



12th INTERNATIONAL CONFERENCE ON THE EUROPEAN ENERGY MARKET

Lisbon, 19-22 May 2015 | Portugal



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Optimizing Neighborhood Consumption of Renewables through Clustering and H₂ Storage: An Economic Assessment of an Austrian Community

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Abstract — Renewable energy sources make the matching of production and storage in the electric grid a major challenge. Aside of introducing additional storage the possibility of on-site consumption of renewable energy is a valid option. The system boundary is not necessarily a single building, but may consider neighborhoods of buildings, which can be clustered in order to maximize use of local generation. Clusters of producers and consumers achieve a higher on-site consumption ratio and thereby show economic advantages. This is shown in a scenario where clustering of consumers connected to common a PV plant increases the discounted cash flow significantly, making it economically viable without subsidies. For additional benefits also the effect of Demand Side Management (DSM), short and long term storages are investigated.

Keywords — data integration; distributed power generation; energy consumption; renewable energy sources; solar energy

I. INTRODUCTION

Decentralized, fluctuating renewable energy sources make the matching of production and consumption in the electric grid a major challenge. This paper describes an attempt to optimize the neighborhood consumption of renewables in three ways (clustering, DSM and storages) and evaluates the options economically. The goal is to increase the share of fluctuating renewables, reduce the electricity export outside of the community and increase the economical return on investments for renewable energy production.

In this case, the neighborhood consists in an actual, rural Austrian municipality with 1200 inhabitants and a per capita high share of distributed PV production. In addition, the municipality owns detailed energy profiles of their communal buildings and renewable production. The town consists of 140 buildings and has 14 solar power plants in a range between 1.8 kWp and 12.6 kWp including a 72 kWp one.

The work in this paper is funded by the Austrian Research Promotion Agency (FFG) within the 4th call of “Haus der Zukunft Plus” program, project number 3685488, project name “Eigenlastcluster”.

The options investigated in this paper are the clustering and identification of suitable energy consumers, implementation of demand side management measures, usage of short term lithium battery systems and seasonal hydrogen storages. Such clustering can be the identification of e.g. a large PV installation and two relatively large businesses. It can be argued that clusters of producers and consumers only change the local system boundary and do not increase the total share of renewables. However, changing the system boundary has the effect of increasing the plant specific on-site consumption thus making the investment more economically viable. This in turn can lead to a higher share of renewables, however limited by the overall penetration of renewables. Due to the overall small share of PV generation in relation to the total consumption in Großschönau this limitation was not part of the investigation.

The next section describes the relevant state of the art followed by Section III, which gives an overview on the methods that were employed leading to the results of Section IV. The conclusion in Section V shows a positive economic impact through combining various PV plants and consumers.

II. STATE OF THE ART

Fluctuating renewable energy sources in micro grids have been examined [1] towards their ability to be balanced by demand showing significant potential in electrical heating. Klobasa et al. [2] take a look at the integration of wind power, develop DSM strategies and argue that the key factor according to a sensitivity analysis is the accuracy of the wind forecasts. In [3] the authors look from the perspective of buildings towards an energy management of energy neighborhoods and employ a model-based approach to optimize consumption and production on neighborhood level. Load control and demand side management approaches are described in [4][5]. The authors model the available potential as virtual power plants, which allow them to see load shifting potential as actual production. [6] and [7] focus on the economic aspects in liberalized markets and the expectable revenues. The effort for dynamic thermal modeling, which is a tool to improve the prediction

quality of expected consumption, is covered, for example, in [8] and [9].

In the residential sector, an attempt was made to shift deferrable loads such as washing machines, dryers, and dish washers in order to achieve PV self-consumption optimization with the use of storages. The concept was simulated and then implemented on a prototype solar house, equipped with grid connection, PV generation, lead-acid batteries, controllable appliances and smart metering [10]. In another study [11] a DSM control algorithm was developed in order to test the hypothesis that meteorological data forecasting promotes the efficiency of a grid-connected smart home concept. The main objective of the study was to keep the developed smart home running with its renewable energy sources as long as possible, utilizing the information of power forecasts, electricity tariffs and by load shifting. The results obtained from the simulation studies show that a good compromise between the renewable energy production and household energy consumption is achieved with the help of flexible demand as well as the prediction method.

III. METHODOLOGY

The identification of suitable clusters requires the available (monitoring) data to be processed, the PV generation to be simulated and the storages and DSM to be modeled. Finally, the clusters are assessed economically to quantify the effect of clustering.

