PVST Project

Final Technical Report

Project title	PV+STorage Operation and Economics in distribution systems
Project identification	64017-0041
Name of the programme which has funded the project	EUDP (Former ForskEL program)
Project managing company/institution	DTU Electrical Engineering – Centre for Electric Power and Energy
Project partners	Aalborg Universitet, Dansk Energi, Integrate, Livingpower
CVR (central business register)	30060946
Date for submission	19 maj 2020

Short description of project objective and results

The project aims to evaluate the competitiveness of the technology of PV+storage and understand the interactions between the DSO performance (technically and financially) and the perspective retail market, as well as design an operational strategy and requirements for PV+storage for the benefit of owners and the grid. The project has delivered the following,

1) An operational strategy and hardware/software platform for the residential owners of PV and battery to maximize their self-consumption and benefit;

2) Recommendations to distribution grid operators for how their operations and tariffs that can be adapted to support PV + storage customers;

3) Recommendations to retail market design and retailer operational strategy for the best of profitability;

4) Input and suggestions to upcoming regulation and distributed energy resource connection codes;

The project consortium is formed by Technical University of Denmark, Aalborg University, Danish Energy, Livingpower and Integrate.

Executive summary

The ever-decreasing cost of PV and battery technology enhances the competitiveness of both technologies in the future renewable-based energy system. A recent market perspective report predicts that there will be a rapid pace of adoption in the coming years for the two technologies. Industry has led the trend and developed various storage solutions for customers, especially residential households.

The business case for investment in the storage systems, rests on cooperation with local PV to increase the self-consumption rate. The combination of PV and storage can provide benefits to the system owners in the form of lower electricity bills and a greener electricity supply.

However, development has been so fast that several key issues remain unresolved. The technical requirements for storage units are not yet defined. The impact on the current business of distribution grid operators and electricity retailers is also unknown.

In order to prepare the industry for the upcoming change, it is necessary to have the impact evaluated by research institutes, manufacturers, grid operators, and retailers. The project will therefore set out to study the performance of the current technology, as well as the impact on the electricity grid and retailing.

Project objectives

The project aims to develop storage units that can cooperate with PV inverters with also powerful interfaces for external communication and integration. Project will also investigate the hot research topics such as the alternative network tariff model, the optimal social-economic model to integrate all actors in the distribution system considering the increasing PV+storage. Be-sides, it is also an important chance to know the PV+storage technology and understand the state of the art. With this knowledge, future research can be more directed and specific.

To the network operator, the project aims to help them to proactively prepare themselves for the upcoming adoption of PV+battery instead of defensively accepting them in the grid. Danish Energy has identified batteries as a key technology to monitor for its future impact on the distribution grid. This project will transfer in-depth knowledge about small battery systems to the power industry, and thereby help reduce the risk and uncertainty associated with accommodating this new type of network user.

Table of Contents

1. INTEGRATION DESIGN (BEHIND THE METER)

1.1 *Basic PV-battery integration functionalities and Advance grid support functions*

A. *Basic functions of PV+STORAGE system*

- While the primary function of a storage system is to provide power when sunlight is not available, hence increasing the fraction of time the photovoltaic system provides electricity, the addition of batteries has numerous other advantages which means that the batteries can be used for multiple purposes[1].
- For small systems consisting of one or two photovoltaic modules, batteries can act as a load-matching system.
- Alternately, in photovoltaic systems which contain a load with a large initial current draw (such as experienced by an inductive load, typically represented by a motor), the batteries can be used to provide initial start-up current.
- In grid-connected systems, battery storage can be used for peak shifting, in which the power generated by the sun is stored for several hours to better match when the peak load occurs.

Figure 1.1: Typical structure of PV+ST.

B. *Integration approach review*

A brief introduction to the PV+STORAGE integration methods for the evaluation of different hardware platforms for business development is discussed[2].

A Black Box approach will look like this:

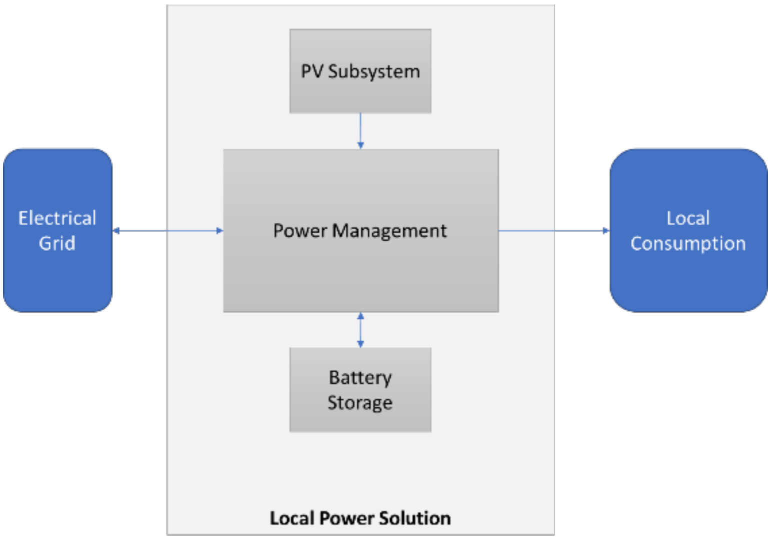


Figure 1.2. Basic black box outline of a Local Power Solution.

---

[1] Uses of batteries in PV systems, https://www.pveducation.org/pvcdrom/batteries/function-and-use-of-storage

[2] Business perspectives, PVST project. Appendix 4: Evaluation of different hardware platforms for business development.

From a functional perspective, there are numerous ways of implementation – all offering the same as seen from the Grid or by the consumer.

However, they exhibit rather substantial differences in terms of

- Uniqueness – does it make sense to invest in development?
- Ability to offer local “high availability” power (“no-break”, “short-break”)
- Flexibility – ability to adapt to emerging business models and services
- Missing elements – things yet to be developed.

a) Traditional discrete approach

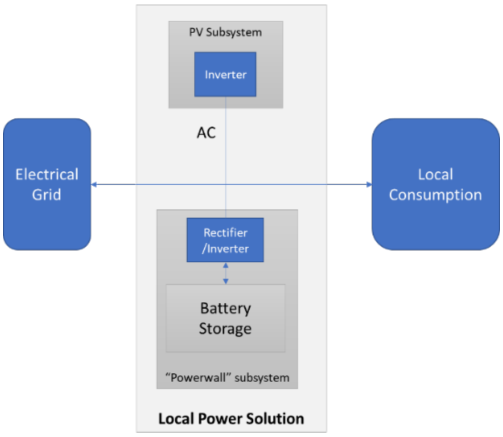


Figure 1.3. The traditional discrete approach based on commercially available components.

For this type of design, the characteristics are

Pro’s and Con’s	*How to…*
Uniqueness – there are thousands of suppliers Standard PV inverter Direct Grid: Yes Short-Break Power: Yes (See Options) No-Break Power: No (see note) Scalable, modular: Yes Efficiency: Highest possible efficiency for PV power	Develop: Software to manage charging/discharging of the battery (grid service) Develop: Islanding capability of “Powerwall” subsystem if not already present. Optional: Disconnect function to isolate the system from the Grid to enable operation during Grid Outages

Note: No-break power (Class I uninterruptible power according to IEC 62040) is not offered by traditional “reactive” solutions where the output is connected to the Grid and thus the output will be forced to “follow the Grid down” in case of a grid outage – at least until a relay disconnects the output from the Grid. Class I performance is normally provided by means of a so-called Double-Conversion solution, where the load is continuously supplied by an inverter that operates independently of what is taking place elsewhere.

b) Integrated DC Solution

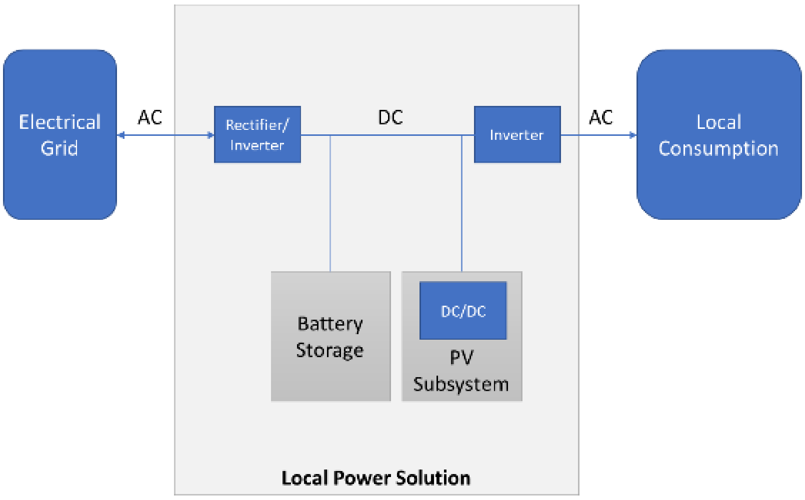


Figure 1.4. An example of a solution where battery and PV (and other local sources) are integrated on a shared DC bus.

The characteristics of such solutions are:

Pro's and Con's	*How to…*
Can operate (including PV) during Grid outages Offers no-break power to all outlets Direct Grid: No Short-Break Power: No No-Break Power: Yes (all) Scalable, modular: Yes Efficiency: • PV power is passing through several power conversion steps • Only no-break power outlets (double conversion on all outlets)	Develop: Software to manage charging/discharging of the battery (grid service) Develop: DC/DC converter for PV subsystem Develop: Software to control PV production through the DC/DC converter (maximum power) Optional: Bi-directional rectifier at system inlet to offer Grid Export capability

Even though such a solution requires a rather high development effort, it is not considered to bring forward any form of uniqueness nor novelty.

c) Classic UPS approach

This solution is based on a variant of a traditional UPS subsystem. Therefore, uniqueness is considered rather low.

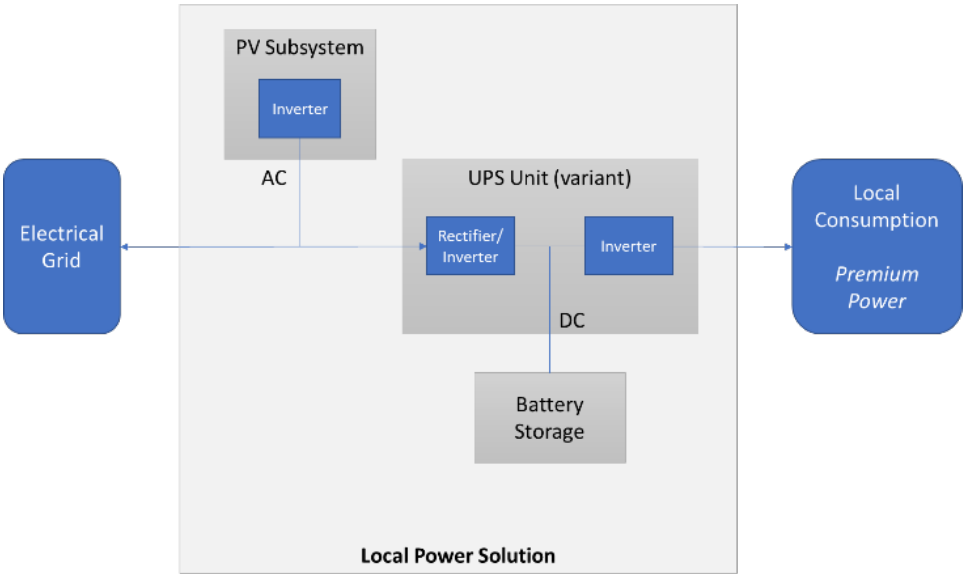


Figure 1.5. A solution based on a modified UPS product and a standard PV subsystem/PV inverter.

The characteristics of such an approach are:

Pro's and Con's	*How to…*
Standard PV inverter Direct Grid: Yes Short-Break Power: No No-Break Power: Yes (all) PV can operate during Grid outages (Optional) Scalable, modular: Yes No PV power production during Grid outlet (see Options) Efficiency • PV production operates at highest possible efficiency • Only no-break power outlets (double conversion)	Develop: Software to manage charging/discharging of the battery (grid service) Optional: Bi-directional rectifier at system inlet to offer Grid Export capability Optional: Bi-directional rectifier capable of importing power from PV during Grid outages (requires that the PV is connected to the UPS on the inside of the UPS's isolation switch)

d) Approach based on UPS and Power Virtualization

This solution is based on Power Virtualization technology – a unique concept.

