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Modelling Dynamic "PV Parity" in different European Countries

G. Lettner and H. Auer

Abstract-- **By increasing market shares and decreasing cost of photovoltaic (PV) in recent years, the future point of time of competitiveness of PV for the European energy system will be a more interesting question. The competitiveness of PV is referred to as "PV Parity", i.e. the "Levelized Cost of Electricity" (LCOE) of PV is compared according to market participants and market segment of the energy system with the traditional cost factors. Through a dynamic economic analysis of the PV system over its lifetime compared to a conventional energy system, the "PV Parity" is reached when the PVaddition of PV to the electricity supply decreases the overall price of the electricity consumed. By sensitivity analysis of the influence parameters of the LCOE of PV and developing of scenarios of future price a window of time or framework conditions for different European countries for achieving the "PV Parity" for different market participants can be determined.**

***Index Terms*-- Different Customer Groups, Dynamic Modeling, Levelized Cost of Electricity Generation (LCOE), Load Profiles, Photovoltaics (PV), PV Parity, Wholesale/Retail Electricity Price**

I. Introduction

In recent years, market shares of electricity generation from photovoltaics (PV) have been growing continuously. As a result of that, significant cost decreases of the PV technology have been observed (technological learning). This leads to an increased competitiveness of PV generation in comparison to remaining electricity generation technologies (both conventional and renewable) when using levelized cost of electricity generation (LCOE) as a benchmark. In general, LCOE describe the economics of a technology on an aggregated level (i.e. annual basis) only. Due to the variable/intermittent characteristics of PV electricity generation (e.g. day/night characteristics), however, different challenges have to be taken into account when integrating the PV technology into electricity systems where electricity generation and demand have to be met simultaneously at each point in time. Nonetheless, the gradient of LCOE development of PV generation is expected to open a wide range of different applications of this technology in different market segments in the future. In this context, the household customer always has been playing an important role when considering the implementation of decentralized PV technologies. And as a consequence of that, already in the past the retail electricity price (i.e. the end-users electricity bill/statement) always has been some comparative parameters of the LCOE of PV generation. Straightforward, the term "PV Grid Parity" has been established in recent years; in its static definition the determination of the point in time in the future when the trade-off of the retail electricity price and LCOE of PV generation is reached (see e.g. [1]). This definition, however, lacks twofold (see e.g. [2]): (i) there is no dynamic consideration of the dynamic development of different parameters, and (ii) nothing is said about the net present values (NPV) of the economics of PV generation when considering different revenue streams (e.g. self-consumption (reduced electricity purchases from the grid and therefore reduced electricity bill) versus selling into the grid), on the one hand, and cost of PV generation, on the other hand. In this paper, different interpretations of fully dynamic definitions of "PV Parity" over the lifetime of PV generation plants are modeled for different customer groups (taking into account different characteristic load profiles) and utilities in different European countries.

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Georg Lettner is with Vienna University of Technology – Institute of Energy Systems and Electrical Drives - Energy Economics Group (EEG), Vienna University of Technology, Gusshausstrasse 25-29, 1040 Vienna Austria (email: lettner@eeg.tuwien.ac.at)

Hans Auer is with Vienna University of Technology – Institute of Energy Systems and Electrical Drives - Energy Economics Group (EEG), Vienna University of Technology, Gusshausstrasse 25-29, 1040 Vienna Austria (email: auer@eeg.tuwien.ac.at)

II. Methodology

A. Definition "PV Parity"

To determine the "PV Parity", an economic cost comparison of a market participant with PV and a market participant without PV is made. As a basis for this economic cost comparison are the "Levelized Cost of Electricity" (LCOE). For systems that primarily produce electricity to be consumed elsewhere, the LCOE is compared with the electricity production costs for the different power generation technologies. For a consumer, for example a household, the LCOE is comparable with the retail electricity price. For the calculation of future LCOE for PV technologies, a variety of different boundary conditions and assumptions about the future development of several important parameters (e.g. specific cost, efficiency, etc.) is required. To carry out the economic cost comparison, the development of future Wholesale-/Retail-Electricity-Prices and other technology options that affect the load profiles of different customer groups (e.g. increase their self-consumption through the implementation of additional storage technologies) must be considered.