A. Monitoring Data Preparation

The goal is to have individual energy consumption profiles for each building in Großschönau in 15 minute resolution of generated origin where no monitoring data is available.

The available data that has been collected in previous research projects consists of monitoring data for mostly public buildings and data gathered from a survey in 2010 containing information about e.g. total electric energy consumption, electric domestic hot water provision, PV installations etc.

Due to the disperse nature of the data access, transformation, validation and analytics is performed in Konstanz Information Miner (KNIME), an open source platform for data analytics, reporting and data integration. The usage of such software assists the data access of over 89 individual files with monitoring data and the joining of survey data with synthetic load profiles.

Analysis revealed not only missing samples in the monitoring data but also steady state conditions such as daily energy consumption being the same for subsequent days. As it is highly unlikely to have the exact same energy consumption in subsequent days it is assumed that missing data is carried forward to fill gaps by the monitoring system. Validity of resulting profiles is ensured through comparing survey data with yearly sums of generated data.

B. PV Systems

Due to the lack of detailed monitoring data of PV installations their energy profiles had to be generated. The output power of a photovoltaic module is given by (1), where n is the efficiency of the photovoltaic cell, A is the total area of

the photovoltaic panels in m^2 and S_{module} the solar irradiation in W/m^2 that reaches the panel.

$$P = n * A * S_{module} \quad (1)$$

Inputs of the model developed are global solar irradiation and temperature, provided for the year 2012 in 15 minutes resolution and PV panels' characteristics; size, material, orientation, inclination. A set of cascading equations form the PV model and result to the calculation of the power output.

The energy produced each day for the time period of 345 days is depicted in Figure 1 and compared with the measured data. The PV plant at hand has 10 kWp, consisting of 54 inclined panels with an inclination angle of 35° and south-east orientation. The model corresponds to the real measurements except from a deviation between the simulation and the measured data the first months of the year and some outliers in August. Weather phenomena, like snow or fog which are not taken into consideration in this physical model as well as losses of measurement data or faulty measurements result to peaks in the comparison diagram. The total error of the PV model is 0.83% when excluding the faulty measurement data.

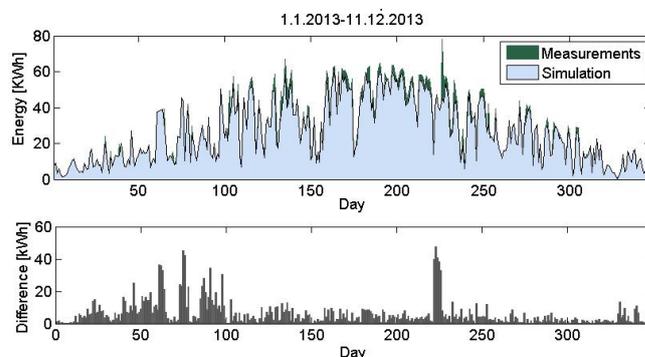


Figure 1. Photovoltaic energy produced from a 10 kWp installation. Comparison between simulation and measured data

C. Battery Modell

The battery model is based on the Fronius Symo Hybrid Inverter and the Fronius "Energiezelle" H_2 storage technology. In the hybrid inverter a modular lithium ion battery is used with capacities of 3.2, 6.4 and 9.6 kWh. The Energiezelle is capable of converting electric energy to H_2 with an efficiency of 50 % and back with 60 %. The model consists therefore of two different parts modeled with MATLAB:

- The chemical battery model; It implements the capacity, the charging losses, discharging losses and the self-discharge losses, but without considering aging effects.
- The H_2 storage model; here are also the losses while charging and discharging included. At the moment the leaking losses are not considered, since they need further investigation.

In order to test and simulate the batteries, ten measured profiles of Austrian households and the profiles of the PV modeling are applied to the simulation. As control scheme a simple energy balancing method is used: If more energy from

PV is available, the left over energy is stored in the storages and if less energy is available, the energy is released from the storages. Figure 2 shows an exemplary output of the storage model.

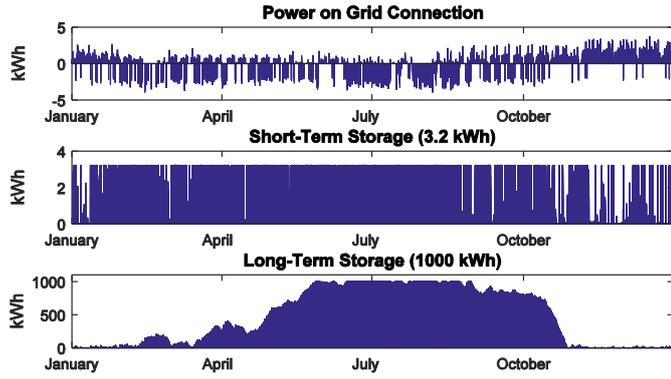


Figure 2. Output of the Storage Model. The results shows the combination of two consumers (3.700 kW/year and 1.700 kW/year) and PV (5 kWp).