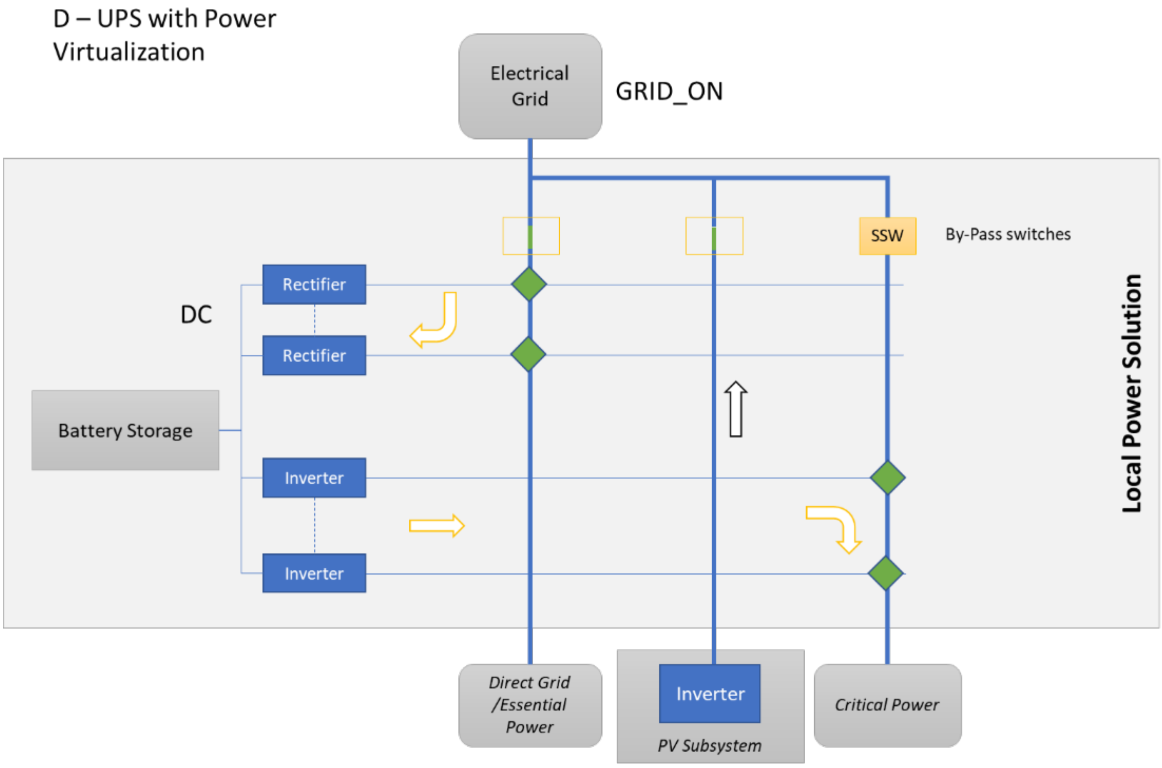


Figure 1.6. Power Solution based on UPS with Power Virtualization. The PV subsystem runs in normal grid parallel mode (when the grid is nominal). No-break outputs ("Critical power") are feed through a so-called Double Conversion topology that is industry standard for professional UPS products. Short-break outputs are feed directly from grid. During grid outages, they are feed from battery, using the rectifiers (now transformed into inverters).

The characteristics of such an approach for the actual application are:

Pro's and Con's	*How to…*
Standard PV inverter Direct Grid: Yes (Configurable capacity) Short-Break Power: Yes (Configurable capacity) No-Break Power: Yes (Configurable capacity) PV can operate during Grid outages (Optional) Scalable, modular: Yes Efficiency • PV production operates at highest possible efficiency • Direct-Grid/Short-Break outlets offers highest possible efficiency	Develop: Software to manage charging/discharging of the battery (grid service) Optional: Bi-directional rectifier at system inlet to offer Grid Export capability (software development) Optional: • Bi-directional rectifier capable of importing power from PV during Grid outages – OR • The PV inverter must be capable of also operating in islanding mode • EV fast charging (DC/DC function, EV charging digital interfaces)

Moreover, battery charging capacity is also configurable and scalable. This is advantageous to adapt to enhanced battery capacity or when changing the battery technology (e.g. to Li-ion). The functionality as seen from the Grid or by the consumer may be described as:

- End user services

    - Enhanced power availability (uptime) for local loads by bridging all grid outages below a certain duration (the so-called Runtime)
    - Protection of local loads against Grid noise, disturbances, over- and undervoltage, spikes, etc.
    - Configurable availability ("self-healing" (zero-time-to-service), scalable redundancy, prioritization of loads)
    - Dynamic, scalable battery charging capacity (to adapt to changing battery capacity or to adapt to different battery technologies)
- Grid services (examples)
    - Smoothing of PV power production variations (may be important to the Grid, as such variations – however small they are – are often correlated across many PV installations in the same area)
    - Smoothing of local load steps (normally not correlated across many sites, but they may be rather large in size, like 0-100% or vice-versa).
        - Note: The not trivial load step variations caused by the switching between free-cooling and active (compressor) cooling in server rooms is to some extent correlated across many sites, as it relates to changes in the outdoor temperature.

In additional to such predictable services, the solution based on Power Virtualization furthermore is capable of yielding

- Substantial cost savings from sharing power converter capacity – by dynamic re-allocation of power converter capacity among
    - Sources, e.g. Grid inlets (rectification)
    - Grid outlets (grid parallel inverter)
    - Loads (AC inverters or DC/DC converters)
    - Or even across inlets and outlets
- Local, fast EV charging ("Supercharging") based on the local battery bank and piling together an adequate power conversion capacity for charging the EV – without exposing the grid to such excessive peak loads.

Practically, any of the Grid Services may be implemented by controlling the battery charge state: A control loop that manages

- Increased battery charging to "remove power from the equation"
- Decreased battery charging to "add power to the equation".

The implementation of such basic functions is independent of the power solution – the Grid only sees the actual net power going into the power solution – with sign. In other words, the Grid cannot tell the difference among the elements that contribute:

- Local consumption
- PV production
- Battery charging/discharging.

I.e., the Grid only sees the net power drawn from the grid by the local solution (with sign).

C. *Aspects of battery capacity*

The UPS battery storage capacity shall be enhanced in order to support the grid services.

Most battery technologies exhibit an asymmetric charging behavior: When their charging state reaches approximately 80%, the speed of charging declines substantially, such that it typically lasts 5-10 times longer to charge the remaining 20% than the first part of the capacity.

To obtain a symmetric charge/discharge behavior, one could define the nominal working point of the battery bank to be around 60% of its capacity – and then allow for the grid services to operate in a range ±20% around this working point.

For the business case – and attractive to the consumer – an enhanced battery capacity will substantially elevate the power availability performance provided by the UPS: When the grid fails, all battery capacity can be exploited by the UPS function.

D. *Advanced grid support functions*

The high variability of solar irradiance, originated by moving clouds, causes fluctuations in Photovoltaic (PV) power generation, and can negatively impact the grid stability. For this reason, grid codes have incorporated ramp-rate (RR) limitations for the injected PV power. To allow RR control, PV plants are required to have additional power in reserve, this is achieved by e.g. operating the PV plant below the rated capacity, or by the use of energy storage systems (ESS), which allows compensating for the PV power variability.

a) RAMP-RATE CONTROL PRINCIPLE

The principle behind the proposed ramp-rate smoothing method is to generate a battery power reference, based on a PI controller, which opposes the PV fluctuations. The result is a smoothing of the injected grid power and a consequent increase or decrease in the battery storage energy[3].

The RR control comprises of a PI controller Fig. 1.7 (orange), which is commanded based on the grid RR and obtained by the RR calculation block Fig. 1.7 (blue). Adding to this, the control operation also requires two other functionalities: a ramp-rate limit control, which dynamically changes the RR limits depending on the system operation Fig. 1.7 (purple) and an anti-windup control, to limit the integral action of the PI controller Fig. 1.7 (green).

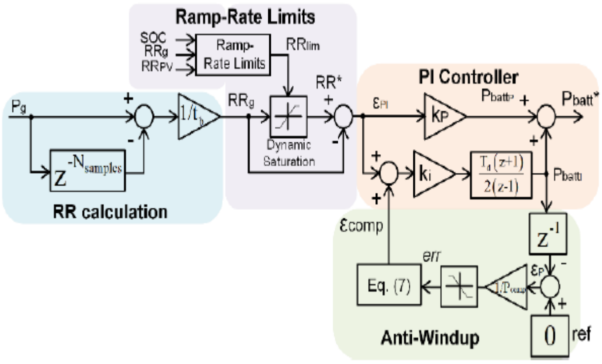


Figure 1.7 Control structure of the proposed RR power limitation.

The battery power reference Pbatt* can be generated based on the difference between the maximum allowed ramp rate RRmax and the current grid ramp-rate RRg. Based on the error between the two, the PI controller generates a battery power reference that compensates for the grid power variation. However, when the grid power fluctuations are within the acceptable RRmax range, the PI controller does not generate any power reference. This is accomplished in practice by considering a dead zone region.

---

[3] João Martins, et. al., A Ramp-Rate Control Algorithm for PV with Energy Storage Systems based on linear controllers, *Digital Object Identifier 10.1109/ACCESS.2017*

b) IMPROVING THE BATTERY LIFETIME EXPECTANCY

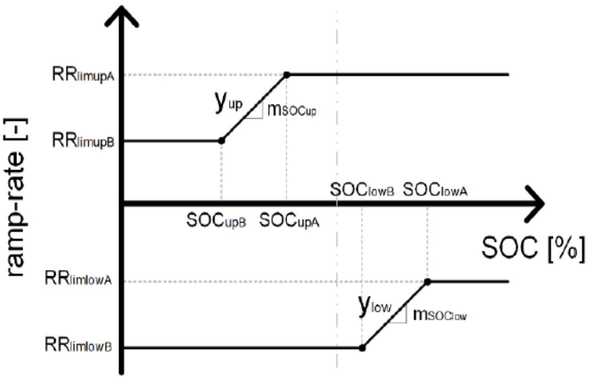


Figure 1.8: Ramp-rate limits selection based on the actual battery SOC.

In order to optimize the injected grid power and at the same time preventing the battery from operating at undesirable SOC levels, the ramp-rate limits can be utilized. The basic idea is that during the normal charge/discharge smoothing operation, the battery is required to process extra power and that by doing this being capable of balancing the SOC level. In Fig. 1.8 an illustration of the manipulation in the RRlim in order to obtain the mentioned SOC control is presented. If the SOC is above the limit of SOClowB (meaning the battery is charging) the RRlim changes linearly from RRlimlowB to RRlimlowA. Alternatively, if the SOC is below the limit of SOCupA (meaning the battery is discharging), the RRlim changes linearly from RRlimupA to RRlimupB.

1.2 ***PV-battery system prototyping platform design strategies***

Researching and testing control systems for PV+BES systems under realistic operation conditions can be difficult to achieve in practice. Testing and integrating different battery technologies and capacity sizes, in a PV system, is time-consuming and costly. Moreover, battery packs for residential PV applications are in the kWh range and can pose an electrical safety risk. In this situation, battery emulators are ideal for research and development purposes.

A. Prototype platform design

The experimental procedure[4] consists of three different tests that aim to validate and illustrate the versatility of the proposed battery emulator. The experimental test setup, shown in Fig. 1.9, consists of an 800W DC/DC boost converter and two back-to-back connected 2.2kW Danfoss VLT-FC302 inverters, connected to the grid through LC filters and a 1:1 transformer. One of the converters operates in PV inverter mode, whereas the other as a battery emulator.