- **Dynamic "Grid Parity"**

PV generation can be partially or completely replace the current consumption. This is commonly referred to as "PV Grid Parity" because the economic comparison with the current retail electricity price (= generation costs & grid costs & taxes) is made. The conditions for the competitiveness of PV generation, savings on end-users electricity bill by self-consumption and revenues through feeding PV generation into the grid.

- **Dynamic "Wholesale Price Parity"**

PV generation compensates few or no electricity consumption at all. In this case, the PV generation is competing with the wholesale electricity price on the energy market.

- **Dynamic "Fuel Parity"**

PV generation is in competition with a specific power generation technology but cannot entirely replace it. For example, island grids that rely on power generation by diesel engines may replace some of the capacity with PV but not all. Some of the diesel generation (or other generation) needs to be retained to cover the times when the intermittent PV generation is down.

These three different "PV Parity" definitions can be applied mainly to four different market participants:

– Households < 5 kWp
– Commercials < 100 kWp
– Industries < 500 kWp
– Utilities > 500 kWp

The 3 "PV Parity" definitions are not for any of the above market participants relevant or useful. The "Grid Parity" is relevant for rooftop installed or building-integrated PV systems for households, commercials and industries. Commercial or industrial facilities with low power consumption and for power utilities, which are operating with ground-mounted systems, the "Wholesale Price Parity" and in exceptional cases (e.g. island grid), the "Fuel Parity" is decisive. In individual cases, the "Fuel Parity" is of interest to households.

B. Mathematical Approach

1) Levelized Cost of Electricity for PV

By calculating the "Levelized Cost of Electricity" (LCOE) can be the specific costs of a PV system in €/Wp, which are common in the PV industry, transform into the usual specific costs for the energy industry in €/kWh, see (1).

$$LCOE_{PVSystem,i} = \frac{CAPEX_i + OPEX_i}{EP_i} \qquad i = 1,2,...,N \tag{1}$$

$$CAPEX_i = C_{Invet} \cdot crf \qquad for\ i > n : CAPEX_i = 0 \qquad n \leq N \tag{2}$$

$$crf = \frac{WACC \cdot (1+WACC)^n}{(1+WACC)^n - 1} \tag{3}$$

$$WACC = \frac{E}{E+D} \cdot k_E + \frac{D}{E+D} \cdot k_D \cdot (1 - s_C) \tag{4}$$

$LCOE_{PVSystem,i}$	Levelized Costs of Electricity per year in €/kWh
$CAPEX_i$	CAPitel Expenditure per year in €
$OPEX_i$	Operational Expenditure per year in €
EP_i	electrical energy yield per year in kWh
C_{Invest}	Investments in €
crf	capital recovery factor
WACC	Weighted Average Cost of Capital
E	equity in €
D	debt in €
k_E	return of equity
k_D	return of debt
s_C	corporate tax rate
N	lifetime of the PV-System
n	depreciation time of the PV-System

2) Calculation of annual cost of different "PV Parity" definitions

Depending of market participants and the application of the corresponding "PV Parity" definition, there are different approaches for calculating to achieve the parity of PV systems with and without storage technologies.

- **Dynamic "Grid Parity"**

The dynamic "Grid Parity" is the most complex of the 3 "PV Parity" approaches. The special load profile of the market participant and the specific generation profile of PV systems (day-night characteristics and difference by irradiance-winter-summer) three different situations to be generated for the energy system of the prosumer (= producer and consumer):

1. <u>External procurement from the grid (term 1 in (5)):</u>

During the night there will be no PV generation, therefore must be gather the required energy from the grid. However with the use of storage technologies, the share of external procurement from the grid may be reduced or substituted. The cost of external procurement is determined by the retail electricity price and the savings from their self-consumption or storage of PV generation.