D. Demand Side Management

DSM is defined as the adaptation of the electricity consumption on the consumer side, including load shedding and shifting, to energy production rate and prices. DSM is also used to mitigate the variations in production of renewable energy, like PV and in that way to maximize local consumption, to minimize energy transfer and thus losses and to protect the electricity network from overload. In this work, the focus is on maximization of self-consumption.

The general principle is that after merging the consumption profiles of the specific region into clusters and assigning to each cluster a suitable PV profile (see E), it is attempted to shift the time of operation of some controllable loads in the residential and commercial sector as visualized in Figure 3.

For the DSM in the residential sector, first we had to distinguish between deferrable and non-deferrable loads, assume a typical consumption and the time of operation during the day. According to literature research [10], [12], [13] washing machine, dryer and dishwasher are the most common deferrable loads, with a share of 15 % of the total daily load. In this study we chose to shift the share of 10 % and 5 % of these controllable loads, from the typical operation time (morning and evening hours), to the time span of maximum photovoltaic production (usually around noon) as seen in Figure 3.

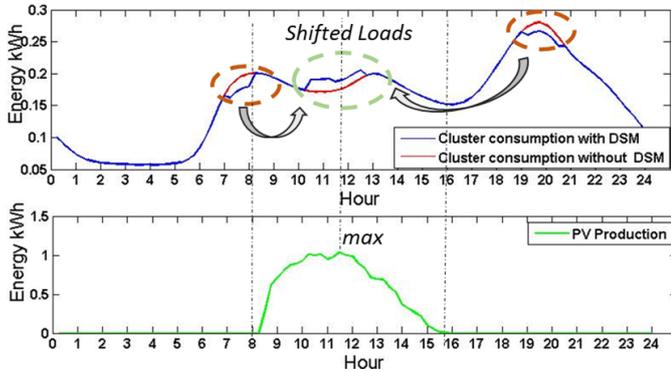


Figure 3. DSM results on cluster 5 (residential sector) on 12.01.2012

For the commercial sector, usual deferrable loads are Heating, Ventilation and Air Conditioning (HVAC) loads, which commonly have a share of 30 % over the total consumption of a commercial building. The flexibility of these loads varies during the day from 30 % - 100 %. Therefore an amount of 9 % - 30 % of the total consumption of a commercial building can be shed during the operation time [14]. Here, a safe amount of 5 % was shed from 08:00 - 20:00.

E. Clustering Consumers and Producers

The principle idea of the clustering method is the minimization of the energy fed into the grid. The calculations refer to the year 2012, so 366 days are to be considered. The consumption profiles are identified as positive and the generation as negative, according to the product of current flow and voltage at a hypothetical single point of connection to the grid. The first step is to compute all possible combinations by the binomial coefficient. The number of available profiles is 98 and each cluster is defined to consist of three consumption profiles (\vec{p}_1 , \vec{p}_2 and \vec{p}_3) with a single photovoltaic power plant (\vec{p}_{PV}). The power plants are sorted in descending order according to production.

$$N = \binom{N_p}{N_c} = \binom{98}{3} = 152096 \quad (2)$$

$N_p = \text{Available Consumption Profiles}$

The profiles are then stored in a matrix (3) as combinations without repetition.

$$\begin{bmatrix} \vec{p}_{1,1} & \cdots & \vec{p}_{3,1} \\ \vdots & \ddots & \vdots \\ p_{1,N} & \cdots & p_{3,N} \end{bmatrix} \quad (3)$$

The profiles used in already formed clusters (4) are removed from the pool and N_p is reduced by N_c .

$$\vec{p}_k = [\sum_{k=1}^N \vec{p}_{1,k} + \vec{p}_{2,k} + \vec{p}_{3,k} + \vec{p}_{PV}] \quad (4)$$

The energy fed into the grid (5) is represented as negative value; therefore the best cluster formed has the absolute minimum sum of negative values.

$$P_{cluster} = \min (\sum \vec{p}_1 (\leq 0), \sum \vec{p}_2 (\leq 0), \dots, \sum \vec{p}_k (\leq 0)) \quad (5)$$

This process is repeated for each PV plant and therefore nine clusters are identified to have the best fit i.e. the highest own consumption.