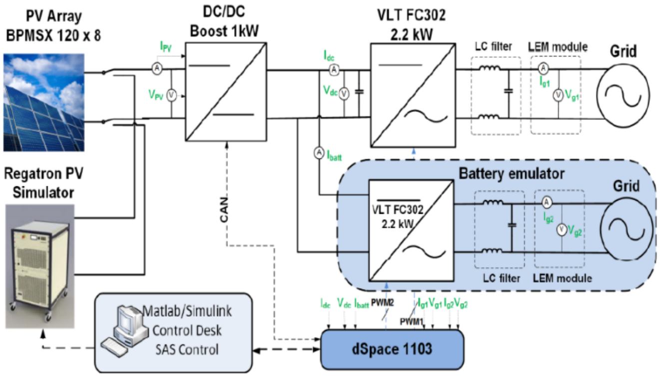


Figure 1.9: Results of the system with power smoothing algorithm. (a) PV power and grid power, (b) battery power, and (c) PI error

The control system has been implemented in Simulink and runs in real-time on the dSpace 1103 controller board. The boost

---

[4] S. Spataru, J. Martins, D. Store and D. Sera, "Test Platform for Photovoltaic Systems with Integrated Battery Energy Storage Applications," *2018 IEEE 7th World Conference on Photovoltaic Energy Conversion (WCPEC)*

converter control is implemented on a Texas Instruments TMS320F335 digital signal processor.

The PV input of the system can be connected to a 1000V/40A high bandwidth PV simulator with a linear post-processing unit, or directly to a 0.8kWp PV string.

This platform allows for power hardware-in-the-loop tests (PHIL) for different solar irradiance and temperature profiles, different PV module types, and array sizes, as well as different battery sizes and technologies.

B. Experimental results of the proposed ramp-rate control algorithm

To analyze and validate the proposed power smoothing algorithm, an irradiance profile along with originating RRg, with a duration of 2 hours was collected from the Aalborg University weather station Fig. 1.10. The collected data is obtained with a calibrated crystalline silicon reference cell (Si-RS485TC-WT-v-MB) sensor, at a 1 Hz sampling rate.

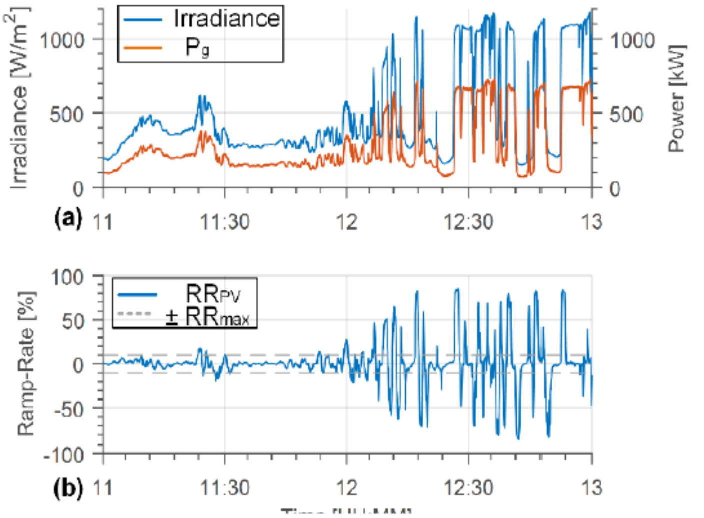


Figure 1.10: System with no power smoothing algorithm. (a) Irradiance and grid power, (b) grid ramp-rate

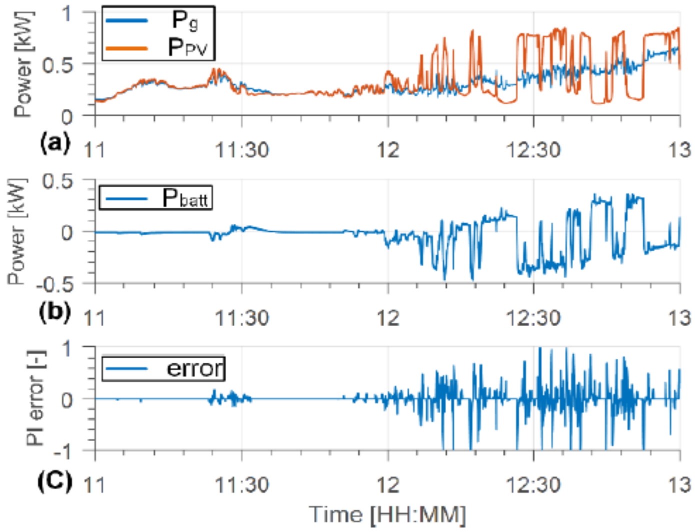


Figure 1.11: Results of the system with power smoothing algorithm. (a) PV power and grid power, (b) battery power, and (c) PI error

The results of the use of the proposed smoothing method algorithm can be observed in Fig. 1.11. First, whenever RRg is higher than the threshold for the RRlim, a PI controller error is generated in Fig. 1.11 (c). This PI error generates a battery power reference which opposes the grid power variations Fig. 1.11 (b). The results of this smoothing can be observed in Fig. 1.11 (a) where the PPV and Pg are presented on the same plot for comparison. As can be observed the high variations in the PV power are eliminated from the injected grid power. Furthermore, the injected Pg increases following the increase in the PPV this is beneficial as indicates that the proposed power smoothing algorithm is capable of reducing the high RR variation and at the same time optimizing the injected grid power[5].

C. Developed source codes to the project and the functionalities

P&Q + CURRENT CONTROLLER

This implements the current controller based on the SOGI. The P&Q control generates the grid current reference.

Inputs:

- Reset – a signal to reset the integrators.
- P – Active power reference.
- Q – Reactive power reference.
- Va – the alpha transformation of the grid voltage, calculated by the PLL. (can be calculated from a SOGI implementation)
- Vb - the beta transformation of the grid voltage, calculated by the PLL. (can be calculated from a SOGI implementation)

Output:

- Ug_ref – grid voltage reference.

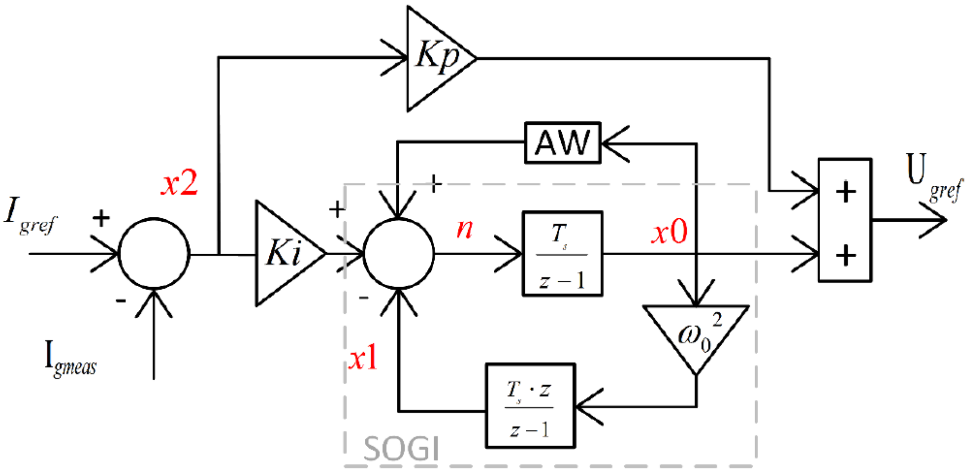


Figure 1.12: Current controller implementation.

ANTI-ISLANDING (AI)

This implements the anti-islanding algorithm. This AI is implemented based on the latest Danish Energy regulation of April 2019. The mentioned regulation can be found on page 39 of [6]. Based on this regulation it is required to implement a passive AI for the voltage or frequency detection.

Inputs:

- Vamp – grid voltage amplitude per unit (p.u.).

---

[5] João Martins, et. al., A Ramp-Rate Control Algorithm for PV with Energy Storage Systems based on linear controllers, *Digital Object Identifier 10.1109/ACCESS.2017*

[6] Dansk Energi, "Guide for connection of power- generating plants to the lo w-voltage grid (≤1 kV)," no. April, pp. 1–101, 2019.

- cl – real-time system clock.

Output:

- trip – trip signal (logic ‘0’ normal operation; logic ‘1’ AI detected).

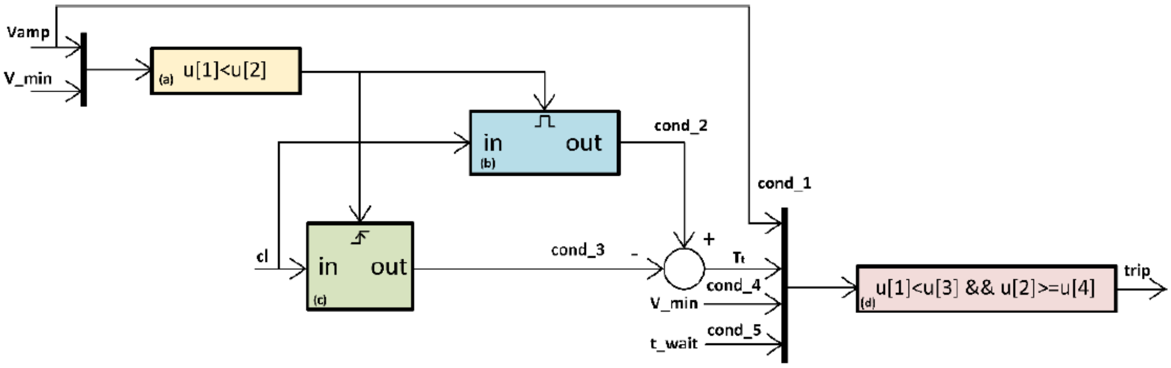


Figure 1.13: Simulink implementation of the Anti-Islanding algorithm.

Further, the Simulation Models, Experimental Models and Build C code for the controllers can be obtained form[7].

---

[7] João Martins and Dezso Sera, PVST Project Documentation, Aalborg University (AAU) report on the C implementation for Living Power with current controller, P&Q reference generation and Anti-Islanding algorithm (AI)

2. OPERATIONAL IMPACT STUDY

2.1 ***Technical impact of PV+storage on the distribution grid and impact on DSO plan tool***

The Danish Energy report "RA 595 – Part 2, Load profiles for dimensioning of low voltage networks; method for aggregation of load profiles" ["RA 595- Del 2, Belastningsprofiler til dimensionering af lavspændingsnet, metode til aggregering af belastningsprofiler"] describes how to create aggregated load profiles for use in the Net-Pro network planning tool. The report also documents the load profiles of several types of residences, electric vehicles, and PV. The PVST project has used simulation tools to predict how customers with both PV production and battery storage will react to various energy prices and tariff scenarios. With small modifications, the method described in RA 595 for producing load/production pro-files for varying numbers of PVST customers will be followed.

Unlike the other customer-types in Net-Pro, PVST customers are extremely flexible and can both consume, or produce power, depending on local circumstances (i.e. weather, spot-market prices). Thus, there are two separate "worst-case" scenarios for these customers: maximum production or maximum consumption in a given hour. The extent of flexibility of PVST customers is explored by simulating their optimal operation under 4 different tariff scenarios. If the network planners using Net-Pro are certain of the future tariff regime in their network, they can choose the load profile that best matches their situation. Alternatively, if the planners are uncertain of the structure of future tariffs, they can plan a network that is adequate in all tariff scenarios.

Profiles are produced for single customers, as well as aggregate profiles for 5, 10, and 20 customers. Profiles for 5 customers are recommended for use in all cases because this profile is similar to profiles for large numbers of customers, while accurately representing the few pioneer PVST customers initially expected in the coming years.

A. Introduction

Fair tariffs reflect the actual cost of utilizing a network at a given place, at a given time. Done right, they will establish an equilibrium between the value network users gain from network capacity and the cost of providing that network capacity. Power-based tariffs are an important tool for fairly internalizing network costs. The motivation of this study was to show how power-based tariffs affect the optimal use of batteries in households with PV production.

METHOD

The profiles documented in this report are based on simulations. The simulations are initialized using measurements from smart meters, and assumptions about the behavior of customers in the future.

