Residential versus Communal Combination of Photovoltaic and Battery in Smart Energy Systems

Marczinkowski, Hannah Mareike; Østergaard, Poul Alberg

Published in:
Energy

DOI (link to publication from Publisher):
10.1016/j.energy.2018.03.153

Publication date:
2018

Document Version
Early version, also known as pre-print

Residential versus Communal Combination of Photovoltaic and Battery in Smart Energy Systems

Hannah Mareike Marczinkowski*[a], Poul Alberg Østergaard[b]

[a] Department of Planning, Aalborg University, Rendsburggade 14, 9000 Aalborg, Denmark,
e-mail: hmm@plan.aau.dk

[b] Department of Planning, Aalborg University, Rendsburggade 14, 9000 Aalborg, Denmark,
e-mail: poul@plan.aau.dk

This draft presents work that was preliminarily introduced at the 12th SDEWES Conference, Dubrovnik, October 4-8, 2017 and later submitted, reviewed and published in Energy: https://doi.org/10.1016/j.energy.2018.03.153
It presents work that is supported by the ERA-Net Smart Grids Plus through the project MATCH (Markets – Actors – Technologies: A comparative study of smart grid solutions) as well as by the Horizon2020 research programme through the project SMILE (SMart IsLand Energy systems) under the grant agreement no. 731249.

Highlights

- EnergyPLAN simulations of residential and communal batteries in combination with PV
- Residential PV and battery set-up enables higher self-supply and customer involvement
- Communal battery set-up leads to higher share of electricity fed to the grid
- PV and batteries improve demand side management, balancing and production planning

Abstract

This paper presents an analysis of small consumers' involvement in smart island energy systems with a focus on the technical feasibility of photovoltaic (PV) systems in combination with batteries. Two approaches may be observed in the literature: the optimization on a household level with the aim of being self-reliant versus coordinated and collective technologies with increased integration across sectors and energy carriers. Thus, for household systems, the placement of a battery – whether aggregated or residential – creates the basis for this investigation. The study is based on the case of the Danish island Samsø for which the two battery approaches are simulated using the energy system simulation model EnergyPLAN. Results indicate a tendency towards aggregated batteries being more favourable from a systems perspective – while on the other hand, residential batteries are more motivating and involving the consumers. The importance of minimizing flows to and from the grid as a result from fluctuating energy sources is addressed in both approaches. While residential batteries improve the individual household electricity supply, a communal battery would further regulate other inputs and demands.

* Corresponding author

Keywords

Photovoltaic, battery, smart energy system, residential versus communal regulation, demand side management

1. Introduction

Europe has ambitious energy targets with a 40% CO_2 emission reduction before 2030 with respect to 1990 levels [1]. The electricity sector, being a key element in the energy system, will need to play a key role in meeting this reduction target, thus a modernization of the electricity system is required and as part of this, flexible smart energy systems are explored in academia [2], [3]. In addition, while an increasing influx of fluctuating renewable electricity production combined with a growing electricity demand from the transport and heating sector stresses the load-following capability of the electricity system, the very same technologies in a coordinated smart energy system approach can in fact help establish balances between production and demand and reduce problematic peak demands. Main technological solutions for this approach include wind power [4], [5], photovoltaic (PV) [6], [7], power-to-heat [8], [9], power-to-gas [10], [11] and battery technologies [12], [13].

The role of battery systems in smart energy systems are also focal point in e.g. the ERA-Net Smart Grids Plus project MATCH [14], which investigates the involvement of small consumers in electricity generation and balancing of the grid (prosumers). Micro-generation though e.g. PV systems, and storage technologies, for example home batteries, are main aspects of the analysis. The European Union Horizon2020 project SMILE (SMart IsLand Energy systems) [15], also addresses the role of batteries, PV systems and more with the aim to provide grid stability and flexibility for islands.

Targeting the various problems that the energy sector is expected to be facing, the projects focus on smart energy systems and their development in small communities, islands and regions. Here, the question arises, which direction the development should take: to communal and common technological solutions and operation or to the demand side and individual technologies and management. Taking a point of departure in the ideas of these projects, the options of communal versus individual contribution to the energy system are investigated on the exemplary case of Samsø.

The island Samsø is known for being Denmark's Renewable Energy Island in terms of testing and demonstrating sustainable energy solutions [16]. Samsø has been involved in various development projects since 1997 and in both the MATCH and the SMILE project, which have a focus on PV and battery technology. These technologies are addressing the possibility of small consumer involvement, as well as the idea of integrating smart energy technologies for stability and flexibility. The PV/battery combination is but one out of many potential energy technology combinations, but it opens up for the interesting question of a communal vs. a residential approach. By analysing these two development trajectories on a Scandinavian island, local conditions are considered and discussed.

Samsø has already been studied extensively in the academic literature, however mainly from an implementation perspective. Sperling [17] used Samsø as a case to show how an energy transition is carried out, stressing the importance of *"intensive processes of sensing and priming linked to the* *local population"* in terms of ensuring that the transition projects are anchored locally. Likewise, Mey & Diesendorf [18] investigate community renewable energy projects in Denmark using Samsø as a case, finding amongst others that "*shared identification and objectives that go beyond environmental and technology motivations"* have been for instrumental for action on such projects.

A certain body of work also address the nexus between technology options and implementation, with Möller et al. [19] using Samsø as a case for testing their so-called *Energy SWOT* (Strengths Weaknesses Opportunities Threats) approach for planning islands energy system transitions, taking into consideration different settings of different islands. Lin et al. [20] investigate eight islands including Samsø, finding that transitions should be based on "*efficiency improvements on renewable generation, the design of energy storage systems, and possible energy savings on the demand side"*. In a review of a series of remote villages and islands including Samsø, Neves et al. [21] find that current energy system design, storage systems and demand profile are main factors in reaching high RES shares. Pasqualetti & Stremke [22] compare the resulting literal landscape of different energy strategies, with Samsø having a "Complex energy landscape" with the "use of more than two technologies within a particular landscape". Finally Soshinskaya et al. [23] analyse a number of energy islands with respect to barriers to micro grids of a technical, regulatory, financial, and stakeholder nature, where Samsø was identified as a successful case as it already provides renewable electricity back to the mainland.

The world holds a very large potential for solar energy, which Korfiati et al. [24] estimate at a global technical potential of 613 PWh/y compared to a global electricity demand of approx. 20.2 PWh/2015 [25]. A substantial body of literature is available on PV systems and the combination of PV systems and batteries. Much of the literature probe into the technical workings of the combination including grid stability and power quality analyses. Batteries may be used to increase the self-consumption in PV systems, as noted by Buß et al. [26], and as such, a large body of literature focuses directly on reducing grid reliance, with Hanser et al. [27] finding that *"distributed PV-battery systems as a means to offset but not totally circumvent grid electricity consumption is practical."* using an American case. In another American case, Kantamneni et al. [28] investigate PV/battery systems in Michigan, finding that the combination is in fact competitive against grid electricity – and further elaborates that prices or policies are to be changed in order to prevent *"mass-scale grid defection"*.

Bertsch et al. [29] analyse the investment in household PV systems with batteries, finding that such systems may decrease grid electricity uptake by 75% in Germany and 65% in Ireland, however, only focusing on "*PV and storage systems from a household perspective"*. Khalilpou & Vassallo [30] investigate the feasibility of batteries in grid-connected PV systems in Australia, finding that only low-cost batteries are feasible – though there is a strong sensitivity to solar radiation, electricity prices, system costs and system specifications. In other work by Khalilpou & Vassallo [31], the authors find it is infeasible to leave the grid due to costs, but also find that it is optimal to minimize grid purchases.

Ogundari et al. [32] assess the feasibility of off-grid PV/battery systems in a situation where grid power is not a viable option due to insufficient capacity and grid stability. Thus, they compare to a diesel generator alternative, finding that the former has significantly less costs seen over the lifetime of the system than the latter. The listed analyses do not compare different battery alternatives, but only look into the distributed PV/battery combination. Tomc & Vassallo [33] on the other hand compare a number of PV/grid/battery strategies including a) systems with individual residential storage at a household level, and b) individual storage as well as a shared common storage. The authors find that *"the largest improvement in grid independence results from the installation of solar systems with storage on each individual dwelling"* – and thus see grid independence as a positive result to be attained. While [33] focuses on two Australian cities, other articles also concentrate on the correct integration and management of PV/battery on the household level, such as Wu et al. [34], instead of evaluating the possible implications on a system level. PV and batteries could contribute greatly to smart energy systems instead of aiming for optimisation on a local scale. Its importance is pointed out by a number of articles dealing with the problems of integrating local PV systems into the grid, specifically PV penetration issues by Karimi et al. and supply and demand problems in relation to PV-EV systems [35], [36]. Motalleb at el. [37] on the other hand already discuss the optimal placing and sizing of batteries under consideration of transmission and distribution networks, but exclude the additional impacting factor of PV power production.