2. <u>Self-consumption and storage (term 2 in (5)):</u>

By fluctuating PV generation during a day, the external procurement from the grid can be replaced partially or completely by the PV generation. If the PV generation is higher than the load, the surplus energy can be feed into the grid (see item 3) or be saved if a storage technology is available. The cost for their self-consumption without storage is determined by the LCOE of PV system and energetic self-consumption. If a storage technology used, the LCOE of PV system and the LCOE of the storage system should be considered general, this leads to overall higher LCOE of PV and storage system. These higher LCOE and the resulting changes in self-consumption (additional reduction of the external procurement in the night) then determine the costs

3. <u>Feed into the grid (term 3 in (5)):</u>

The higher the capacity of installed PV power system, the higher is the maximum of the PV generation. If the PV generation is higher than the possible self-consumption or storage potential, the surplus PV generation is feed into the grid, provided that it is also possible. By feeding into the grid revenues can be gain, the feed amount of electrical energy is compensated by a market price. Market prices can be fixed feed-in tariffs, green premium tariffs or the "wholesale" price. A reduction of the total cost of the energy system for the prosumer receives only, if the LCOE of PV system or rather the LCOE of PV and storage system is smaller than the achieved market price.

The net present values of annual cost of a market participant who had installed a PV system or alternatively PV and storage system is described in (5).

$$\begin{aligned} NPVof\,C_{PVSystem,i} = {} & p_{\mathrm{Re}\,tail,i} \cdot \left(Demand_i - Selfconsumption \,\&\, Storage_i\right) + \\ & + LCOE_{PVSystem,i} \cdot Selfconsumption \,\&\, Storage_i + \\ & + \left(LCOE_{PVSystem,i} - p_{Market,i}\right) \cdot Feedin_i \end{aligned} \tag{5}$$

$NPVof\,C_{PVSystem,i}$ Net Present Value of the cost of the PV system per year in €

$Demand_i$ annual electricity demand in kWh

$Selfconsumption\&Storage_i$ annual self-consumption and storage of the PV generation in kWh

$Feedin_i$ feed into the grid in kWh

$p_{Retail,i}$ annual retail electricity price in €

$p_{Market,I}$ annual market price of the feed into the grid PV generation in €/kWh

The net present value of annual costs for market participants without a PV system are calculated from the annual retail electricity price and the annual consumption, see (6).

$$NPVof\,C_{withoutPVSystem,i} = p_{\mathrm{Re}\,tail,i} \cdot Demand_i \tag{6}$$

Fig. 1, shows an example of the comparison of a typical household load profile compared to a PV generation profile for a summer day without additional storage technology. The installation of a storage technology can be reduce or completely substitute the share of the external procurement from the grid on a summer day, see Fig. 2. Depending on storage capacity, it may then come to a feed into the grid of PV generation or not. On winter days, the PV generation by the lower irradiation intensity and the shorter hours of sunlight is correspondingly low, so only a small share of PV generation can to be feed into the grid, see Fig. 3. If a storage technology is used in the PV system, in the winter days a low share of the external procurement can be reduced during the night by the PV generation. The surplus of the PV generation is not more feed into the grid, but rather is saved in the storage technology, see Fig. 4.

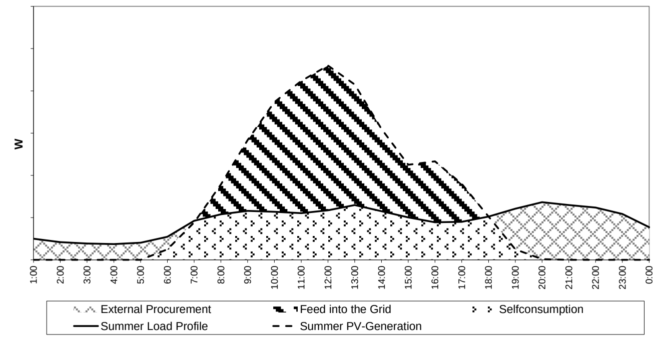

Fig. 1. Example of household electricity profile relative to the PV generation in the summer WITHOUT storage technology