The smart meter measurements from a large Danish distribution utility were made available to the project, and 4 216 "prosumer" households with distributed generation (DG) were selected for further analysis. PV is the primary source of DG, but household wind power is also evident from the production profiles with injections at night. For this study, it was assumed that all these prosumers invested in identical battery storage systems (BSS) with the following specifications:

Table 2.1: Specifications

Battery Capacity	6 kWh
Battery Power	4.2 kW
Round trip efficiency	90 %

In the simulations, the measured loads of the prosumers are modified by controlling the BESS to minimize the total operations costs. The cost function includes energy costs in the day-ahead market, losses in the battery, and two types of network tariffs: volumetric tariffs (DKK / kWh) and capacity tariffs (DKK / kW). Battery losses are a function of battery utilization, prices in the day-ahead market in 2017 are used in the simulations. The level of network tariffs is modified in alternative scenarios that are compared in the analysis section.

Battery degradation is not modelled explicitly, however, the round-trip efficiency is chosen intentionally to be lower than datasheet values, thus approximating the costs of battery wear-and-tear. Full documentation of the method used to solve the optimization problem can be found in "A network-constrained rolling transactive energy model for EV aggregators participating in balancing market" in the journal *IEEE Access*.

TARIFF SCENARIOS

Four tariff scenarios are simulated to capture the full range of possible futures tariffs.

Table2.2: Tariff scenarios

Scenario Name	Volumetric Tariff (DKK/kWh)	Capacity Tariff (DKK/kW per day)
Constant kWh	0.38	0
Time-differentiated kWh	0.32 (off-peak) 0.75 (peak1)	0
KW low	0.08	1
KW high	0.08	5

Volumetric tariffs are only charged for energy purchases from the grid. Production from the prosumer does not incur volumetric tariffs. This is consistent with current practice. The scenarios with capacity tariffs include a relatively low volumetric tariff, which is set to the tariff the TSO charges all network users.

For optimization purposes, the cost of capacity tariffs is calculated based on the maximum power exchange with the grid during the optimization horizon (24-hours). Power tariffs are calculated for both consumption and production separately. Charging customers for their daily peak power is probably undesirable in practice, but for optimization, it was infeasible to optimize power over multiple-day horizons.

The optimal operation of PVST prosumers is stimulated for 30 days in winter (Jan. 1st – 30th) and summer (June 3rd – July 3rd). Data is grouped for each hour of the day in each season, and the measurements representing the 98 % and 2 % fractiles (highest production, highest consumption) are selected for creating two profiles for an individual PVST prosumer. Note that all days of a given season are grouped in the same category, weekends and holidays are not differentiated because limitations in the amount of simulation data did not produce enough data to create robust profiles of holiday consumption patterns.

AGGREGATED PROFILES

Profiles for groups of prosumers are not accurately represented by a summation of individual profiles because such a method does not account for coincidence. To account for the coincidence of loads, aggregate profiles were generated for 5, 10, and 40 prosumers.

These profiles were generated by randomly selecting N individual prosumer time-series and adding them together to create a simple sum of the sampled prosumers. This was done 250 times, to create a population of N-prosumers. From this population, for each hour, in each season the 98 % and 2 % fractiles of maximum and minimum load are selected to create two profiles for N PVST customers.

B. Results and analysis

AGGREGATED PROFILES: 5, 10 AND 40 PROSUMERS

The aggregated simulation profiles show that there is a large difference between profiles for one prosumer and aggregations of several prosumers, which is expected. What is surprising is how little difference there is between 5 and 40 prosumers. This can be explained by the fact that parameters in the optimization, such as energy prices and solar radiation, are identical for all prosumers, the primary source of variation in the input is the households' own domestic consumption. Domestic consumption appears to have a magnitude that is small compared to the capacity of the batteries. The similarity of profiles with more than 5 prosumers indicates that further analysis of the simulation profiles is not strongly sensitive to the number prosumers aggregated together, as shown in Fig. 2.1.

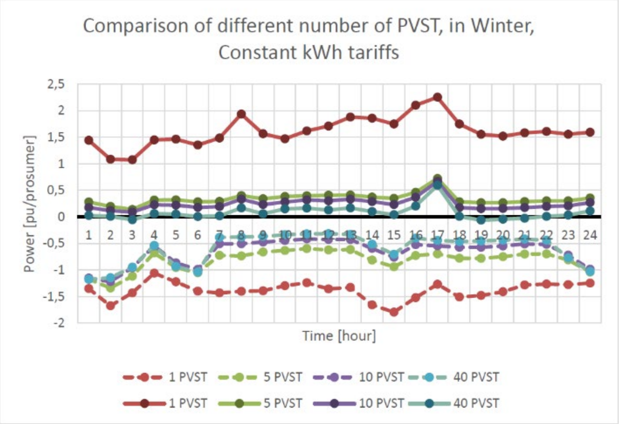


Figure 2.1: Comparison study. Solid lines indicate maximum production, dashed lines maximum consumption.

[Note that in the figure negative values imply consumption and positive values production. The y-axis units are per unit of a prosumer rated battery power, in this case, 4.2 kW]

Considering this and considering that these profiles are intended for planning studies for the initial rollout of BESS in LV distribution systems, profiles of 5 prosumers are used in the analysis that follows.

TARIFF REGIME

Considering the effect of alternative tariffs, the profiles that result from optimizing the 2 types of volumetric tariffs resemble each other, and the profiles optimized for two levels of capacity tariffs also show a strong degree of similarity.

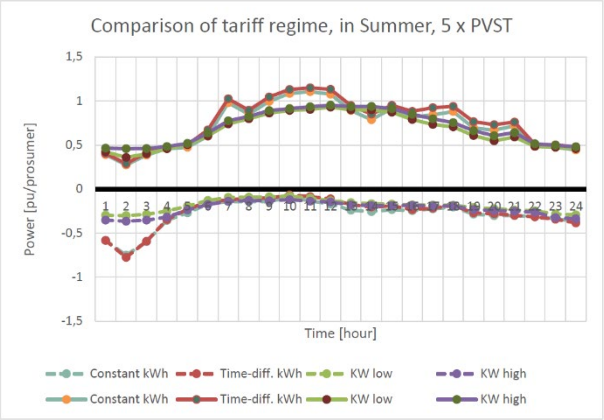


Figure 2.2: Comparison study, summer.

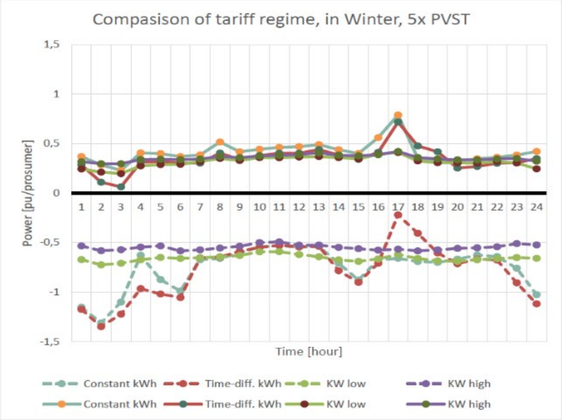


Figure 2.3: Comparison study, winter.

The summer profiles of both types of volumetric tariffs are identical because the peak tariff only applies in winter. The winter profiles of the volumetric tariffs show that the peak tariff reduces consumption during peak hours and increases consumption in the late-night; production, which is not charged volumetric tariffs, is mostly unchanged.

Compared to scenarios with volumetric tariffs, capacity tariffs flatten load and production profiles, as expected. The difference between the low- and high-tariff scenarios are less distinct, even though the difference in capacity price was large (5 times). This indicates that there are greatly diminishing returns, and higher costs, associated with aggressively pursuing an optimization strategy that limits peak capacity usage. Also, notice that during peak hours, the load is higher, and production is lower when using capacity tariffs, compared to volumetric tariffs. Even constant kWh scenario, without peak volumetric tariffs, the price signal from the DAM motivates the aggressive use of the battery to deliver power during peak times (which are also high-price times). At the price levels simulated, the capacity tariff dampens this DAM price signal. This has implications during the transition from today's passive consumers to tomorrow's active prosumers. Someday prosumers may synchronize their use of the distribution grid to create new bottlenecks, but at present, there is a strong correlation between high network load and high prices, which aligns the interests of the network operator and prosumer when using volumetric tariffs.

C. Conclusion

The range between maximum production and maximum consumption of PVST customers is large under any given tariff scenario and increases when variations in tariff regimes are considered. This makes it costly to build a distributions network that can handle the worst-case scenario of all tariff regimes. On the other hand, network planners have an opportunity to optimize infrastructure based on knowledge of long-term strategies about the tariff the regimes that will apply to network users.

Load profiles for summer and winter capture the seasonal extremes found in the consumption/production patterns. Separate profiles for weekend and weekdays were not produced because the quantity of simulation data was too small to create robust weekend profiles.

Profiles created for varying population sizes reveal little variation in profiles above a population size of 5. Considering that public networks with fewer than 5 PVST customers will see limited impact from this type of customer, it is recommended to use the profile created from aggregating 5 PVST customers when dimensioning low voltage networks.

These profiles represent optimal schedules and assume perfect knowledge of future consumption, production, and energy prices. This is unachievable in practice, and it is not clear if practical limitations to the optimization will increase or decrease the demand for network capacity.

2.2 ***Design of new interacting mechanisms among the actors in distribution systems***

With the decreasing cost of solar photovoltaics (PV) and battery storage systems, more and more prosumers appear in the distribution systems. Accompanying with it is the trend of using home energy management systems (HEMS). HEMS technologies can help the households to schedule their energy prosumption with aims such as reduced electricity bills or increased self-sufficiency. However, their economic-driven operation can affect the grid security. Therefore, it is paramount to design a framework that can accommodate the interests of the key stakeholders in distribution systems, namely the grid operators, aggregators, and prosumers.

A. Proposed Transactive Energy Network for Prosumer

Transactive energy (TE) represents a group of promising technologies that facilitate the operation and coordination among intelligent devices as well as stakeholders using price as the sole media. As only prive is exchanged among the parties, their privacy and autonomy can be retained[8].

- Prosumers equipped with HEMS may participate in the electricity market directly, provided that they have access to the marketplace and knowledge of the operation. Otherwise, they can subscribe to an electricity aggregator/retailor whose role is to guarantee their power supply as well as aggregate the distributed resources for market operation.
- In the latter context, HEMS communicates directly with the aggregator to submit their schedule and obtain price information based on their type of supply contracts. Such two-way communication among prosumers and aggregators enables a TE network.
- While from the grid operator side, to ensure efficient grid operation and fulfill the network security, a TE framework can be set between the aggregator and the network operator through a distribution independent system operator (DISO). In this way, a TE framework can be established to ensure a coordinated operation of prosumers, aggregators, and distribution grid operators at the same time.

The proposed TE strategy extends the previous work in several respects. Firstly, TE models proposed in the literature usually consider only two parties, e.g. aggregator and prosumer, or aggregator and DSO, where to the authors' knowledge, there have not been work addressing the interactions of all three parties. Secondly, an innovative PA is designed to represent the network conditions and used to activate the response from the prosumers. Thirdly, the proposed TE framework will not stop unless the constraints are satisfied, which provides a closed-loop framework for the prosumer's operation in the distribution network. The overall conceptual architecture is shown in Fig. 2.4.

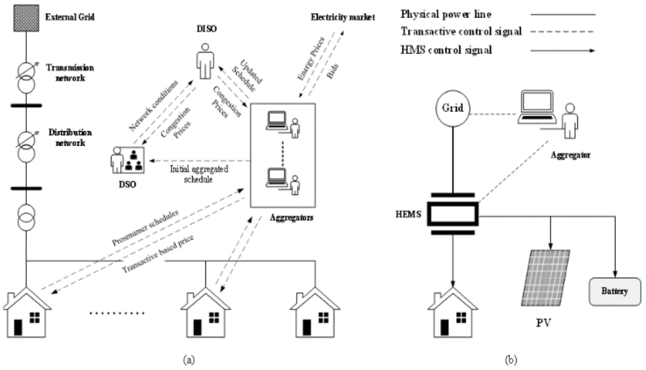


Figure 2.4: (a) The proposed TE architecture. (b) HEMS for PVST prosumers.