Concluding, there is no detailed modelling of the energy systems into which the distributed or common PV/battery combinations are included, neither in the Australian case nor in any of the other reviewed work. The relations to other influences on the electricity grid, as well as interconnected sectors, is not further studied in the work that has been reviewed for this article. A more holistic energy system analysis of Samsø would therefore complement the research on PV and battery application and its possible contribution to a smart energy system.

This article investigates two options for PV/battery combinations. In both options, PVs are installed at individual households, however in the one option, these are supplemented by batteries in the individual households, while in the other batteries are communal. The overall system's effects of the two are investigated using the hourly simulation tool EnergyPLAN. In Section **Error! Reference source not found.**, the approaches and applied tools are introduced. After the presentation of the required data, Section 3 sums up the scenario development in the resulting scenario description. All relevant numbers for the analysis and the underlying reference model can be found there. The results on both approaches are presented in Section 4. After detailed presentation of the case of residential and the case of communal batteries, the consequential comparison and discussion follows in Section 5. Conclusions are drawn in Section 6; after which acknowledgements and references follow.

2. Methods

This section presents the two approaches taken to investigate the PV/battery combinations. The modelling tool EnergyPLAN, which is used to evaluate the approaches, is presented afterwards. Finally, the hourly simulations and considerations to realise the analysis are explained, including the hourly data that are used.

2.1 The two approaches of regulation

The analysis of PV systems is based on two alternatives. In the first, the produced electricity is directly used to supply the household's demand and surplus feeds a home battery system, which is discharged to supply the homes when the PV production is not sufficient to meet demand. Any additional production is fed to the grid. In the second, the produced PV electricity is supplied directly to the common grid and the communal battery is operated according to overall system requirements, and thereby also affected by other productions and demands not on PV fitted households. The communal battery has the same aggregated capacity as the home batteries combined. These approaches are presented in Table 1.

Table 1. Overview of approaches in the analysis of PV and batteries

	Approach 1: Batteries at residential households	**Approach 2: Communal battery**
Description	Households are equipped with PV panels and batteries.	Households are equipped with PV panels. Batteries are communal.
PV Sizing	PV sizing is fixed to standard installation sizes. This number is not seen from the overall energy systems analysis model where rather the demand is modified according to production and battery charge/discharge.	PV sizing is fixed to standard installation sizes. This number is modelled in the overall energy systems analysis model as any other grid-connected capacity.
Battery sizing	Standard installation sizes.	Standard installation sizes.
Operation strategy of batteries	Battery systems are operated under a strict priority 1: Demand covered by PV 2: Demand covered by battery 3: Demand covered by grid 1: PV production covers demand 2: PV production charges battery 3: PV production is fed to the grid	Batteries are operated according to overall energy system needs as determined by EnergyPLAN subject to all productions and demands in the system with a focus on avoiding or reducing critical excess electricity production
Hourly demand distribution	A composite is constructed where the profile for individual households is changed according to how the individual households are seen from the grid including effects of PV and batteries. The un-altered demand profile of individual households is the same as for the common battery case	A composite distribution file for Samsø based on hourly panel date for a variety of consumer types along with known annual aggregates for these consumer groups.
Electricity demand	The electricity demand entered into the energy system analyses model is reduced by the amount of electricity that goes straight from PV to demand in individual households and batteries.	No modification in demand

Figure 1 show the two approaches of placing the battery residentially or communally with one building representing the total amount of households included. The rest of the diagrams represent the island's energy system with the import/export possibility connecting it to the mainland. Other renewable energy sources (RES) includes wind power and other PV installations that are included in the energy systems analyses but not further discussed. While the first approach has a battery interacting solely with the household, the second has a battery placed to interact with the whole electricity grid. The impact of electricity transmitted is demonstrated in Figure 1 with smaller line widths to and from the grid for the Approach 1; the Approach 2 would not have an impact on the amount of electricity to and from the grid.

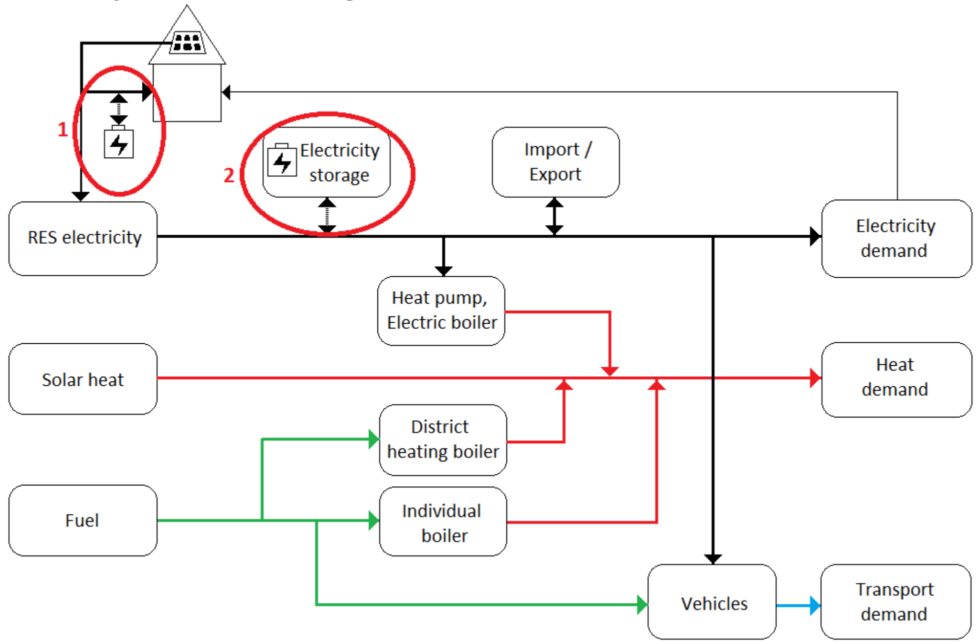

Figure 1. Schematic overview of Theoretical Approaches 1 and 2

2.2 EnergyPLAN

The EnergyPLAN model is used to simulate the electricity, heating, cooling, industry, and transport sectors of an energy system [38]. It simulates each sector on an hourly basis over a one year time horizon and can be used on various levels and sizes of energy systems, as previously pointed out by Østergaard [39]. Further, Østergaard points out that EnergyPLAN fulfils the requirements for integrated energy modelling, such as for modelling relations of PV and battery systems in an energy system and that EnergyPLAN has been widely used in the academic field. It has been used at all scales from continental analyses [40], over national systems [41] to cities and islands [42], [43]. It is intended for the simulation of user-defines systems as opposed to endogenous investment optimisation [44].

The model simulates the mix of technologies in the whole system by identifying and utilizing synergies across the sectors. This makes modelling of fluctuating energy sources such as wind and solar possible, and simulates their effect on the rest of the energy system. Depending on the inputs, such as technology capacities, efficiencies, and costs, as well as the demand and supply of the investigated project – here of Samsø – various simulations become possible.

EnergyPLAN operates with either a market economic or a technical operation strategy. With the market economic simulation the focus is on the most feasible operation of a given energy mix. This strategy is focused on optimising the given system's behaviour against an electricity market with dispatchable units able to increase production if export is favourable or decrease if import is favourable. The technical operation strategy focuses on the technical optimal operation of the energy system in terms of fuel use and load-following capability. Import and export only occurs if required from a technical perspective.

The technical simulation is chosen for the simulation of PV and battery systems in this case for two reasons. First, while the market economic operation strategy alters import and export to the system, the technical strategy allows to investigate the more physical import/export response to systems changes. Secondly, for wider implications beyond the immediate case, hourly price variations that are very specific for a certain time and place will make results less transferable.

In regards to electricity storage, EnergyPLAN models these with a capacity to and from the storage, efficiencies to and from the storage and a maximum storage contents. In the technical regulation strategy, the storage is only filled during times of critical excess electricity production (excess that cannot be exported with the given interconnection capacity) and is drained to replace import and condensing mode power generation [45].

A reference scenario functions as basis for comparisons, simulating the current energy system with its demand, supply and individual specifications. This scenario is adjusted to fit to the reference year 2015, which can be compared to scenarios that include the additions of PV capacity or battery. These additions are simulated in a separate spreadsheet model and its results combined with EnergyPLAN, since the impact on the households cannot be evaluated separately in the complete system analysis EnergyPLAN performs. The following analysis must be understood as technically optimal, neglecting economic aspects – and therefore deviating from realistic cases in these regards. The results from EnergyPLAN can be presented through e.g. primary energy supply (PES) and RES shares, CO_2 emissions, or import/export balance.