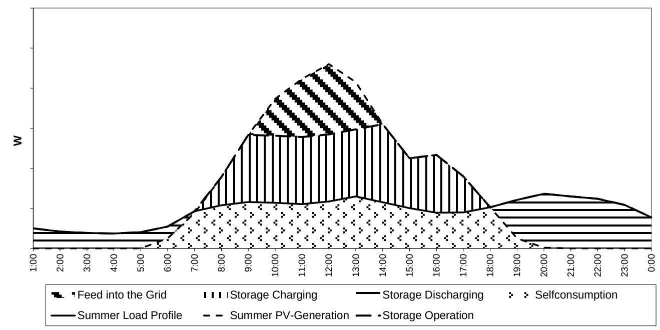

Fig. 2. Example of household electricity profile relative to the PV generation in the summer WITH storage technology

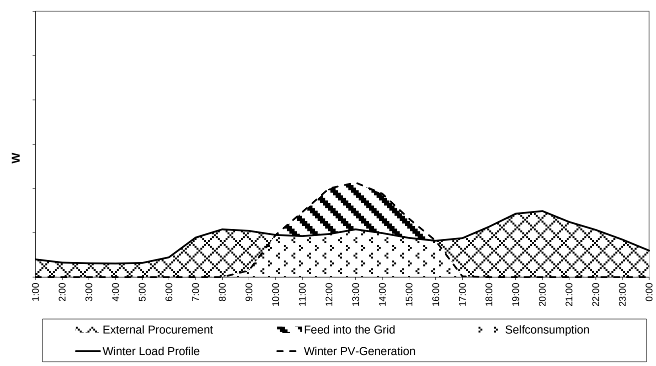

Fig. 3. Example of household electricity profile relative to the PV generation in the winter WITHOUT storage technology

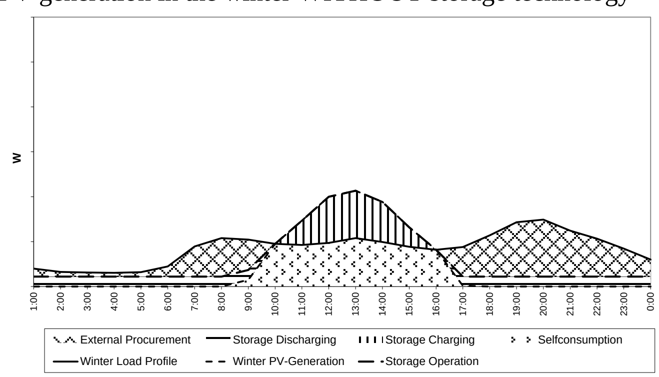

Fig. 4. Example of household electricity profile relative to the PV generation in the winter WITH storage technology

- **Dynamic “Wholesale Price Parity”**

When looking at the "Wholesale Price Parity" is the market price, the LCOE of PV system and the corresponding PV generation, the decisive parameters. If the market price is higher than the LCOE of the PV system, can make revenues/profits. The market price falls below the level of the LCOE of the PV system, losses are generated. The market price could be a spot market price, a hedged forward price or something else. Schematic illustration of the profit and loss areas of the PV generation for summer and winter are shown in Fig. 5 and Fig. 6.