---

[8] Hou, Peng, et al. "An Interactive Transactive Energy Mechanism Integrating Grid Operators, Aggregators and Prosumers." arXiv preprint arXiv:1912.07139 (2019).

B. Rolling Operation for Prosumers

The operation of prosumers is expected to follow a forward rolling time window, where within the time window the forecasted production and consumption are used for scheduling. The time window length is designed for 3 hours, with a 1-hour resolution. The proposed rolling window optimization (RWO) model is illustrated in Fig. 2.5.

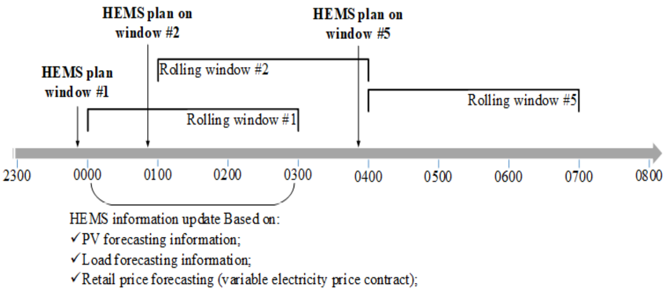


Figure 2.5: Rolling procedure for HEMS controlled PVST prosumers.

The overall operation flow is shown in Fig. 2.6. It is an iterative process until the aggregated schedule from prosumers is valid for the network. In each iteration, the PVST prosumers will first optimize their schedules according to the predicted information and submit the schedule to the subscribed aggregator. The aggregated schedules will be passed to DSO by the aggregators. If network constraints are violated, the TE mechanism will be triggered to help reschedule the PVST prosumer's schedule until the agreement reached among the aggregators and DSO (step 4). Afterward, the aggregator sends the PA to its associated prosumers and then obtains an updated schedule from them. The HEMS manages each prosumer's schedule and the control strategy is designed according to each PVST prosumer's preferences. The aggregator can indirectly influence the prosumer's behavior through a designated price adder.

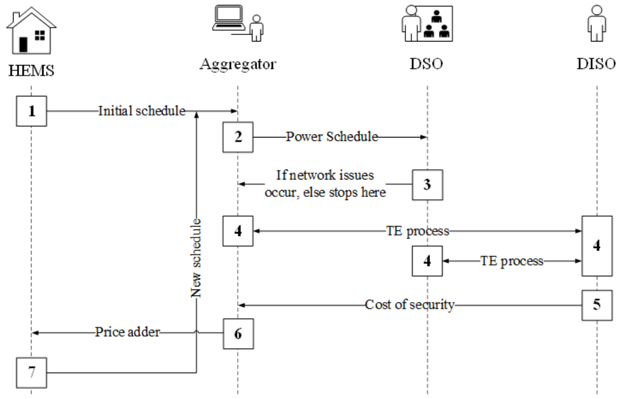


Figure 2.6: The operation flow for the TE system in each RWO

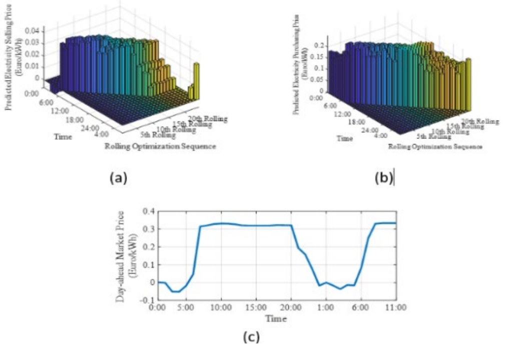
C. Simulation method and results

In this work, it is assumed that there are in total 18 PVST prosumers contracted with two different aggregators in a 0.4 kV low-voltage distribution system which is the same test system [9]. Due to low diversity in PV production and likely similar forecast of the electricity price, schedules from prosumers can have high coincidence where there can be periods network constraints are violated. To simplify the study, it is assumed in the case study that all the prosumers under one aggregator have the same forecast of electricity prices. The predicted variable electricity price that applied for the PVST prosumers are compared with the original variable electricity price in Fig. 2.7. The rolling window length is 8 hours. The day-ahead market prices shown in Fig. 2.7(c) is obtained [10], between 00:00 to 23:00, 5 Mar 2019 for the DK2 area. The profits of each aggregator are considered by using a profit coefficient, which is a profit margin that each aggregator expects assuming each aggregator is a price-taker. This profit coefficient concept applies in both purchasing and selling prices of the aggregator

---

[9] J. Hu, G. Yang, H. W. Bindner, and Y. Xue, "Application of Network-Constrained Transactive Control to Electric Vehicle Charging for Secure Grid Operation," *IEEE Trans. Sustain. Energy*, vol. 8, no. 2, pp. 505–515, 2017.
[10] Energi Data Service, [Online]. Available: https://www.energidataservice.dk/en/dataset/nordpoolmarket

and reflects the differences in aggregators' bidding strategies. The predicted purchasing/selling electricity prices by the PVST prosumers associated with the aggregator 1 are shown in Fig. 2.7(a) and (b) which is obtained based on the prices in Fig. 2.7(c). To be concise, the predicted electricity prices from aggregator 2 is neglected.



(a)

(b)

(c)

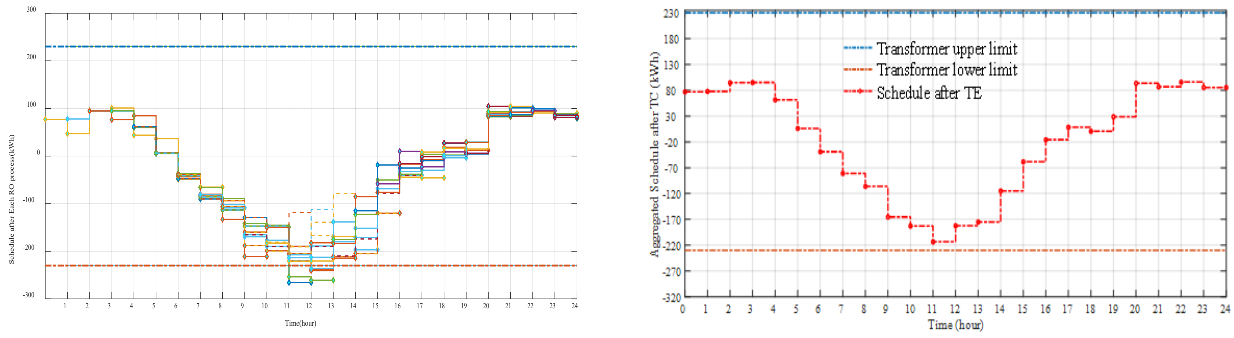
Figure 2.7: Variable electricity price provided by the aggregator. (a) The predicted electricity selling price in each rolling process. (b) The predicted electricity purchasing price in each rolling process. (c) The day-ahead market price.

The aggregated schedule before and after the TE in each RWO process is compared in Fig. 2.8(a) where the solid color lines represent the schedules for each RWO without the TE process and the dot lines represent schedules for each RWO with TE. The final aggregated schedule after each RWO is shown in Fig. 2.8(b). Due to the congestion constraint, the TE will be activated at the 14th-time interval. The aggregated schedules before/after TE in the 6th rolling process is shown in Fig. 2.8(c) while the voltage profile is shown in Fig. 2.8(d). It can be seen that there is a remarkable voltage rise in each bus node. Correspondingly, the CoS is shown in Fig. 2.8(e). The aggregated schedules before/after TE in the 7th rolling process is shown in Fig. 2.8(f) while the voltage profile is shown in Fig. 2.8(g). Both congestion and voltage violation problems occur in this period. After TE, the system voltage constraints are met as indicated by the green line in Fig. 2.8(g) while the congestion problem is also solved as shown in Fig. 2.8(c). The corresponding CoS is illustrated in Fig. 2.8(h). The CoS for each node is the same even when the voltage violation problem is solved. This benefits from the flexibility of PVST prosumers especially the storage units.

To elaborate on this, we reduce the battery size of the PVST prosumer on Bus No. 16 and 32 to 13.1 kWh and 12.3 kWh to 4.8 kWh and 3.6 kWh, power rating to 1.05 kW and 0.80 kW respectively and rerun the program. The overall simulation results are quite similar to the figures illustrated in Fig. 2.8.

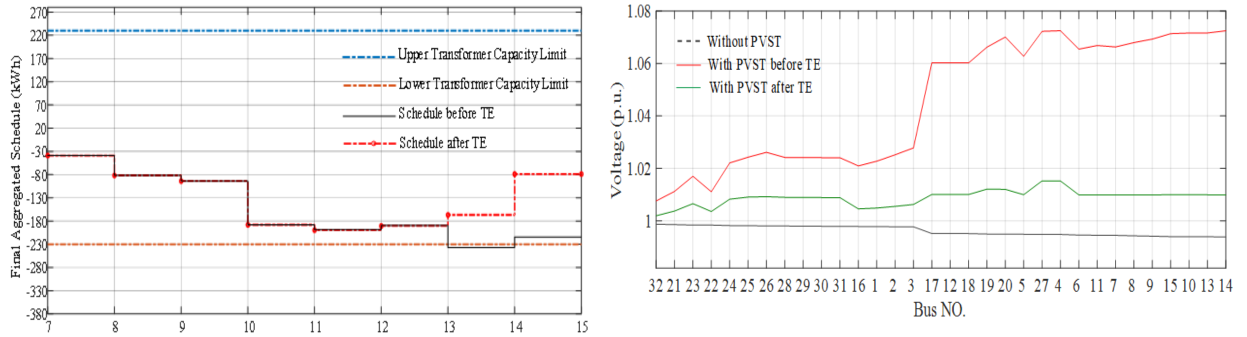
To have the scheme work, the following conditions need to be fulfilled,

- Prosumers can schedule their presumption with a certain accuracy level and are willing to respond to external prices.
- The marginal cost of the TE operation is low, which means the communication channels are reliable, and mathematically the problems can be solved quickly and reliably.
- A balance or imbalance market is available for the aggregators to modify their day-ahead schedule.



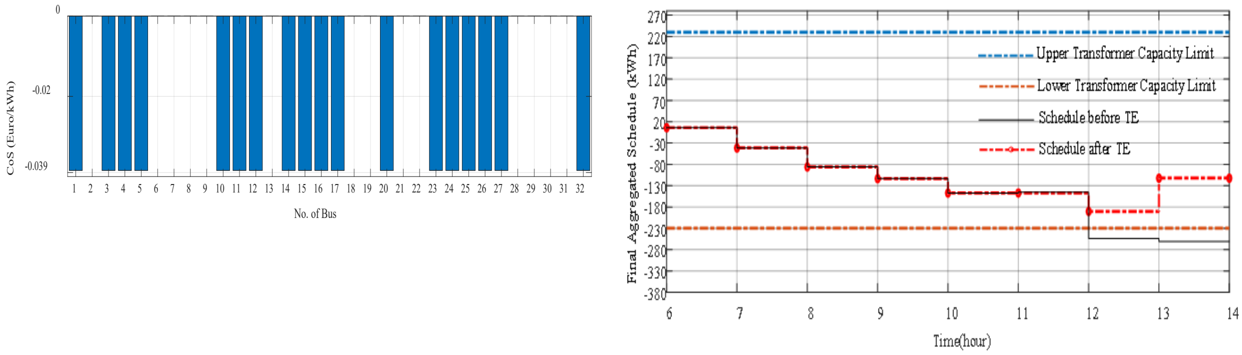
(a). Aggregated schedule of prosumers before/after TE in each RWO process

(b) Aggregated schedule that is submitted to DSO.