2.3 PV model with and without battery

The simulation of electricity production from PV and its use is done in a spreadsheet model. As the Approach 1 in Table 1 shows, it follows certain priorities and restrictions. Based on hourly demand profiles and PV productions profiles, the model covers demands directly as a first priority. Any excess feeds the battery, taking the charger efficiency into consideration and maximum charging power. Excess beyond this is fed to the grid. When demand exceeds PV production, batteries are discharged taking maximum discharge power and converter efficiency into consideration. Any remaining deficit is met using grid supply.

For the model, hourly distribution files of demand and supply, as well as characteristics of the PV and the additional battery system are required. Additionally, the building register of Samsø influences the model through the numbers on relevant buildings suitable for these approaches. The result is a modified distribution profile of electricity demand that is used in EnergyPLAN. This modified electricity demand distribution file gives the residual demand after the effects of PV and battery for households.

The following distribution profiles, which are presented further in the following, are required as a base for the hourly calculations:

- Hourly PV electricity production
- Hourly electricity demand of Samsø
- Hourly electricity demand of residential households

Hourly PV production

Regarding the appropriate hourly PV distribution, a comparison of profiles and sources is made. First, solar radiation measurements from CFSR (*Climate forecast system reanalysis*) was extracted [46], secondly, national PV production data was downloaded from [47], thirdly, data from Samsø Energy Academy was requested [48], and all three are reviewed for suitability. The former was disregarded due to missing information in relation to PV production simulations, for which temperature influence and PV system specification, besides other information, would be needed. The national data was neglected, since the data included more than the island Samsø and thus contains strong geographical flattening of the data. Finally, locally measured PV production data for a whole year was provided from Samsø Energy Academy.

Figure **2** shows the production of this ca. 100 m² PV system, which is installed at a 50° angle facing nearly south at 184°.

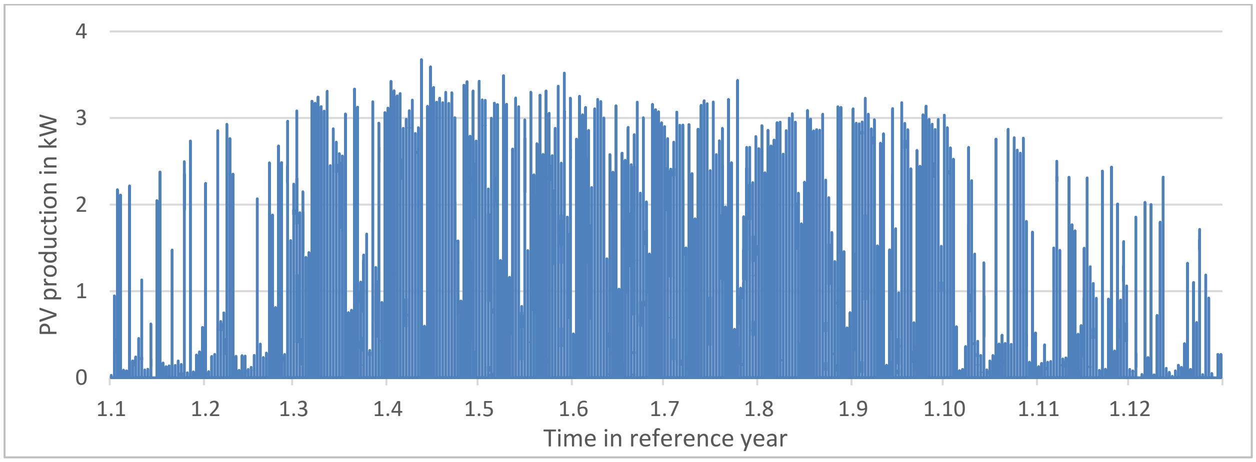

Figure 2. PV production in 2015 at Samsø's Energy Academy as reference for PV electricity production

Hourly electricity demand

The electricity demand of Samsø is simulated with the energy balance of Samsø for 2015 [49] and a study on temporal electricity demand profiles [50]. With the energy balance, various consuming sectors, such as households and businesses, can be made out, which are connected to the specific profiles that apply to Samsø. With a total of 25.5 GWh annually, the biggest demand sector is the residential. All sectors and their shares are presented in Figure 3.

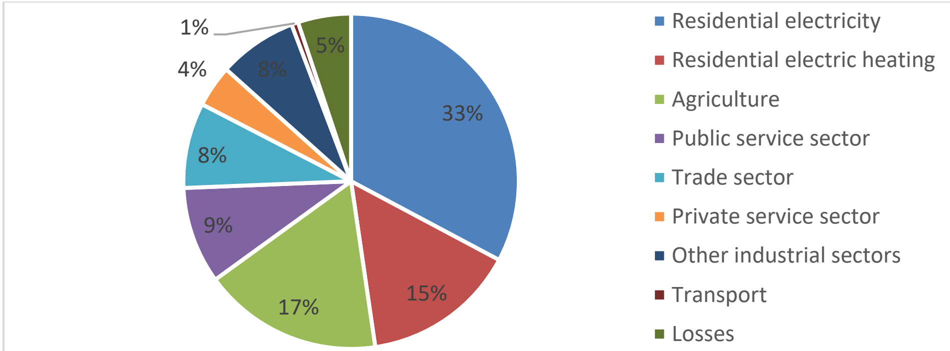

Figure 3. Distribution of the electricity demand Samsø. The total is 25.5 GWh/year.

Figure 4 presents the annual profile of Samsø's electricity demand for 2015, including separate data for residential households, which are being more closely investigated in this analysis. The residential electricity demand is made up of direct use of electricity, e.g. for lighting and appliances, and electricity used for heating, using heat pumps or other electric heating devices. The demand profile of electricity for heating is simulated based on the outside temperatures for 2015 on Samsø and a typical heating season for space heat, which explains the comparably low demands from June 1st to August 31st, when these electric devices are providing merely hot water.

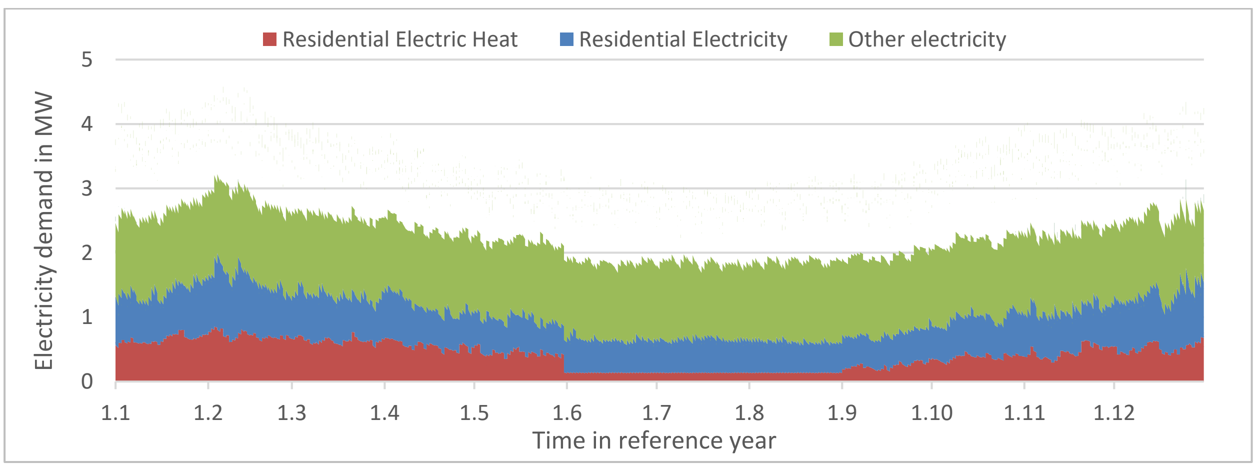

Figure 4. Electricity demand on Samsø in 2015, divided into residential demands for electricity and electric heat, and other demands

3. Scenario description

For both approaches, the analysis evaluates the effects of PV and battery on an island level, including all electricity customers. The individual households are modelled separately in Excel for Approach 1 prior to evaluating the consequences in EnergyPLAN, while Approach 2 is solely modelled in EnergyPLAN. While the impacts and importance of the individual households can be assessed in the first approach, the effect for the whole island is addressed, representing how one sector can influence the whole system.