The net present value of annual costs for market participants with a PV system are offering on a market price is described in (7) and (8).

$$NPVof\,C_{PVSystem,i} = CAPEX_i + OPEX_i - \mathrm{Re}\,v_i \tag{7}$$

$$\mathrm{Re}\,v_i = \sum_{t=1}^{8760} Gen_{PVSystem,i,t} \cdot \left(p_{Market,i,(t)} - LCOE_{PVSystem,i}\right) \tag{8}$$

$$t = 0, 15', 30', 45', 1h, 1h15', \ldots, 8760h$$

Rev_i	annual revenues from the PV generation on the electricity market in €
$Gen_{PVSystem,I,t}$	15 minute PV generation per year in MWh
$P_{Market,I(,t)}$	electricity market price (on spot market in 15 minute) per year in €/MWh

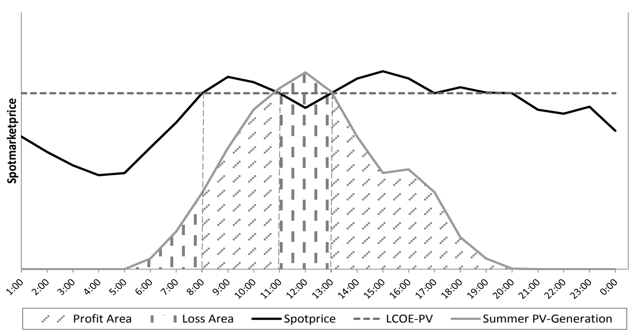

Fig. 5. Schematic illustration of the profit and loss areas at the "Wholesale Price Parity" on a summer day

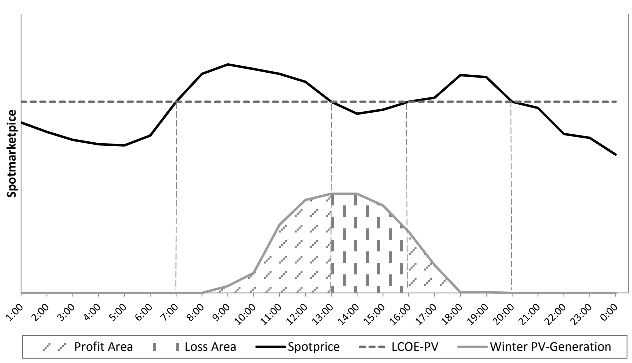

Fig. 6. Schematic illustration of the profit and loss areas at the "Wholesale Price Parity" on winter day

- **Dynamic "Fuel Parity"**

The dynamic "Fuel Parity" compares the required fuel cost of an already existing thermal power generation unit (diesel / oil, gas, biomass, etc.) with and without an installed PV and / or storage system to cover the load in an island (network) for operation. This "PV Parity" definition is similar to the "PV Grid Parity", but not the current retail electricity price is the main comparison parameter, but rather the current electricity generation cost of an existing thermal power unit, that is the fuel cost. On the one hand, on summer days the surplus of the PV generation without or insufficient storage is not used and is lost in the worst case, see Fig. 7. On the other hand, on winter days the PV system, with and without storage, cannot cover the load completely, hence the use of the existing power unit is required, see Fig. 8. An optimal size of the PV system with and without storage technology is therefore one of the most important prerequisites for achieving the "Fuel Parity".

The net present value of annual cost of the electricity demand of a market participant with a PV system on an island (grid) are calculated as the share of generation of the thermal power and the share of PV generation and storage according to (9).

$$NPVof\,C_{PVSystem,i} = \frac{p_{Fuel,i}}{\eta_{el}} \cdot \left(Demand_i - Selfconsumption\,\&\,Storage_i\right) + LCOE_{PVSystem,i} \cdot Selfconsumption\,\&\,Storage_i \tag{9}$$

The net present value of annual cost of the electricity needs for a market participant without a PV system are calculated with the annual fuel cost and the annual demand, see (10).

$$NPVof\,C_{withoutPVSystem,i} = \frac{p_{Fuel,i}}{\eta_{el}} \cdot Demand_i \tag{10}$$