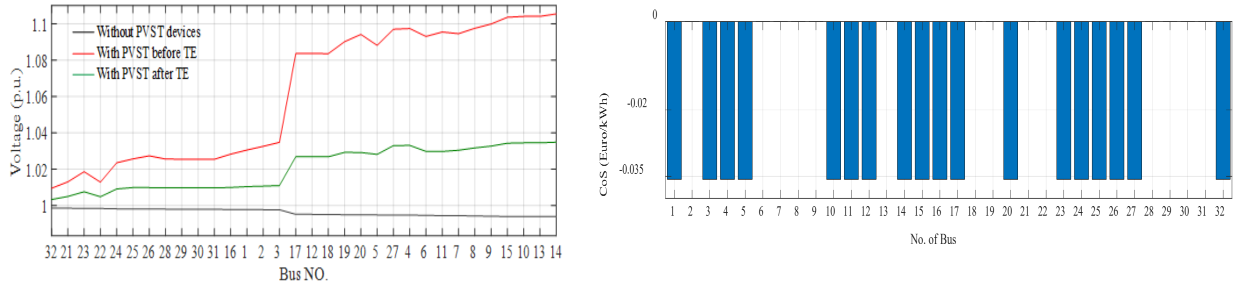
(c). Aggregated schedule of prosumers before/after TE in 6th RWO process.

(d). System voltage before/after TE at 14th time interval in 6th RWO process.



(e). CoS for each node at 14th time interval in 7th RWO process.

(f). Aggregated schedule of prosumers before/after TE in 7th RWO process



(g). Grid voltage before/after TE at 14th time interval in 7th RWO process.

(h). CoS for each node at 14th time interval in 7th RWO process.

Figure 2.8: Summary of TE results.

3. ECONOMIC ASSESSMENT ANALYSIS

3.1 *Cost-benefit assessment from the customer side*

The objective of this study was to simulate the grid on the household side, e.g. the low voltage customer with photovoltaic (PV) and storage (ST). A dynamic energy simulation model of Bornholm is the basis for testing different scenarios with a focus on consumption, photovoltaic, and storage – of course with a target to create a beneficial setup for consumers (and the society).

Bornholm – the island with energy simulation

The island is ideal to use as a test environment because of the isolated position in the Baltic Sea and possess great scalability since the island:

- Represents 1% of Denmark's area
- Contains 1% of the population in Denmark
- Consumes 1% of the energy in Denmark

Figure 3.1: Bornholm pinned out. An island in the Baltic Sea.

And at the same time an island with own infrastructure, industry, hospital, etc. Thus, a community gathered on one isolated island – a test environment in real life. The only (energy) connection to the outside world is one power cable, connected to Sweden, for import and export of power.

A. *Model behavior and control*

The simulation run-period is one year – where the production of energy from traditional production facilities starts immediately depending on the demand of the connected consumers. Wind turbines, and solar panels, etc., only produce energy if the proper conditions with regards to the weather exist.

Also, the consumption of heat will fluctuate according to the weather, because of temperature, where the consumption of heat is calculated by a fixed and a variable parameter. So, consumption is also dependent on geographic location in the matter of heat.

Refreshing demand: The rate of consumption refreshes every five minutes, where also a signal of demand is given. For every hour that passes by, there is a calculation of the expected consumption the following hour. In this way, the model has indicators of the direction (e.g. increase/decrease) that changes per hour but adjusts every five minutes. This turns out to be a very realistic result, which is very close to what happens in real life.

Consumption of electricity occurs on almost the same basic adjusting and calculation technique. Though it is not affected by anything else than a standard pattern based on the data and the current time – call it a typical circadian rhythm tied up according to consumer type.

Summary: A validated model based on an entire island, which represents a small society, is basis and contains:

- The entire electricity grid and consumption
- The entire heat grid and consumption
- 40.236 inhabitants

- 26.023 heated buildings
- 6.500.000 square kilometers
- 19 different production units with their real operational logics including 7 heat-storage tanks
- 6 different heat distribution grids
- 1 electricity grid
- 1 sea cable
- Wind turbines
- Solar cells
- 57.000 weather registrations per year from 3 different measure stations.

Steps in modelling: Every model is created in an iterative process, that can be described by four steps:

1. Analysis
2. Model
3. Simulate
4. Results

For the current project, the following steps are in use:

- Analysis and data collection
- Build the current state model (AS-IS / Baseline)
- Calibrate and validate acc. to data
- Set test scenario(s)
- Simulate
- Results

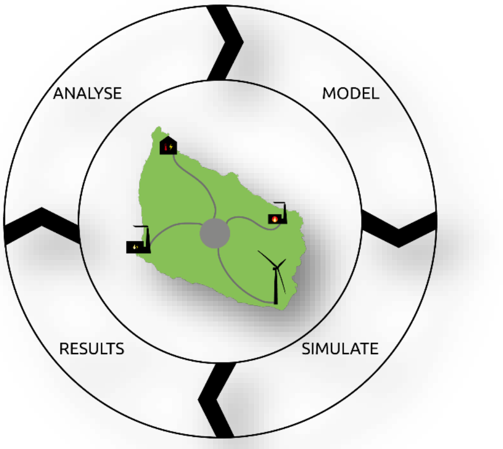


Figure 3.2: The workflow during dynamic energy simulation.

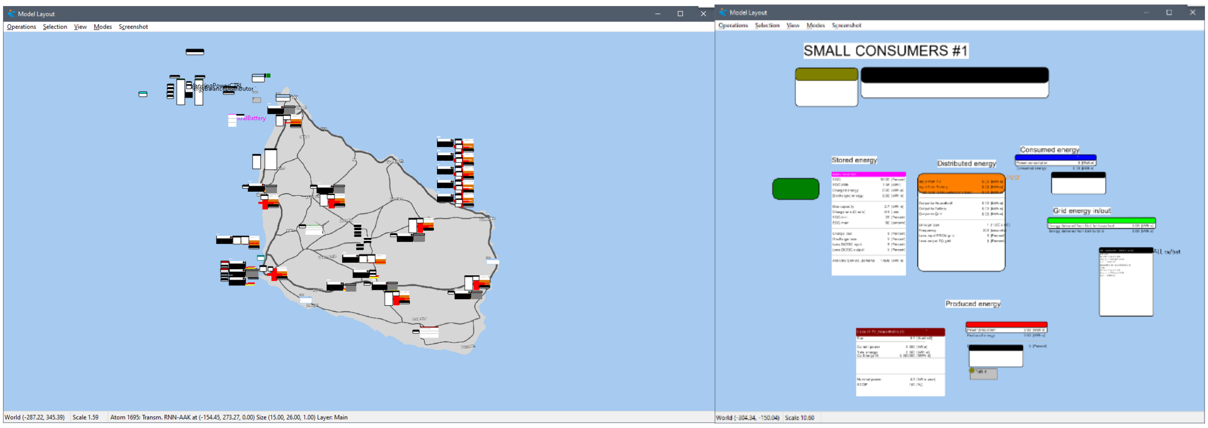


Figure 3.3: Snapshots from the simulation model.

B. Collecting data for PVST

In collaboration with Bornholms Energi & Forsyning (BEOF) a section of the island is selected as a basis to create consumption patterns for power consumption. The data are selected by BEOF based on their insight and knowledge combined with the level of detail in data. For the purpose substation no. 29 (Tejn) is selected to represent consumers in the following.

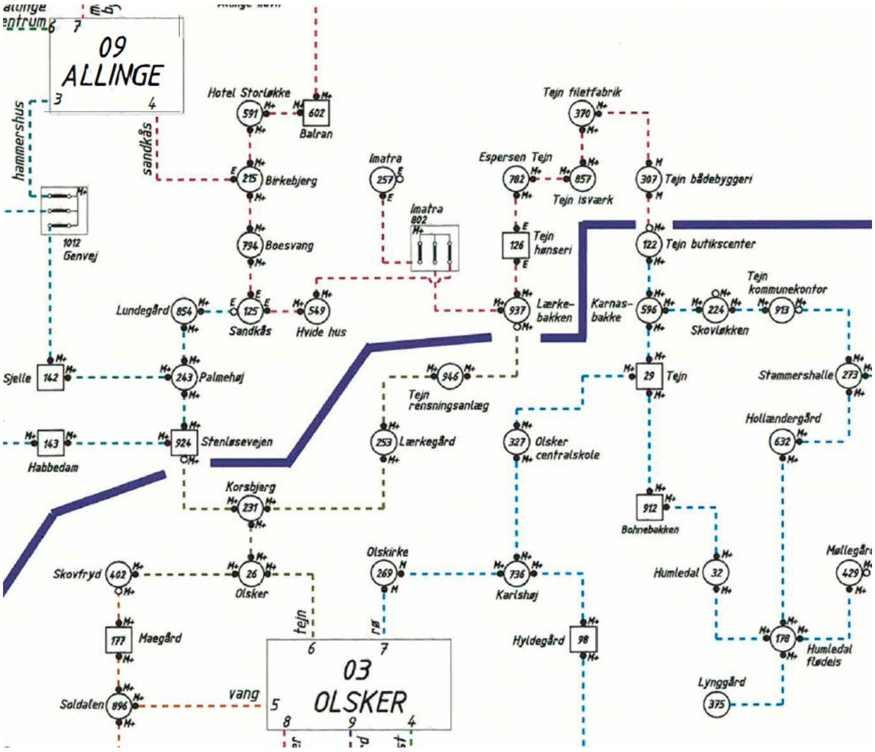


Figure 3.4: Electrical map showing the substation targeted for simulation data.

The data contains different types of households, which can be divided into 3 main groups: Electrical heated, not electrical heated, and with heat pumps, where further analysis is based on data from LOADs without electrical heating and no photovoltaics installed. Data reveals 6 different profiles (3 x weekday and 3 x weekend), which is paired, thus ending with 3 different generic load profiles for consumption patterns:

- Small consumers
- Medium consumers
- Large consumers

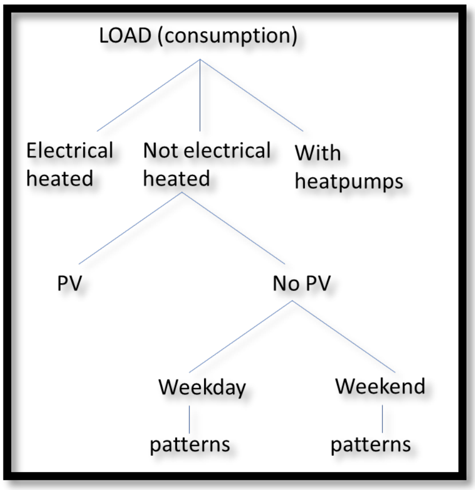


Figure 3.5: Selecting focus for data.

The patterns are derived by using the General Gauss model:

$$f(x) = a_1 e^{-[(x-b_1)/c_1]^2} + a_2 e^{-[(x-b_2)/c_2]^2} + \ldots + a_n e^{-[(x-b_n)/c_n]^2}$$

Thus, it is assumed, that the data is a good representative collection of data for the generic user. The load profiles reveal consumption patterns in intervals of 15 minutes from Monday to Sunday.

The load profiles are implemented in the model, that is calibrated and verified, which leads to a current state model – AS IS.

The load profiles are linked to customer household sizes according to:

- Small household: 1 person
- Medium household: 2-5 persons
- Large household: 6 or more persons

In the data the size of households is represented in the following distribution:

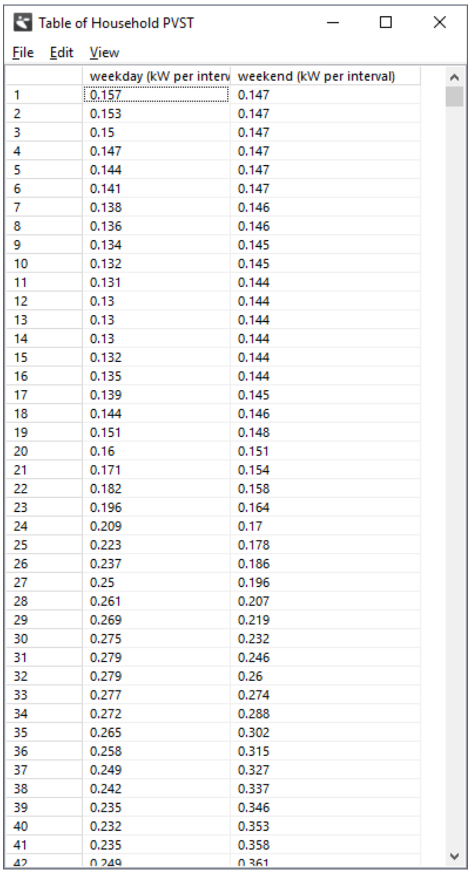
- 4352 small households
- 6687 medium households
- 115 large households

C. Scenario

Preliminary tests were conducted with the following settings:

- PV and battery installed at each household (100% penetration)
- PV power-peak: 6 kW
- Battery capacity with 6 kWh and a c-rate of 0.5 and 10% loss in transmission.