F. Parameters for Economic Evaluation

For the economic evaluation one specific cluster setting is presented within this paper. This cluster consists of a PV-plant (10 kWp) operating agricultural load profile (total yearly electricity consumption of 12.7 MWh) which is combined with 2 other agricultural load profiles (13.1 and 11.7 MWh/a). In order to calculate discounted cash flow (DCF) values (after taxes and duties) for the operator of this exemplary load cluster/PV-combination the following parameters were chosen:

- Evaluation period of 25 years

- Self-consumption tariff of 12.5 cents/kWh for commercial customers (excl. taxes, yearly increase by 2 %)
- Grid export revenues of 6 cents/kWh (excl. turnover tax, average value)
- PV installation cost of 1620 €/kWp
- Yearly PV running cost of 1.5 % (of investment cost)
- Weighted Average Cost of Capital (WACC) = 3 % (high own capital share)
- Average inflation rate = 2.5 %
- Taxes and duties rate of 50 % for the cluster operator

Yearly costs are calculated as the sum of capital (annuities after taxes) and running cost (increased by inflation rate per year). Yearly revenues are the product of self-consumption (in kWh) and the corresponding tariff (increased by 2 %/year) as well as grid exports revenues at a contracted tariff. Future cost and revenues are then summed up and discounted according to the chosen discounting rate. For a detailed description of the discounted cash flow method see [15].

IV. RESULTS

A summary of how the electric consumption is distributed across various consumer groups is seen in Figure 4. The consumer groups are expressed in APCS standard profiles with G denoting commercial, H households and L agriculture [16]. The numbers express subgroups therein. As can be seen, the largest consumer group is households H0 with 29% of total energy consumption in 2012, followed by agriculture L0.

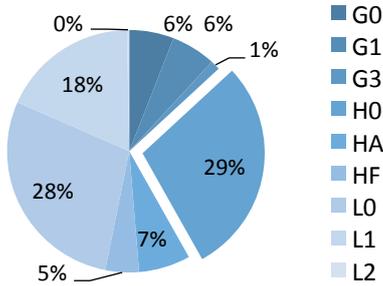


Figure 4. Distribution of total energy consumption 2012

Großschönau has a lower electricity demand during summer months with 57.4 kW to 188.4 kW and a mean of 120.9 kW in July and 76.1 kW to 238.3 kW during winter months and a mean of 153.2 kW in January. This clearly shows the need of seasonal storage in a potential scenario of high PV penetration that can be provided by e.g. a battery or hydrogen (H₂) storage system.

A. Economic Impact due to Clustering of Loads

As described above, the presented economic results reflect a cluster of different agricultural loads as well as generation of a 10 kWp PV-plant. To calculate the daily grid exports of the PV plant on the one hand the PV generation unit is first solely combined with the operating agricultural load. In a second calculation the PV plant is combined with the analyzed cluster (using two agricultural loads). If this cluster is implemented, the self-consumption rate increases to about 94 % compared to

a situation without clustering (52 %). Compared to that it would be necessary to decrease the PV-plant size to about 3.2 kWp in order to achieve a similar self-consumption rate. However, this smaller size would lead to higher PV-plant cost due to economies of scale effects (higher cost shares of inverter technology and installation efforts).

Corresponding to the chosen cluster setting, the development of discounted cost, revenues, the DCF as well as cumulated DCF are presented in Figure 5. If no clustering is applied the overall DCF values sum up to about -4000 €.

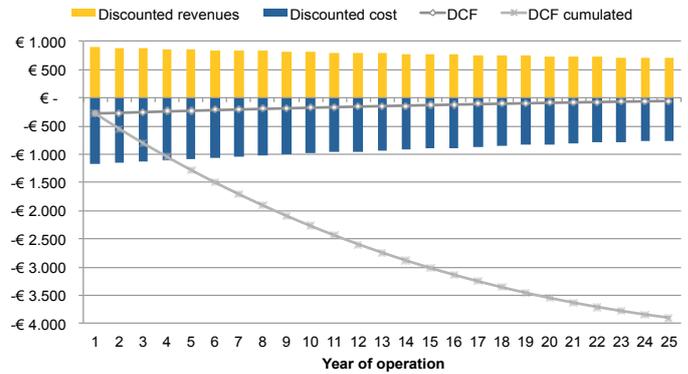


Figure 5. DCF development if no clustering is applied.

This shows that under chosen market and self-consumption conditions the operation of a PV-plant at this size is not economic if no further subsidies are eligible. In contrast, the chosen cluster increases the yearly DCF value to about 2000 € after taxes as shown in Figure 6.