The first approach to analyse PV systems in combination with batteries focuses on residential use of batteries on a household level. Residential households are addressed, relating to the need for more demand side management and customer involvement. With a total number of around 3,800 listed residential households, including around one thousand households for holiday purposes [51] and almost 200 existing PV systems [52], a number of 2,000 households is selected to be equipped with the selected technologies. This value represents 54% of all residential households on Samsø.

The PV systems are scaled based on the suggestion for residential households in the Technology Catalogue published by the Danish Energy Agency [53]. It states a typical PV capacity of 4-6 kW for residential users. For battery sizes, a range of 4.5-12 kWh of full capacity is typical, while usually 80% of it is usable [54]. In the PV model, the sizes of 4-10 kWh are applied.

For simulation including batteries, the efficiency of charging and discharging is assumed constant with each 87%, as studies show a round trip efficiency of 75-77% [55]. An additional self-discharging of the battery of 0.208 % per hour [56] is further taken into account. The charging and discharging powers are set to 66% of the usable battery capacity [54] i.e. for a 4 kWh battery, maximum charging and discharging is 2.67 kW.

For Approach 2, the same PV capacities and battery sizes and efficiencies are used. In contrast to Approach 1, where 4 kW or 6 kW PV systems are used on 2,000 households individually, the second approach merely uses the combined capacities of 8 and 12 MW, since EnergyPLAN sees a number of the same technologies as one unit. The same applies for the battery sizes, which vary individually from 4 - 10 kWh in steps of 2 kWh, while Approach 2 uses the values 8, 12, 16 and 20 MWh as inputs. Additionally for both approaches, the situation of PV systems without an additional battery is modelled.

Next to the specifications related to the two approaches, the reference system of Samsø is made up of 34.4 MW of wind power capacity and the already existing 1.4 MW of PV capacity. Together, they produced around 115 GWh in 2015, supplying Samsø's electricity demand of 25.5 GWh mainly with RES. A transmission line of 50 MW supplies the island with imported electricity or exports the excess production. The additionally needed imported electricity is modelled to come from various power plants, being fuelled with coal, natural gas or biomass with a share of 50% to 25% and 25% at an average efficiency of 45%. Heat on Samsø is also supplied to a large extend with renewable sources, such as the district heating using biomass, as well as a large number of residential biomass heaters and some electric heating, leaving only around 20% supplied by fossil fuels. Lastly, the transport sector is 99% fossil-based in 2015. The analysis of employing batteries to store produced electricity for better use locally is therefore well-founded. [49]

The reference model has an export of 91.9 GWh and an import of 2.6 GWh of electricity after simulation with EnergyPLAN. This shows on the one hand how only 20% of the produced electricity is used on Samsø and on the other hand, how the lack of wind and solar power still causes an import of 10% of the electricity demand. When considering the CO_2 emissions from the whole island, the renewable excess electricity production outweighs the fuels burned in heating and transportation. The total CO_2 emissions in the reference system are therefore -24.4 kilo tonnes (kt) annually. The negative value occurs as EnergyPLAN credits the system for electricity exports at a rate corresponding to emissions savings at a condensing mode power station.

4. Results from modelling the two approaches

The two approaches, which are outlined in Section **Error! Reference source not found.**, are presented in the following. After presenting the residential battery solution, the communal approach is shown. While the first focuses more on the effects for the households, both address the consequences for the rest of Samsø. Section 5 discusses both approaches in a comparison afterwards.

4.1 Residential batteries

The spreadsheet model is adapted to interchangeable inputs for the number of households, the PV and the battery size. Table 2 shows the results of combining PV with a battery. It shows an annual production of 4.6 MWh per households with 4 kW panels, resulting in 9.2 GWh for the case of 2,000 households adapting the same solution. A PV panel size of 6 kW increase that result by 50%, while the battery contribution shows a non-linear impact on the households. Having no battery limits the potential of using the locally produced PV power, as this is restricted to hours of sunshine only.

Adding a battery of 4 kWh increases the use of locally produced PV power by 11-16 percentage points while possible sales to the grid is reduced by 15-22 percentage points, showing that using a battery causes electricity to be lost. Changing the battery from 4 to 6 kWh increases the local usage by 3-4 percentage points while the sale to the grid is reduced by 3-5 percentage points, with even smaller improvements with larger batteries. In total, 33-68% of households' demands can be covered and even 42-99.9% of the summer demands (Apr-Sep).

Table 2. Results for a household with various PV and battery sizes

PV capacity [kW]	4	4	4	6	6	**6**	6	6
Battery [kWh]	0	4	6	0	4	**6**	8	10
PV production [MWh/year]	4.60	4.60	4.60	6.90	6.90	**6.90**	6.90	6.90
Usable at household [MWh/year]	1.07	1.81	1.96	1.17	1.95	**2.11**	2.20	2.24
Usable share [%]	23%	39%	43%	17%	28%	**31%**	32%	32%
Available for sale [MWh/year]	3.52	2.54	2.32	5.73	4.68	**4.45**	4.31	4.22
Coverage of household demand	33%	55%	60%	36%	59%	**64%**	67%	68%
Coverage […] April-September	42%	92%	97%	46%	95%	**99%**	99.8%	99.9%

Figure 5 visualizes the shares of PV production being used at the households and being fed into the grid, as well as the household demand coverage by the combination of PV and battery technologies. The coverage of the household demand increases strongly by adding a battery, but it saturates with larger batteries in line with diminishing marginal utility. The total usable share barely exceeds 1/3 of the produced electricity, as it reaches a limit at the household levels, but can be used in other sectors of the island. The EnergyPLAN simulations investigate this in the following.

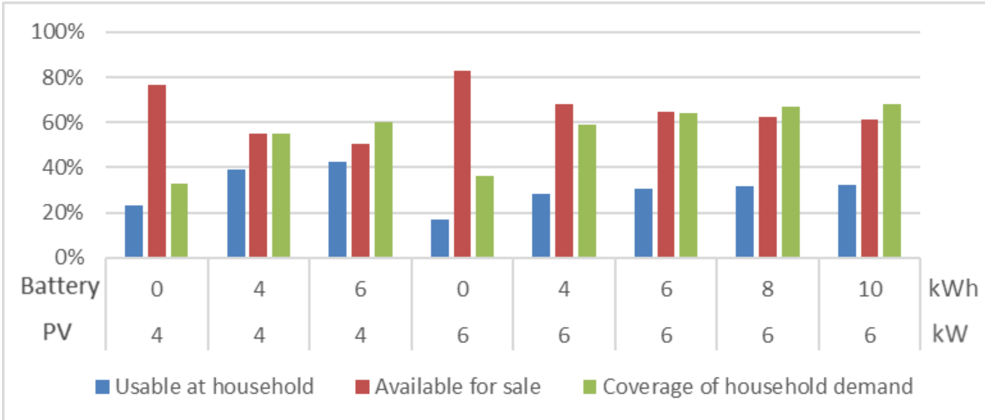

Figure 5. Results on households from various PV and battery sizes: share of directly usable PV production, excess production for sale and share of household coverage

When aiming at covering the households demands, a system of 6 kW PV and 6 kWh battery would be able to supply the demand by 99% for April until September. A recommendation based on self-sufficiency, therefore, results in choosing 6 kW PV and 6 kWh battery system and is presented in more detail in the following.

The electricity produced with the 6 kW PV panels and stored with 6 kWh batteries in all the 2,000 households results in an annual PV production of 13.8 GWh. How it is further used shows Figure 6. A total of 30.7% of the PV electricity is used either directly or indirectly through the battery in the households equipped with PV/Battery, while another 25% can be used by other consumers on Samsø, if neglecting other electricity production from wind turbines. The majority, however, leaves the island via the transmission line.

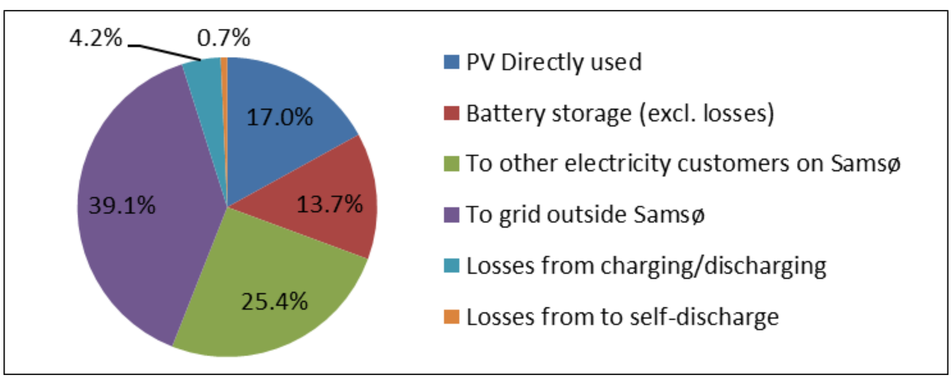

Figure 6. Electricity production from 2,000 households with 6 kW PV systems with 6 kWh batteries each and its use

In the final step, the spreadsheet model results are transferred to EnergyPLAN. Figure 7 presents the PV production of all household installations and the supply of their electricity demand compared to the same PV supplying not only the households but also the rest of Samsø to the best extent. While the PV production covers 99% of the PV-equipped households' summer demands and 64% of the annual demand, it covers 30% of the annual demand of the whole island. This influences the resulting export of electricity, while at nights and certain days the demand cannot be fully satisfied with local PV production and imported electricity is still required.