It revealed a noticeable impact on grid consumption and the import/export of the entire island. Before setting the final scenarios, then Frequency restoration reserve is implemented to gain access to the possibility to test Frequency restoration reserve in the system.



	weekday (kW per interv	weekend (kW per interval)
1	0.157	0.147
2	0.153	0.147
3	0.15	0.147
4	0.147	0.147
5	0.144	0.147
6	0.141	0.147
7	0.138	0.146
8	0.136	0.146
9	0.134	0.145
10	0.132	0.145
11	0.131	0.144
12	0.13	0.144
13	0.13	0.144
14	0.13	0.144
15	0.132	0.144
16	0.135	0.144
17	0.139	0.145
18	0.144	0.146
19	0.151	0.148
20	0.16	0.151
21	0.171	0.154
22	0.182	0.158
23	0.196	0.164
24	0.209	0.17
25	0.223	0.178
26	0.237	0.186
27	0.25	0.196
28	0.261	0.207
29	0.269	0.219
30	0.275	0.232
31	0.279	0.246
32	0.279	0.26
33	0.277	0.274
34	0.272	0.288
35	0.265	0.302
36	0.258	0.315
37	0.249	0.327
38	0.242	0.337
39	0.235	0.346
40	0.232	0.353
41	0.235	0.358
42	0.249	0.361

Figure 3.6: Example of data for power consumption.

Thus, following the final six scenarios were outlined for the PVST:

Table 3.1: Scenarios

Scenario	PV [kW]	Storage [kWh]	Frequency restoration reserve provided
1	0	3	Yes
2	0	6	Yes
3	6	0	No
4	6	3	Yes
5	6	6	Yes
6	12	13.5	Yes

RESULTS: The different scenarios are measured on the households by:

- Consumption from the grid
- The ability to consume from own production – directly when producing or by storage
- Ability to deliver to the grid

Table 3.2: Results

RESULTS PER HOUSEHOLD		Scenario						
		BASELINE	#1	#2	#3	#4	#5	#6
Consumed from grid [kWh]	Small	2353	1973	1834	1367	946	799	11355
	Medium	5425	4721	4559	3503	2818	2529	2239
	Large	12096	11355	11098	8755	7963	7698	7422
Consumed from PV/ST [kWh]	Small	0	400	546	1210	1846	2177	780
	Medium	0	741	912	2146	2828	3188	3608
	Large	0	780	1051	3565	3957	4082	4281
Delivered to the grid [kWh]	Small	0	0	0	3267	2630	2300	0
	Medium	0	0	0	2331	1649	1289	869
	Large	0	0	0	912	520	395	196

In total, the households have delivered Frequency restoration reserve according to the figures below (in MWh), which also is an important performance measure.

Table 3.3: Frequency restoration reserve

Frequency restoration reserve Provided	**Up**	**0**	**786**	**2018**	**0**	**4786**	**7889**	**13691**
	Down	0	9285	13010	0	6504	9607	14790

The economic benefit for the household is calculated based on data from Energidataservice.dk based on the DK2 area and the year 2018:

- Frequency restoration reserve demand and prices
- Elspot prices (cost without taxes)

The economic benefit is evaluated on an average estimate for the total power delivered by the PVST setup.

In the table below some totals to compare the different scenarios according to economic value on consumption for households based on introducing PVST. Remark: Scenario 1,2,4,5 and 6 also includes Frequency restoration reserve.

Table 3.4: Economic comparison of different scenarios

Grid consumption		Scenario						
		BASELINE	#1	#2	#3	#4	#5	#6
Cost in DKK based on average spot price	Small	810	680	632	471	326	275	252
	Medium	1868	1626	1570	1206	970	871	771
	Large	4165	3910	3822	3015	2742	2651	2556

The trend is obvious – a significant decrease in energy cost by installing PVST. It seems like the benefit increases with the highest incline until scenario #4 where the PV peak power is 6 kW and the ST capacity is 3 kWh.

Adding the value of delivery to the grid, it provides the following results (using the same cost profile):

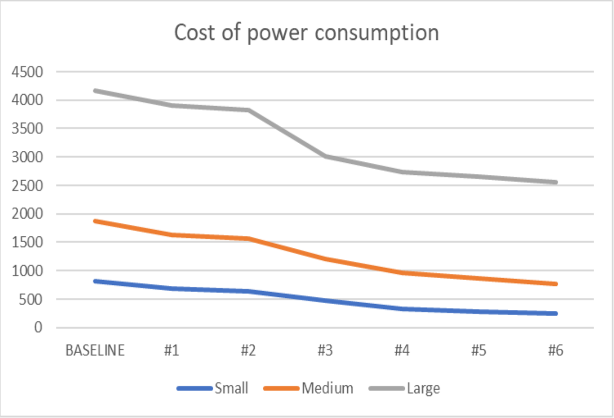


Figure 3.7: Cost of power consumption.

Table 3.5: Updated Economic comparison of different scenarios

Grid consumption		Scenario						
		BASELINE	#1	#2	#3	#4	#5	#6
Cost (net) in DKK based on average spot price	Small	810	632	567	327	107	17	160
	Medium	1868	1538	1462	952	635	493	343
	Large	4165	3818	3697	2592	2273	2167	2048

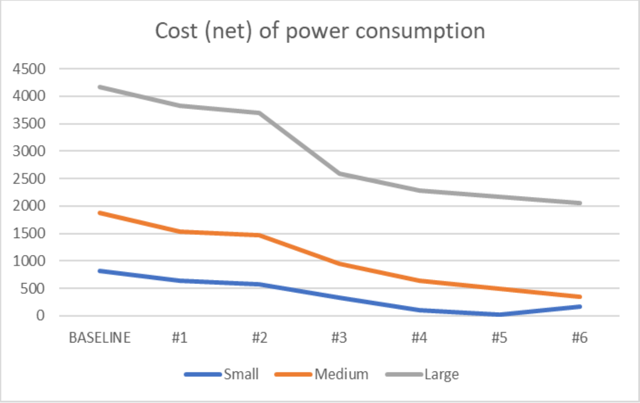


Figure 3.8: Cost (net) of power consumption.

Frequency Restoration Reserve Service

Introducing the use of Frequency restoration reserve will be evaluated on the premise, that every kilowatt-hour of service is compensated according to the rate of balancing power price (up and down) in DKK (2018 data). The results are shown in the table and graph below, and it is obvious that large households don't have a valuable effect in respect to Frequency restoration reserve – at least not according to the given basis of parameters behind this simulation.

Table 3.6: Frequency restoration reserve

Frequency restoration reserve Cost compensation in DKK		Scenario						
		BASELINE	#1	#2	#3	#4	#5	#6
	Small	0	1174	118	0	792	1374	2570
	Medium	0	1264	1725	0	1353	1953	2857

Cost compensation in DKK acc. to the scenario and household size	Large	0	21	30	0	22	30	37

By the simple view of results, that are based on pure power costs and balancing power cost compensation without consideration to taxes etc., then it seems like a valuable business case to the consumer depending on the investment cost of photovoltaics and storage. Large consumers should be investigated further for the size of PV and ST to facilitate a better outcome with regards to Frequency restoration reserve if this feature is desirable according to taxes etc.

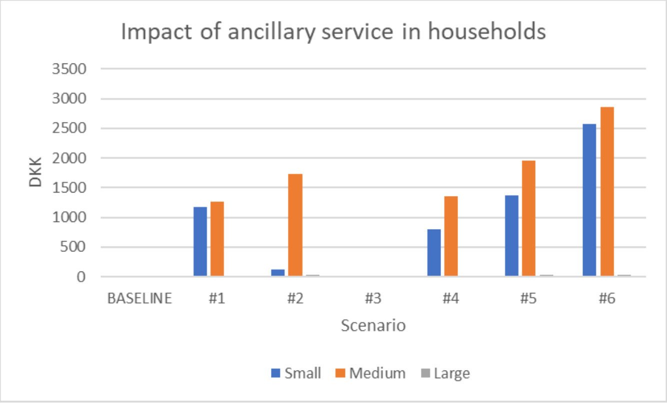


Figure 3.9: Impact of ancillary services in households.

3.2 ***Social-economic assessment of PV+storage system***

A. Reduction of CO2 Emissions

The solar-based system is very different from the traditional power system, such as the coal system. For the coal system, the operational processes, including coal preparation and coal combustion, always generate over 98% of the life cycle for the carbon emission. However, the carbon emissions mainly occur in upstream processes, for example, raw material extraction, materials production, module manufacture, and so on. The upstream processes generate 60% to 70% carbon dioxide of the whole life cycle. The operational processes of solar-based systems, since operation and maintenance are fuel-free, only has about 20% carbon emissions of the total amount compared to fossil fuel.

Due to the difference, it is not reasonable to use only fuel consumption to estimate the CO2 emissions of a different system. A carbon footprint is introduced to avoid the problem. A carbon footprint measures the total greenhouse gas, usually, carbon dioxide caused directly and indirectly by a person, organisation, event, or product. A carbon footprint considers almost all processes of an energy system. In this report, it can be used as a proper estimation of the environmental impact of the solar energy system.

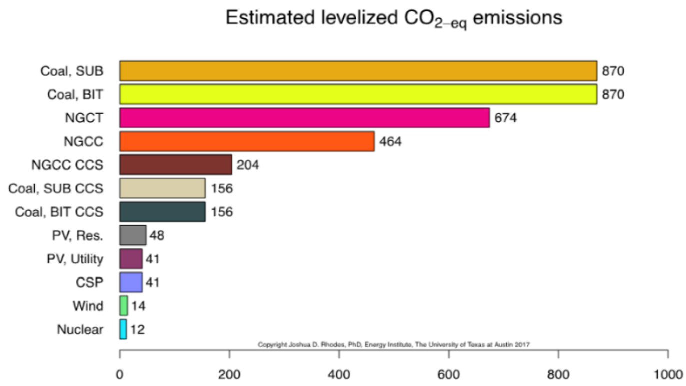


Figure 3.10: Estimated levelized carbon footprint of different source.

Fig. 3.10 shows the estimation of the carbon footprint of electricity generation by different sources. It can be seen in the picture, coal, as one of the most common energies in the world, has the highest carbon footprint of 870g CO2/kWh when used without carbon capture and storage. Even though it is significantly decreased when there is a carbon capture system (about 150g CO2/kWh), It is still much higher than that of solar power, which varies from 40 to 50g CO2/kWh.

The Heath and colleagues at the DOE's Brookhaven National Laboratory found that, when using use different types of material, the footprints of solar power varied from 14 to 45g CO2/kWh [11]. Even then, the footprint of solar power is still over 3 times smaller than that of coal with carbon capture technology.

In the future, the carbon emissions of solar power tend to be even lower. Nature Energy has published research that measures the full life cycle greenhouse gas emissions of a bunch of electricity out to 2050 [12]. The result shows that solar, wind and nuclear power has will have notably lower carbon footprint than conventional fuel such as coal and gas. More specifically, the footprint of solar comes in at 6g CO2/kWh, while coal (109g), gas (78g), hydro (97g), and bioenergy (98g) have much higher emissions, compared to the global target of 15g CO2/kWh in 2050. Thus, solar power is regarded as one of the best choices for the environment.

B. Employment Opportunities and Job positions

In addition to environmental benefits, there is also a social benefit of solar power. The job creation potential is one of the most important metrics when considering the economic impacts of new technologies. There are a lot of studies about job creation, while they use different types of jobs as metrics. So, it is necessary to clarify the definitions of different job positions related to renewable energy. The International Renewable Energy Agency (IRENA) provides understanding definitions of them [13].