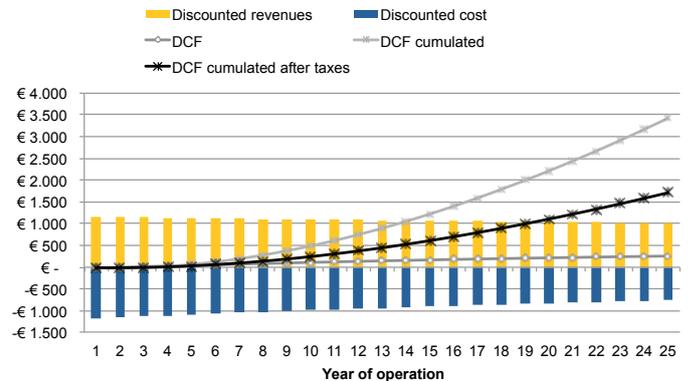


Figure 6. Yearly DCF values after taxes if clustering is applied.

The increasing of the system's boundary through clustering increases the plant specific self-consumption by about 42 %, leading to significant economic advantages.

B. Long Term and Short Term Electrical Storage

The storage system by Fronius allows for further increase of self-consumption. Ten household profiles and the nine most important PV plants were fed into the simulation. In order to get comparable results, every household was combined with every PV plant. This led to a self-consumption indicator SC_1 as calculated in (6) with $E_{GridDemand}$ as the energy used from the grid and $E_{OverallDemand}$ is the energy needed in the household.

$$SC_I = 1 - \left(\frac{E_{GridDemand}}{E_{OverallDemand}} \right) \quad (6)$$

Table 1 shows the results of the simulations: The smaller the indicator the lower the self-consumption of the PV and vice versa. The mean factor of self-consumption of clusters without storages is about 0.56. In other words, 56 % of the energy needed by the households was produced at the same time as it was needed. With the use of only battery storages the factor can be improved to 0.90 in case of a 9.6 kWh battery. The improvements with the use of the H₂ storage technology is slightly better. The combination of both technologies yields to higher self-consumption. However, to get 100 % of coverage is nearly impossible, because of the maximum of storable energy within time. The reason is that the maximum of deliverable energy of the system is exceeded by the demand itself. The combination of both systems will result in a maximum of 7 kW. So if the demand is greater than this value, additionally energy from the grid is needed. This has to be covered by DSM to get the 100 %. The measured household did also not intentionally consume energy when the PV produced energy.

TABLE 1. COMPARISON OF BATTERY AND H₂ STORAGE SIZES

SC ₁		H ₂ storage			
		0 kWh	400 kWh	800 kWh	1200 kWh
Battery storage	0 kWh	0.57	0.87	0.89	0.89
	3.2 kWh	0.82	0.92	0.93	0.94
	6.4 kWh	0.88	0.93	0.94	0.95
	9.6 kWh	0.90	0.94	0.95	0.95

V. CONCLUSION AND OUTLOOK

We have shown that the clustering of electric consumers and producers is beneficial for the amount of energy consumed on-site and for the financial revenue of the operator or owner. The necessary calculations for such a virtual cluster require detailed electric profiles, which are not always available in the required quality.

From an economic perspective, future village, city and electricity grid design should promote clustering of suitable consumers in a user acceptable way. Newly built multi-family houses could be planned mixed use with e.g. offices and prepared for shared PV installations. This could lead to higher cost- and energy system efficiency due to higher self-consumption rates, decreased grid losses and optional economies of scale effects for PV-installations.

With the use of storage systems the degree of self-consumption and self-sufficiency of buildings or clusters can be increased even further. Short-term-storage-systems, in this case a lithium battery storage, manages to increase cluster self-consumption from 57 % to 82 % for a 3.6 kWh storage. However, performed calculations showed for all analyzed clusters that storage options are not economic at current market conditions. A seasonal energy storage system manages to further increase own consumption to 92 % for a 400 kWh storage. Due to the fact that H₂ storage is an expensive option and its very early market stage, it does not seem to be an economical option for households and clusters at current

conditions. These changes with falling investment costs as well as increasing share of fluctuating energy production from renewable sources. Also 100 % coverage is only possible with short term storage, seasonal storage and DSM.

Results will likely change as the resolution of profiles is increased. Investigations into the magnitude of this effect, as well as into the effect of increasing the share of PV would be interesting in further studies. The study could be extended by other (special) load profiles and considering the geographical distribution, too. Finally, a demonstration site could validate results and uncover further challenges such as technical, social and legal aspects.

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