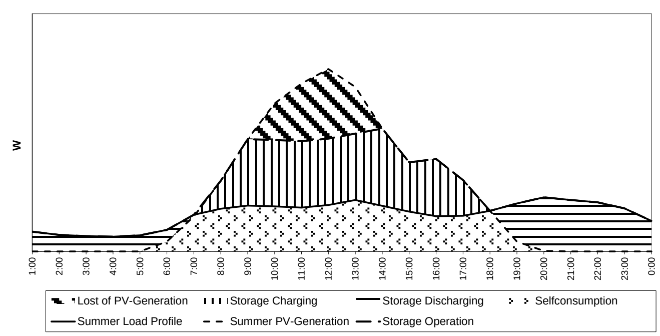

Fig. 7. Schematic illustration of the supporting load coverage of PV generation on a stand-alone operation on a summer day

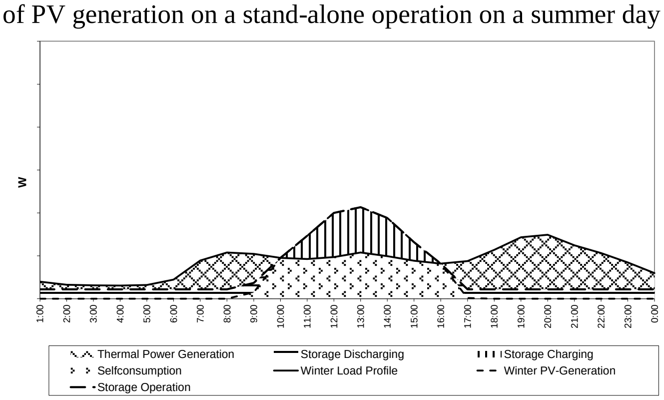

Fig. 8. Schematic illustration of the supporting load coverage of PV generation on a stand-alone operation on a winter day

3) *Economic Trade-Off Approach*

To achieve the "PV Parity" the annual net present value of costs for different "PV Parity" definitions over the lifetime of the PV system are cumulated and afterwards an economic "trade off" criterion is used.

- **Dynamic "Grid Parity"**

The dynamic "Grid Parity" is achieved, if the cumulative annual net present values of the cost of a market participant with a PV system, with or without storage technology, that is less than the cumulative annual net present values of the cost of a market participant without a PV system, see (11).

$$\sum_{i}^{N} NPVof\,C_{PVSystem,i} \leq \sum_{i}^{N} NPVof\,C_{withoutPVSystem,i} \tag{11}$$

- **Dynamic "Wholesale Price Parity"**

To achieve the "Wholesale Price Parity" for a PV system, the cumulated annual net present values of the cost of a market participant is less than zero, see (12). Negative cost means that are revenues/profits can be achieved and therefore the PV system is economical.

$$\sum_{i}^{N} NPVof\,C_{PVSystem,i} \leq 0 \tag{12}$$

- **Dynamic "Fuel Parity"**

As described in Section 2, the cost calculation for a market participant for the "Fuel Parity" is similar to the "Grid Parity". The economic "trade off" criterion is even identical, so (11) is also valid for the "Fuel Parity".

III. Future Scenarios and analysis

In calculating the LCOE have a variety of parameters (e.g. PV system prices, depreciation time, WACC, efficiency, etc.) influence. To determine the future PV system prices and the efficiency can be derived through experience curve of learning rates from the past years. Other parameters such as amortization period, WACC, fiscal conditions, etc. by a Monte Carlo simulation vary sufficiently and this results in a certain bandwidth of future LCOE of PV systems. By different sensitivity analysis under the ceteris paribus clause the influence of different parameters is shown. Future retail, wholesale and primary energy prices will be defined in different scenarios, and thus also results in a certain bandwidth of prices. The cost and trade off analysis is done with the edge and average values of the different bandwidths of parameters.