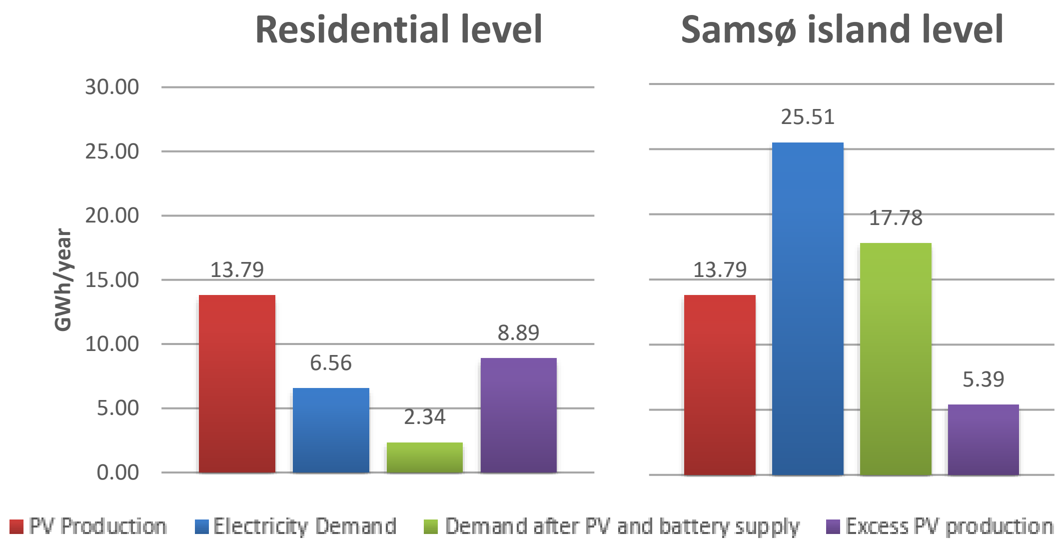

Figure 7. Annual PV production and demand of 2,000 residential households and of Samsø

In EnergyPLAN, the reference model is updated with the hourly residual electricity demand distribution profiles as calculated with the PV battery spreadsheet model. Excess PV production, which can neither be used in the households nor used to charge the batteries, is added as additional source of electricity supply with a certain hourly profile in EnergyPLAN. For the different combinations of PV and battery sizes, the following can be observed for the whole island (values in brackets refer to the closer investigated case of 6 kW/6kWh per household):

- Electricity import is reduced by 22-36% (34%)
- Electricity export increases by 8.4-14.3% (13.3%)
- RES share of primary energy supply increases by 0.9-2% (1.6%)
- CO_2 emissions (after import/export) decreases by 4.2-4.5 kt/year (17-19%) and 6.4-6.8 kt/year (26-28%) for 4 kW and 6 kW PV systems respectively (6.5kt/26.5%)

The last argument points out the relation of battery size with CO_2 savings. With more electricity being stored – and a related higher share being lost, e.g. due to self-discharging – less CO_2 can be saved. This is due to the way EnergyPLAN adjusts emissions' levels for import/export, which in this case corresponds to if the imported electricity is produced at condensing mode power stations running on coal, natural gas and biomass with an average efficiency of 45%.

Considering the amount of households involved in these proposed measures, the effects, as illustrated with

Figure 7, could vary depending on the participation. However, the opposing cycles of PV production in summer and electricity demand peaks in winter are still hard to overcome. In relation to the high wind power utilization on Samsø, some of these winter demands can be covered from wind. However, the installations of the batteries on a household level limit the exploitation of that option to a high extent. Therefore, the second approach of a communal battery is compared to the approach of residential ones.

4.2 Communal battery system

In Approach 2, the PV electricity production is used directly at the residential PV-fitted households like in Approach 1, but the additional production is not stored there and can, therefore, not be used in the households at times when demands surpass the PV production. This results in larger amounts of electricity fed to the grid and respectively lower shares of coverage of the households' own production. The cases of 4 and 6 kW PV systems with no residential battery and their effects on the households correspond to the results seen in Table 2; when there is no battery it is inconsequential whether it is distributed or communal. With batteries, the simulation of the energy system is made with EnergyPLAN, which can simulate the optimal behaviour of batteries considering the entire energy system.

In contrast to the batteries supplying the individual households to the best extent, simulating a communal battery with EnergyPLAN does not distinguish between sectors, and supplies all demands simultaneously. Also all electricity production is considered to potentially charge the battery. Factors, such as excess production from wind turbines or electricity demands in the district heating (e.g. large heat pumps) or transport sector (e.g. charging electric vehicles) influence the operation of a communal battery. Therefore, the results of Approach 2 can only be shown on an island level, including also other PV production on Samsø, resulting in
Figure 8.

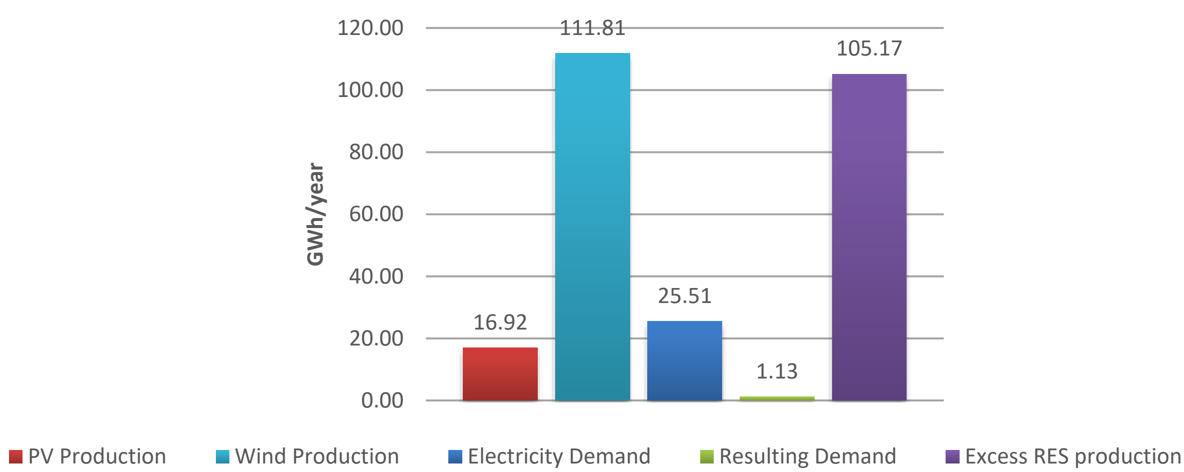

Figure 8. Annual PV and wind production and demand of Samsø

In EnergyPLAN, the reference model is modified with the additional PV capacity and a battery. The storage is modelled with specific charge and discharge powers, just like the residential batteries would have when combined. The different PV and battery combinations result in the following effects (with results for 2,000 6 kW PV systems and a 12 MWh battery in brackets):

- Electricity import is reduced by 22-67% (56%)
- Electricity export increases by 8.2-13.4% (13.1%)

- Self-discharge would increase import and decrease export to a small extent
- RES share of primary energy supply increases by 1.6-2.3% (2.3%)
- CO_2 emissions (after import/export) decreases overall more with 4.4-4.5 kt/year (18-19%) and 6.6-6.8 kt/year (27-28%) for 4 kW and 6 kW PV system respectively; the bigger the battery, the smaller the savings, but not as low as residential systems due to having only one battery (6.7 kt/27.4%)

At this point in the study, the battery is specified with the characteristics of a small battery system of household size. Therefore, the comparison of residential vs. communal battery is more direct, since the charge and discharge efficiencies are assumed the same in the two cases, which it might not be in reality [55]. For large-scale battery installations, efficiencies and charging/discharging specifications would differ from the values typical for small batteries. With likely better efficiencies, the losses might be even lower and the gain higher, when compared to the values above.

