-

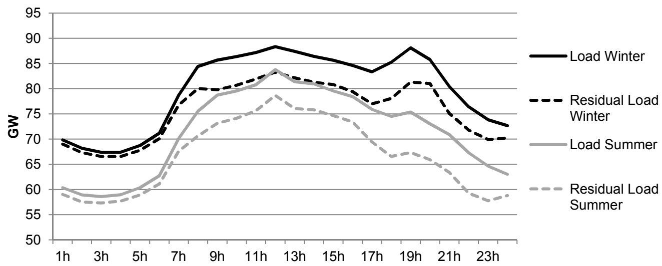

Fig. 7. Average (residual) load on weekdays in the summer and the winter in Germany in 2030

house PV electricity consumption on the single household level cause significant changes in the load supplied by the wholesale electricity market (residual load) in scenario A.[13] On average, the load supplied by the wholesale electricity market on weekdays decreases by up to 12 % in the summer, and by up to 8 % in the winter due to in-house PV electricity consumption. Interestingly, the highest load reduction on weekdays occurs in the evening hours – due to the in-house consumption of PV electricity that was stored in the battery system during the day. However, since Figure 7 and Figure 8 show the average load reduction on weekdays during summer and wintertime, it cannot be concluded that peak load is reduced. For such a conclusion, specific instances in time would need to be analyzed in detail. This is subject to further research.

The partial optimization of the single households (induced

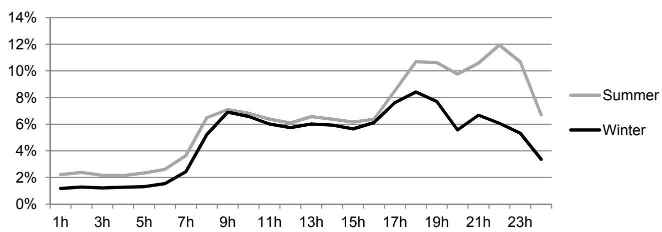

Fig. 8. Average load reduction on weekdays through in-house PV electricity consumption in the summer and the winter in Germany in 2030

by PV grid parity) in scenario A leads to significant excess costs. In comparison to scenario B – which assumes no partial optimization of the single households but instead a total system optimization – accumulated and discounted total system costs increase by 7.1 bn €$_{2011}$ up until 2030. This massive increase in total system costs is caused by the fact that investments in rooftop PV systems and small scale storage technologies (such as lithium-ion batteries) on the single household level do not depict a cost-efficient investment option in Germany before 2030. Instead of rooftop PV and small scale storage systems, wind onshore (plus 7 GW) and gas capacities (plus 9 GW) are deployed in scenario B up until 2030. Furthermore, 11 GW of ground-mounted PV systems are installed as a cost-efficient option in Southern Germany after 2025 in scenario B.[14]

IV. CONCLUSIONS

Our model-based analysis has shown that the rapidly growing gap between the residential electricity tariff and the LCOE of PV may lead to considerable investments in rooftop PV systems and storage capacities for in-house PV electricity consumption in Germany up until 2030. Given our scenario assumptions, 82 GW of rooftop PV systems are installed by 2030 in addition to the 52 GW of PV capacities foreseen by the German NREAP for 2020. Accumulated household storage capacities built in combination with these PV facilities amount to 65 GWh, corresponding to 160 % of currently installed pump storage capacities in Germany.

The optimal dimensioning of the PV and storage capacities from the single household perspective allows on average 72 % of the household's annual electricity demand to be covered by self-produced PV electricity.

The single household's optimization behavior entails direct consequences for the wholesale market, as it changes the residual load both in volume and structure. In terms of volume, residential demand for electricity decreases dramatically, thus leading to significant revenue shortfalls for conventional power plants. In addition, more than half of the total PV electricity generation on the household level is fed into the electricity grid.

Overall, the indirect financial incentive induced by PV grid parity leads to massive excess costs of 7.1 bn €$_{2011}$ until 2030, due to the fact that rooftop PV and small scale storage systems are not a cost-efficient investment option from a total system perspective until 2030.

Further research will check the robustness of the results by performing sensitivity analyses, specifically with respect to both residential electricity prices and investment costs (of both PV and storage systems). Moreover, specific effects of increased in-house PV electricity consumption will be investigated in more detail, such as the impact of PV generation on peak demand levels or on the future development of the capacity mix. It would be particularly interesting to analyze the consequences of PV grid parity for other EU member states where solar resources as well as electricity pricing systems are different than those in Germany.

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[13] In this analysis, the term 'residual load' corresponds to Germany's total electricity demand (load) without the accumulated in-house PV electricity consumption on the household level.

[14] Note that the ground-mounted PV systems are assumed to have 10 % lower investment costs than roof-mounted PV systems due to economies of scale.

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