IV. Results

Due to the natural heterogeneity of sun irradiation and artificial heterogeneity of markets in Europe, of different electricity prices and of PV system prices for various European countries different bandwidths of LCOE, of electricity prices and of PV system prices are obtained. By the bandwidth, defined by each scenario and parameter analysis, the LCOE, the electricity prices and PV system prices will determine a possible window of time or rather framework conditions can be achieved in various European countries in which the different "PV Parity" definitions. This dynamic model is being developed in the project "PV Parity", funded by the Intelligent Energy Europe (IEE) Programmed of the European Commission and empirically scaled. Concrete results are expected in the next few months and will be presented in future national and international conferences. First preliminary results of the "Grid Parity" in the household sector are shown in Fig. 9 and Fig. 10. It is shown the cumulated NPV of the costs from a household with and without a PV-System. In the first model simulation the "Grid Parity" is reached in 2016 with a PV-System price of 2358,- Euro and in the second simulation in 2017 with a PV-System price of 2155,- Euro. The most important differences between the first and the second simulation are the system size, the market price for feed into the grid and the annual increase of the retail price. At a higher market price is a larger PV system size economical than with a lower market price. The economic efficiency of the PV system depends trivially on the growth of future electricity prices, which clearly shows the two preliminary simulations.

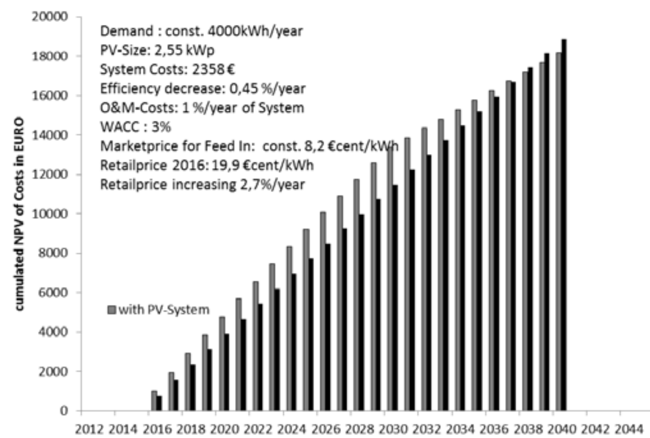

Fig. 9 Monte-Carlo_Simulation 1: Preliminary Result of "Grid Parity" for a Household Austria.

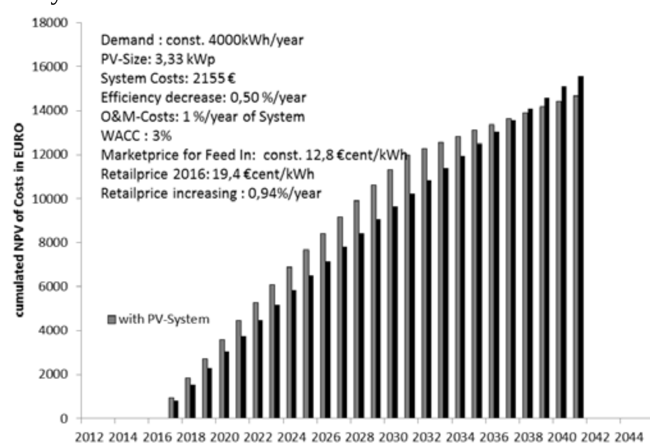

Fig. 10 Monte-Carlo_Simulation 2: Preliminary Result of "Grid Parity" for a Household in Austria.

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VI. BIOGRAPHIES

Georg Lettner was born in Braunau (Austria), on May 9, 1978. He is an electrical engineer. Since February 2009 he has been working as a junior researcher at Vienna University of Technology, Energy Economics Group (EEG). His major fields of research are grid and market integration of DG/RES-E technologies and the development of tailor-made simulation software models.

Hans Auer was born in Schmirn (Austria) on March 26, 1969. He is senior researcher at Vienna University of Technology, Institute of Energy Systems and Electrical Drives - Energy Economics Group (EEG). He joined EEG in 1995. Hans’ main research interests are electricity market analyses in general and grid and market integration policies of DG/RES-E technologies in this context in particular. In the last 16 years, Hans has been involved in many international and national projects in the renewable field for a variety of different clients. He has comprehensive teaching experience, a significant amount of energy conferences contributions worldwide and also authored around 40 peer reviewed scientific papers and book contributions.