5. Discussion of residential vs. communal battery

After presenting the cases of residential and communal battery solutions in combination with PV systems at household level, a comparison and discussion follows. Figure 9 shows the battery behaviour of a 6 kW PV and 6 kWh battery, respectively 12 MW total PV capacity and 12 MWh battery. The upper graphs show the simulation on a household level with high interaction with the battery. The lower graphs show the results from the EnergyPLAN simulation on the Samsø level, where wind power production strongly influences the battery operation. Each graph presents demands along with supply technologies before being supplied by local production. Any resulting imbalances between supply from PV, wind and battery on the one side and demands from consumers and batteries on the other side are balanced through import/export.

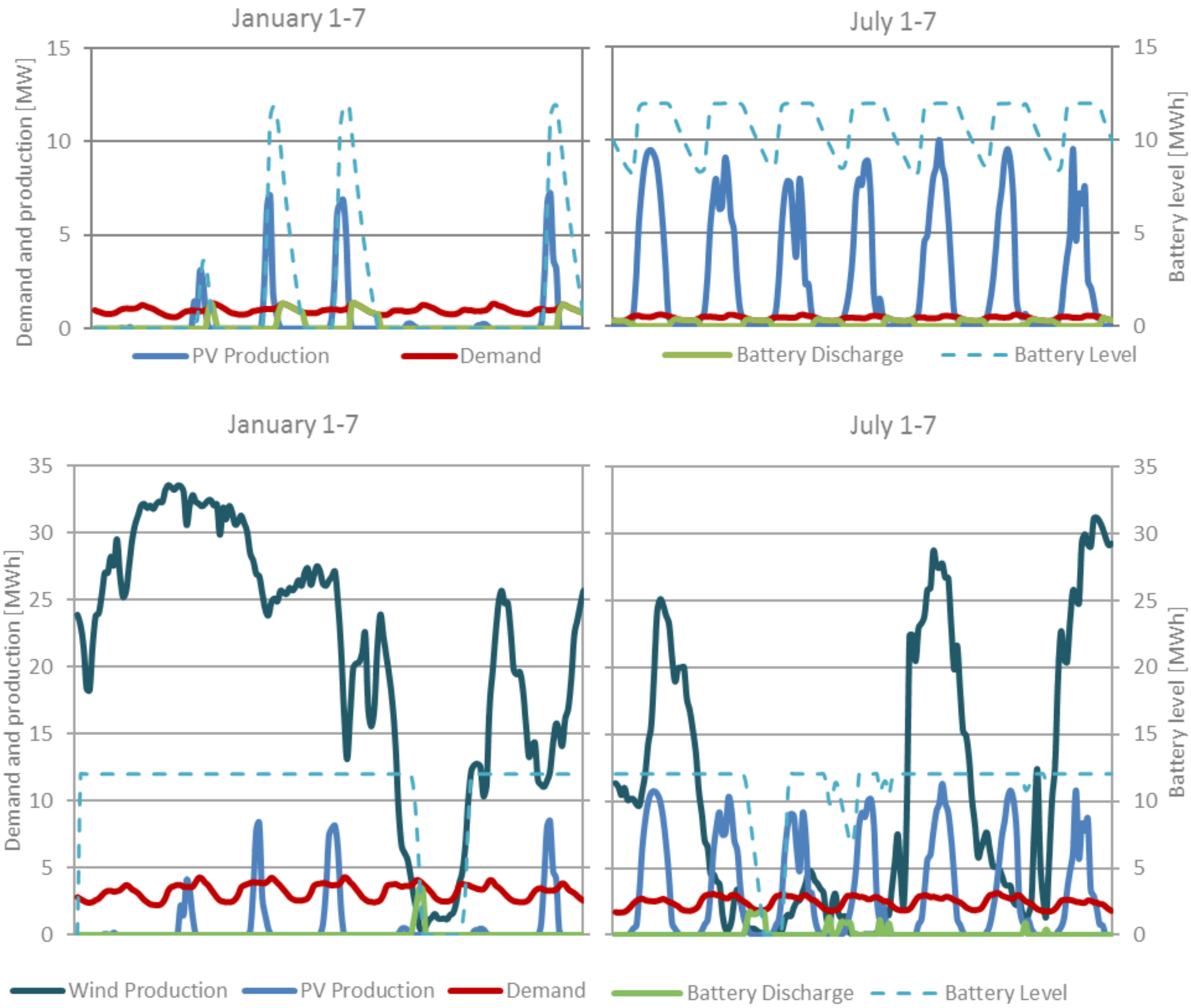

Figure 9. Battery behaviour in relation to demand and production on the household level (above) and the island level (below)

In comparison to the reference model of Samsø, both approaches show improvements in terms of reducing the import of electricity, utilizing more of the locally produced renewable electricity and thereby reducing the CO_2 emissions. Regarding the simulation specifications of EnergyPLAN, this is the result of the modelling under the technical regulation strategy. Table 3 shows these results in comparison to the reference model of Samsø as presented without the additional PV and battery solutions. The import of electricity is reduced by 0.9 GWh for the residential and by 1.5 GWh for the communal battery. The export grows similarly by around 12 GWh, due to the increased local electricity production from PVs.

Table 3. Annual results of battery approaches

Annual results	**Reference**	Residential Batteries	Communal Batteries
Electricity import	**2.6 GWh**	- 34.5%	- 56.3%

Electricity export	**91.9 GWh**	+ 13.3%	+ 13.1%
Share of RES in PES	**68%**	+ 1.6%	+ 2.3%
CO_2 emissions	**-24.4 kt**	- 26.5%	- 27.4%
Full capacity cycles	-	157	68

Table 3 further includes the theoretical capacity cycles of both residential and communal batteries. This can be explained with Figure 9, where the battery levels are indicated. When supplying households, the batteries tend to charge every day with sufficient solar power and discharge after nightfall, while the communal battery is only charged during hours of excess production; a situation strongly influenced by the installed wind power capacity in the system. This reduces the battery interaction with the grid. The synchronization of battery and PV is one of the advantages of the residential solution, while the reduction of imported electricity supports the communal one.

The batteries installed in residential households with PV systems are supplying 64% of the local demands at the suggested capacities and up to 68% with larger batteries, providing if not techno-economic incentives for house then a less tangible sense of self-reliance. Previous work have demonstrated how consumers are even prepared to pay a premium for this [57]. Surplus electricity may furthermore be fed to the grid, supplying neighbouring households with locally produced electricity, while the PV owners may have an economic benefit. However, while the battery can help supply the needed electricity during non-sunshine hours in certain seasons perfectly, specifically summer days do not let the battery discharge completely, leading to the long-term storage of electricity in a battery, instead of using it in another place. The resulting constant loss of electricity might make the residential solutions less favourable compared to communal battery solutions.

Communal battery solutions have a deviation from the residential batteries in a lower usage. The overall higher efficiencies and aggregated electricity management results in fewer losses from charging, discharging and self-discharge. Additionally, the operation of the batteries is affected by further electricity production and considerations of other demands than the residential ones. Thereby, wind power produced on Samsø can also be stored, filling possible electricity gaps on cloudy or winter days, where PV would be insufficient. This way, more local electricity can be stored and used locally. The communal battery can further create synergies to other sectors by offering the battery's stored electricity to local EV charging stations or even to the heating sector, if district heating networks can use the electricity to power heat pumps or if households are equipped with residential heat pumps. This way, a sectorial integration can be approached, merging the electricity, heating and transport sector as suggested by Lund et al. [2], [3].

Compared to residential batteries, communal batteries result in less customer involvement, while wind power could be better integrated. The PV production of the same PV, but with communal batteries, would only supply 36% of the household demands directly. Additionally, a large utilization of wind power would make the selected battery size insufficient since the charging and discharging is strongly influenced by the availability of wind power. The battery would be more suitable to store the local PV power and supply its owners with energy. At this point, a separated management of PV and wind power is not applicable as part of a smart energy system with one electricity system, but could be suggested for further studies.

Furthermore, the EnergyPLAN simulations with a communal battery show the priorities of an energy system model under a technical regulation. Batteries are only used to avoid excess as cycle losses would supersede benefits, since postponing the import does not in itself create benefits. Thus, as long as the losses of the battery are too large, EnergyPLAN will rather import electricity than store it at a loss. This underlines the necessity of proper operation, because the full benefit of PV systems and batteries is not reached unless coordinated and controlled on a systems level. The discussed advantages and disadvantages are summed up in Figure 10.

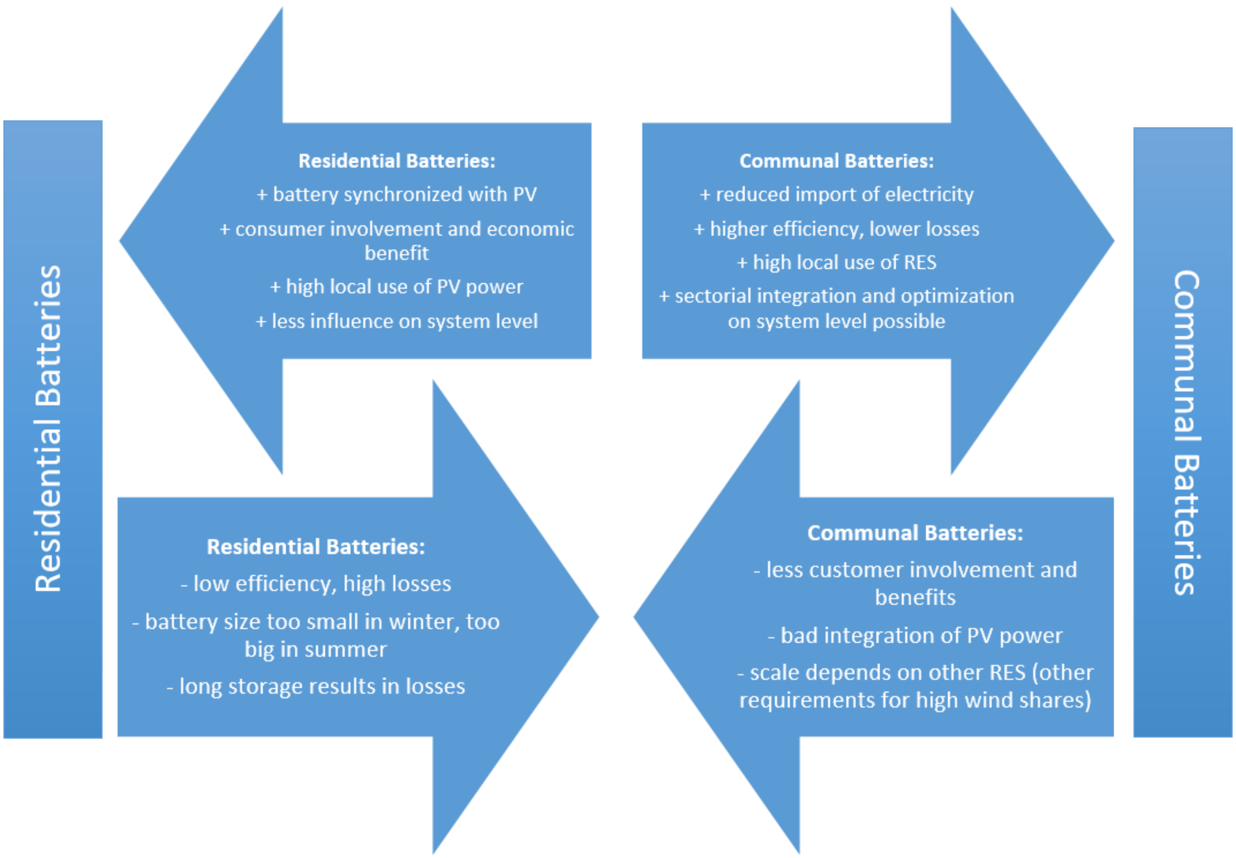

Figure 10. Advantages and disadvantages of residential and communal batteries

6. Conclusions

The questions of whether PV panels and batteries provide a solution to the current energy system transformation towards sustainable energy systems are investigated in this paper. The analyses include the role of combining these technologies as part of a smart energy system and their options and consequences for the case of Samsø. Two approaches of this combination are closer investigated; while the PV systems are always considered to be installed at the household level, the batteries are either individually placed at the household, or in comparison to that at an aggregated grid level. This results in the PV production supplying primarily the households and then either their residential batteries or the communal battery. From the households' perspective, the first leads to higher self-supply, while the other enables a higher share of electricity fed to the battery and grid.

The analysis is made with the PV production profile of an existing system on Samsø and the electricity demand profiles of the residential sector as a share of the whole island. The simulations are considering typical PV and battery sizes, while a system of 6 kW and 6 kWh per household is investigated in detail. This combination is able to cover 64% of the PV-equipped households' electricity demand if a residential battery is used and 36% if one communal 12 MWh battery helps balance the whole grid. When using residential batteries, 5% of the PV production is lost at the residential level in conversion losses in charger/inverter and in self-discharge. The communal battery has a little fewer losses due to the set-up and as to be expected for an aggregated system. Even though the PV panels produce more than what is needed at the residential sites, the excess can be well used on the rest of Samsø with either battery approach, especially at times when no electricity is produced from wind power.

The simulation software EnergyPLAN evaluates these technologies as part of an energy system, pointing out a decrease of needed electricity import by around 35% when batteries are used on the household level and by around 56% when the battery balances within the grid. Either way, export and CO_2 emissions are affected similarly, due to certain common advantages, but also disadvantages in both system set-ups. Overall, the analysis shows the potential of increased PV capacity and the two options of battery placement, which each should be evaluated for itself. Depending on the local targets of an increased customer involvement or a better system management, both approaches show opportunities, as long as the technological specifications are well coordinated and controlled. Concluding, both solutions could support the modernization of the electricity system by managing the demand side, but also the balancing side and support the management of production and demand to fulfil Europe's energy targets.

Acknowledgements

This paper presents work that is supported by the ERA-Net Smart Grids Plus through the project MATCH (Markets – Actors – Technologies: A comparative study of smart grid solutions) as well as by the Horizon2020 research programme through the project SMILE (Smart Island Energy systems) under the grant agreement no. 731249. A preliminary version of the article was presented at the 12th SDEWES Conference, Dubrovnik, October 4-8, 2017.

References

[1] European Commission, "2030 climate & energy framework | Climate Action." .

[2] H. Lund, A. N. Andersen, P. A. Østergaard, B. V. Mathiesen, and D. Connolly, "From electricity smart grids to smart energy systems - A market operation based approach and understanding," *Energy*, vol. 42, no. 1, pp. 96–102, 2012.

[3] H. Lund, P. A. Østergaard, D. Connolly, and B. V. Mathiesen, "Smart energy and smart energy systems," *Energy*, 2017.

[4] K. Hedegaard, B. V. Mathiesen, H. Lund, and P. Heiselberg, "Wind power integration using individual heat pumps – Analysis of different heat storage options," *Energy*, vol. 47, no. 1, pp. 284–293, Nov. 2012.

[5] W. Liu, W. Hu, H. Lund, and Z. Chen, "Electric vehicles and large-scale integration of wind power – The case of Inner Mongolia in China," *Appl. Energy*, vol. 104, pp. 445–456, Apr. 2013.

[6] Q. Zhang, T. Tezuka, K. N. Ishihara, and B. C. Mclellan, "Integration of PV power into future low-carbon smart electricity systems with EV and HP in Kansai Area, Japan," *Renew.*

Energy, vol. 44, pp. 99–108, Aug. 2012.
[7] N. Liu, Z. Chen, J. Liu, X. Tang, X. Xiao, and J. Zhang, "Multi-objective optimization for component capacity of the photovoltaic-based battery switch stations: Towards benefits of economy and environment," *Energy*, vol. 64, pp. 779–792, Jan. 2014.
[8] F. Levihn, "CHP and heat pumps to balance renewable power production: Lessons from the district heating network in Stockholm," *Energy*, 2017.
[9] G. Schweiger, J. Rantzer, K. Ericsson, and P. Lauenburg, "The potential of power-to-heat in Swedish district heating systems," *Energy*, 2017.
[10] I. Ridjan, B. V. Mathiesen, and D. Connolly, "Terminology used for renewable liquid and gaseous fuels based on the conversion of electricity: A review," *Journal of Cleaner Production*, vol. 112. pp. 3709–3720, 2016.
[11] I. Ridjan, B. V. Mathiesen, D. Connolly, and N. Duić, "The feasibility of synthetic fuels in renewable energy systems," *Energy*, vol. 57, pp. 76–84, Aug. 2013.
[12] H. Lund *et al.*, "Energy Storage and Smart Energy Systems," *Int. J. Sustain. Energy Plan. Manag.*, vol. 11, p. 3-, 2016.
[13] M. Miguel, T. Nogueira, and F. Martins, "Energy storage for renewable energy integration: the case of Madeira Island, Portugal," *Energy Procedia*, vol. 136, pp. 251–257, Oct. 2017.
[14] Aalborg University, "MATCH homepage: Markets - Actors - Technologies: A comparative study of smart grid solutions," 2016. [Online]. Available: http://www.match-project.eu/. [Accessed: 10-Jul-2017].
[15] Rina Consulting S.p.A., "SMart IsLand Energy System," 2017. [Online]. Available: http://www.h2020smile.eu/. [Accessed: 20-Sep-2017].
[16] P. J. Jørgensen, S. Hermansen, A. Johnsen, J. P. Nielsen, J. Jantzen, and M. Lundén, "Samsø - A renewable energy island - 10 years of Development and Evaluation," Ballen, 2007.
[17] K. Sperling, "How does a pioneer community energy project succeed in practice? The case of the Samsø Renewable Energy Island," *Renew. Sustain. Energy Rev.*, vol. 71, 2017.
[18] F. Mey and M. Diesendorf, "Who owns an energy transition? Strategic action fields and community wind energy in Denmark," *Energy Res. Soc. Sci.*
[19] B. Möller, K. Sperling, S. Nielsen, C. Smink, and S. Kerndrup, "Creating consciousness about the opportunities to integrate sustainable energy on islands," *Energy*, vol. 48, no. 1, 2012.
[20] J.-H. Lin, Y.-K. Wu, and H.-J. Lin, "Successful Experience of Renewable Energy Development in Several Offshore Islands," in *Energy Procedia*, 2016, vol. 100.
[21] D. Neves, C. A. Silva, and S. Connors, "Design and implementation of hybrid renewable energy systems on micro-communities: A review on case studies," *Renew. Sustain. Energy Rev.*, vol. 31, 2014.
[22] M. Pasqualetti and S. Stremke, "Energy landscapes in a crowded world: A first typology of origins and expressions," *Energy Res. Soc. Sci.*, 2017.
[23] M. Soshinskaya, W. H. J. Crijns-Graus, J. M. Guerrero, and J. C. Vasquez, "Microgrids: Experiences, barriers and success factors," *Renew. Sustain. Energy Rev.*, vol. 40, 2014.
[24] A. Korfiati *et al.*, "Estimation of the Global Solar Energy Potential and Photovoltaic Cost with the use of Open Data," *Int. J. Sustain. Energy Plan. Manag.*, vol. 9, p. Start-End, 2016.
[25] International Energy Agency, "World Final Consumption IEA 2015." [Online]. Available: https://www.iea.org/Sankey/#?c=World&s=Final consumption.
[26] K. Buß, P. Wrobel, and C. Doetsch, "Global distribution of grid-connected electrical energy storage systems," *Int. J. Sustain. Energy Plan. Manag.*, vol. 9, pp. 31–56, 2016.
[27] P. Hanser, R. Lueken, W. Gorman, and J. Mashal, "The practicality of distributed PV-battery

systems to reduce household grid reliance," *Util. Policy*, vol. 46, pp. 22–32, Jun. 2017.
[28] A. Kantamneni, R. Winkler, L. Gauchia, and J. M. Pearce, "Emerging economic viability of grid defection in a northern climate using solar hybrid systems," *Energy Policy*, vol. 95, pp. 378–389, Aug. 2016.
[29] V. Bertsch, J. Geldermann, and T. Lühn, "What drives the profitability of household PV investments, self-consumption and self-sufficiency?," *Appl. Energy*, vol. 204, pp. 1–15, Oct. 2017.
[30] K. R. Khalilpour and A. Vassallo, "Technoeconomic parametric analysis of PV-battery systems," *Renew. Energy*, vol. 97, pp. 757–768, Nov. 2016.
[31] R. Khalilpour and A. Vassallo, "Leaving the grid: An ambition or a real choice?," *Energy Policy*, vol. 82, pp. 207–221, Jul. 2015.
[32] I. O. Ogundari, Y. O. Akinwale, A. O. Adepoju, M. K. Atoyebi, and J. B. Akarakiri, "Suburban Housing Development and Off-Grid Electric Power Supply Assessment for North-Central Nigeria," *Int. J. Sustain. Energy Plan. Manag.*, vol. 12, pp. 47–63, 2017.
[33] E. Tomc and A. M. Vassallo, "The effect of individual and communal electricity generation, consumption and storage on urban Community Renewable Energy Networks (CREN): an Australian case study," *Int. J. Sustain. Energy Plan. Manag.*, vol. 11, pp. 15–32, Jan. 2016.
[34] X. Wu, X. Hu, X. Yin, C. Zhang, and S. Qian, "Optimal battery sizing of smart home via convex programming," *Energy*, vol. 140, pp. 444–453, Dec. 2017.
[35] M. Karimi, H. Mokhlis, K. Naidu, S. Uddin, and A. H. A. Bakar, "Photovoltaic penetration issues and impacts in distribution network – A review," *Renew. Sustain. Energy Rev.*, vol. 53, pp. 594–605, Jan. 2016.
[36] M. Aachiq, J. G. da S. F. Junior, T. Oozeki, and Y. Iwafune, "Evaluation of Residential PV-EV System for Supply and Demand Balance of Power System," *IEEJ Trans. Power Energy*, vol. 135, no. 1, pp. 27–34, 2015.
[37] M. Motalleb, E. Reihani, and R. Ghorbani, "Optimal placement and sizing of the storage supporting transmission and distribution networks," *Renew. Energy*, vol. 94, pp. 651–659, 2016.
[38] Aalborg University, "EnergyPLAN." Department of Development and Planning, Aalborg University, 2017.
[39] P. A. Østergaard, "Reviewing EnergyPLAN simulations and performance indicator applications in EnergyPLAN simulations," *Appl. Energy*, vol. 154, pp. 921–933, Sep. 2015.
[40] D. Connolly *et al.*, "Heat roadmap Europe: Combining district heating with heat savings to decarbonise the EU energy system," *Energy Policy*, vol. 65, pp. 475–489, 2014.
[41] J. J. Vidal-Amaro, P. A. Østergaard, and C. Sheinbaum-Pardo, "Optimal energy mix for transitioning from fossil fuels to renewable energy sources - The case of the Mexican electricity system," *Appl. Energy*, vol. 150, 2015.
[42] P. A. Østergaard, B. V. Mathiesen, B. Möller, and H. Lund, "A renewable energy scenario for Aalborg Municipality based on low-temperature geothermal heat, wind power and biomass," *Energy*, vol. 35, no. 12, pp. 4892–4901, Dec. 2010.
[43] S. Mathiesen, Brian Vad; Lund, Rasmus Søgaard; Connolly, David; Ridjan, Iva; Nielsen, "Copenhagen Energy Vision 2050: A sustainable vision for bringing a capital to 100% renewable energy," 2015.
[44] H. Lund *et al.*, "Simulation versus optimisation: Theoretical positions in energy system modelling," *Energies*, vol. 10, no. 7, 2017.
[45] H. Lund, "EnergyPLAN Advanced Energy System Analysis Computer Model - Documentation Version 12," 2015.

[46] S. Saha *et al.*, “The NCEP climate forecast system version 2,” *J. Clim.*, vol. 27, no. 6, pp. 2185–2208, 2014.
[47] Energinet.dk, “Energinet market data,” 2016. [Online]. Available: http://osp.energinet.dk/_layouts/Markedsdata/framework/integrations/markedsdatatemplate.aspx.
[48] J. Jantzen, “Samsø contact Jan Jantzen,” 2017.
[49] Region Midtjylland, “Energy account Samsø,” 2017. [Online]. Available: http://www.rm.dk/regional-udvikling/klima-og-miljo/strategisk-energiplanlagning/.
[50] F. M. Andersen and et al., “Electricity profiles,” 2012.
[51] B. Möller and S. Nielsen, “Danish Heat Atlas,” 2016. [Online]. Available: http://maps.plan.aau.dk/maps/DKfieHA.php. [Accessed: 01-Sep-2017].
[52] Energinet.dk, “PV in Denmark,” 2017.
[53] Danish Energy Agency and Energinet.dk, “Technology data for energy plants - individual heating plants and energy transport,” no. August, p. 212, 2013.
[54] Fronius International GmbH, “Services and product programme 2017/18.” 2017.
[55] R. R. Mosbæk and I. Katic, “PV Battery System Tested with Real-Life Consumption Data,” 2015.
[56] I. Buchmann, “Battery discharge,” *Cadex Electronics Inc.* [Online]. Available: http://batteryuniversity.com/learn/article/elevating_self_discharge. [Accessed: 04-Apr-2017].
[57] A.-L. Klingler, “Self-consumption with PV+Battery systems: A market diffusion model considering individual consumer behaviour and preferences,” *Appl. Energy*, vol. 205, no. Supplement C, pp. 1560–1570, 2017.