The definitions include direct jobs, indirect jobs, and induced jobs. Direct jobs mean that related to core activities, such as manufacturing/installation and operation and maintenance, which are relatively easy to measure. Indirect jobs related to the supply and support of the solar energy industry, such as extraction and processing of raw materials. Induced job refers to those economic activities of direct and indirect employees, government, and shareholders. It is better to consider more types of job positions when measures.

---

[11] Hyung Chul Kim, Vasilis Fthenakis, Jun-Ki Choi, and Damon E. Turney. Life cycle greenhouse gas emissions of thin-film photovoltaic electricity generation. Journal of Industrial Ecology, 16(s1):S110–S121, 2012.

[12] Arvesen A. Humpen¨oder F. Pehl, M. Understanding future emissions from low carbon power systems by integration of life-cycle assessment and integrated energy modelling. Nat Energy, 2:939–945, 2017.

[13] Abu Dhabi. Irena working paper: renewable energy jobs: status, prospects policies. IRENA, 2011.

A review article by Lachlan Cameron et al. [14] has gathered results from 27 publications about direct employment created from three common renewable energy technologies, including PV energy. They also introduce a metric called the employment factor to consider different types of jobs. Fig. 3.11 shows the comparison of employment factors, where the left part is the number of involved people per megawatt capacity of renewable energy, the right part means how many jobs they create per unit of capacity volume. As seen in the figure, solar power takes advantage of creating jobs among renewable energy.

Increasing the opportunities for employment also helps the development of a region. Solar power has even greater potential in accelerating regional economic development than other renewable energy.

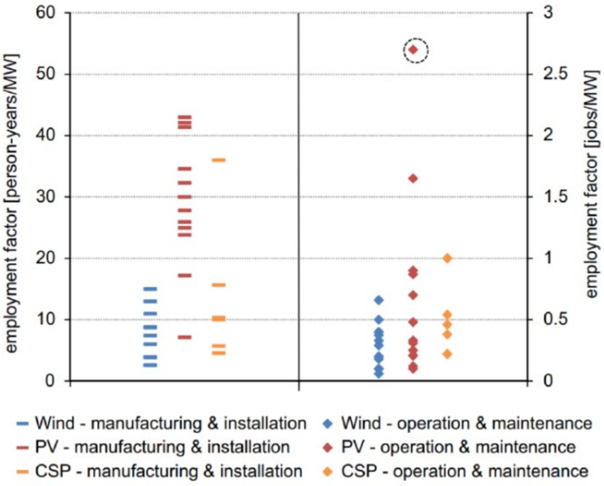


Figure 3.11: Comparison of employment factors for renewable energy technologies.

---

[14] Van Der Zwaan B. Cameron, L. Employment factors for wind and solar energy technologies: A literature review. Renewable and Sustainable Energy Reviews, 45:160– 172, 2015.

4. DSO TARIFF DESIGN

4.1 *Tariff model under PV+STORAGE scenario and Quantifying value of advance grid support*

With the decreasing cost of PV and battery storage, many consumers in distribution networks are now becoming prosumers. Controlling prosumers is an enabling solution for satisfying network constraints via prosumers' flexible consumption/production. In addition to energy prices, the grid tariffs comprise a large proportion of electricity bill in Denmark and thus should be given full consideration in the optimization of operational strategy.

The price of electric energy is set in the day-ahead market (DAM), but some electricity suppliers offer products to customers that reduce customer risk by charging a fixed electricity price.

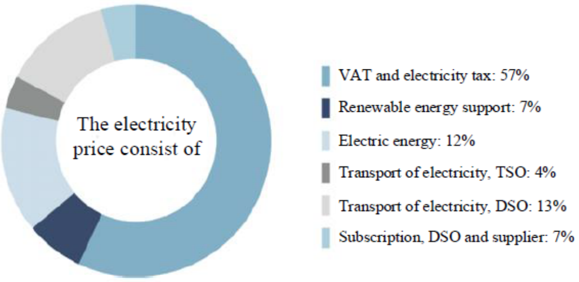


Figure 4.1: Electricity bill for residents in the greater Copenhagen area.

A. *Optimal Operation of PV and Storage System Considering Energy Curtailment*

The energy generated by PV may not be sufficient to meet the load demand, in which case power is delivered from the battery, or purchased from the grid. At other times, the PV output may larger than the consumption and after the battery is fully charged, surplus energy can be sold to the grid. Considering the continuously increasing penetration of renewable energy, there is an increasing frequency of negative electricity prices in the DAM. Hence, a smart control strategy should be made which considers the PV control, electricity price influence, and storage operation at the same time so that the residents will not pay to deliver electricity to the grid[15]. In other words, the PV output should be curtailed in such a case. All the possible scenarios that could appear are illustrated in Fig. 4.2.

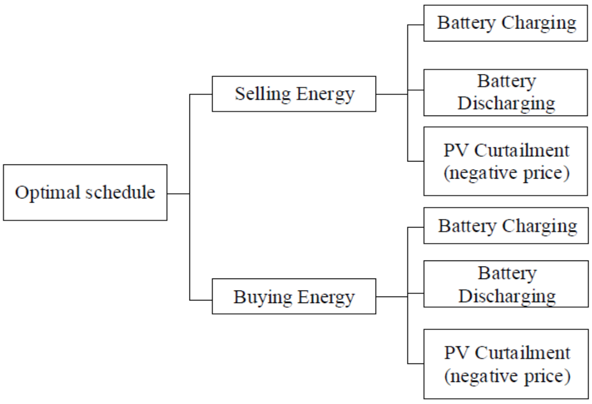


Figure 4.2: Scenario tree for the operation of PV and storage system.

SCENARIO-I: FROM PROSUMER'S PERSPECTIVE

The customer desires to minimize its own cost by controlling the PV and battery optimally. Due to the existence of the negative electricity price, after the optimization energy curtailment phenomenon occurs. The PV output can be controlled through the maximum power point tracking (MPPT) method or it can be curtailed to avoid financial loss when prices are negative.

---

[15] P. Hou, P. J. Douglass, G. Yang and A. H. Hielsen, "Optimal scheduling of PV and battery storage at distribution network considering grid tariffs," The 11th IET International Conference on Advances in Power System Control, Operation and Management (APSCOM 2018), Hong Kong, China, 2018, pp. 1-6, doi: 10.1049/cp.2018.1791.

SCENARIO-II: FROM SUPPLIER'S PERSPECTIVE

In this scenario, the optimal schedule is obtained considering the supplier's interest. The PV's real output is compared with its output assuming an MPPT control strategy

The simulation results for two scenarios are compared in Tab. 4.1.

Table 4.1: Scenario comparison

	Energy Cost (Income) in DAM (Dkk)	Energy Cost with fixed price (Dkk)	Grid Tariffs (Dkk)
Scenario I	0.09	1.48	1.25
Scenario II	-1.87	11.95	9.25

In Tab. 4.1, it can be seen that if the supplier accepts the schedule of the customer as shown in scenario I, he earns 104.81% less revenue in DAM compared with scenario II. However, the customer can save 97.62% of the electricity payment.

The simultaneous activations of the DERs endanger the operation of the distribution system while prosumer flexibility is an enabling solution to help balance the system. To encourage the end-user to participate in the market and help mitigate problems such as congestion and voltage violation in the distribution system, an incentive mechanism should be well designed. It is demonstrated that the grid tariff has a significant impact on the schedule of the end-users while the DAM price influences the schedule of the supplier more than the customers. On the other hand, there is a conflict of interest between supplier and end-user which means that a proper billing mechanism is desired so that the aggregated flexibility from end users can be effectively activated. In the future, the optimization work of billing settlement will be proposed so that the aggregated flexibility from prosumers can be truly activated.

4.2 *Role of retailers under different tariff regimes*

Some of the retailers consider no tariff in the offer to the consumers. Most of the retailers charge the tariffs based on the regulations. The study shows that the optimal solutions are different in the two cases. In the proposed scheme, the retailer will pass a price adder from the DSO. The role of retailer in this scheme is taking responsibility in grid security. This is an assumption in the role defined in the scheme. The current system retailers are dealing with consumers without liability of system security.

4.3 *Economic impact under different tariff regimes*

Residential battery energy storage systems (BESS), alone or in combination with small-scale PV production, are a new and flexible type of customer in low-voltage networks, but presently it is uncertain how their flexibility will be used in operations [16]. Prosumers generally have strong economic incentives to maximize the use of the energy they produce. BESS charging and discharging are often controlled using very simple "greedy" heuristics which succeed in maximizing self-consumption [17] but are sub-optimal when considered in a broader social-economic context.

---

[16] J.M. Santos, P.S. Moura, A.T. de Almeida, 2014, "Technical and economic impact of residential electricity storage at local and grid level for Portugal", Applied Energy, vol.128, 254-264.

[17] J. Moshövel, et. al., 2015, "Analysis of the maximal possible grid relief from PV-peak-power impacts by using storage systems for increased self-consumption", Applied Energy, vol. 137, 567-575.

DSOs can affect the operation of BESS with tariffs that accurately reflect the costs that prosumers impose on the network. Ideally, cost-reflective tariffs would prevent BESS from increasing the cost of operating distribution systems. Alternatively, if BESS operation did increase network operating costs, for example by creating new peaks in consumption during low-price hours, a fair share of the profit generated by BESS operation would be paid as network tariffs, thereby giving the DSO financial resources to reinforce the network.

The combination of RES+BESS in residence risks lowering the volume of transported energy, while simultaneously increasing the range of load on the grid, with higher peaks in both consumption and production. This development challenges DSOs because it undermines their traditional revenue stream, energy-based volumetric kWh tariffs while increasing the cost of providing adequate capacity. This work investigates power-based capacity tariffs that give incentives to BESS to limit their range of load on the grid. This is done using a simulation environment for finding the optimal operation of residential BESS, which reveals the effect of alternative tariffs on the network load and BESS profitability.

A. Study results and discussion

The simulations of RES+BESS customers conducted in this study show that the optimal operation of BESS is sensitive to the network usage tariff. Depending on the tariff regime, the aggregate load of a group of RES+BESS customers may increase their range of load by 80 % (in the High kWh scenario) or reduce it by 40 % (in the Very High kW scenario). Independent of the absolute level of network usage tariff, capacity-based kW tariffs lead to more productive use of distribution network capacity as measured by the DAM profits per kW utilized capacity.

Distribution utilities can use these results to predict the network load from customers with RES+BESS when subjected to different tariffs. This will aid the design of tariff regimes that encourage BESS to optimize their operations considering distribution network constraints, in addition to DAM prices and the value of self-consumption.

5. FACTUAL DATA COLLECTION

5.1 ***Product upgrade implementation aspects***

The development has been implemented by LivingPower with LivingPower's standard UPS product as a starting point. All software developments have been outsourced to PowerCon Embedded.

A. ***Development tasks***

LivingPower's off-the-shelf PowerMind 125 product has been upgraded by means of the following development activities:

- Upgrade of the user interface ("Configurator")
  - Replacement of the physical controller by a more generic and more capable controller platform (Raspberry Pi)
  - Transforming the existing Configurator software and functions into Linux
- Development of a communication interface to support external configuration and control. This is to support development and demonstration of new services.

B. ***Actual implementation of the Demonstrator***

The PowerMind 125 UPS product is modular and scalable for applications up to 3x125 A (3-phase, 80 kW) in steps of 10 kW power converter modules.

The scope has been to demonstrate the concepts and functions – a full product development has not been the objective (and not within reach with this project budget).

This is also the reason why the PV inverter has been connected to the Grid outside the power subsystem, thereby missing the opportunity to exploit PV power during grid outages (average duration 23 minutes per year, accumulated). This is a minor drawback compared to the excessive development efforts otherwise required.

For the selected customer segments (UPS), the local power consumption is statistically rather high (say 10-40 kW). This means that the local load always can use all the power offered by a PV subsystem. Consequently, most grid service algorithms would never require the power subsystem to export power into the grid, as it has a rather large local consumption that it can vary across.

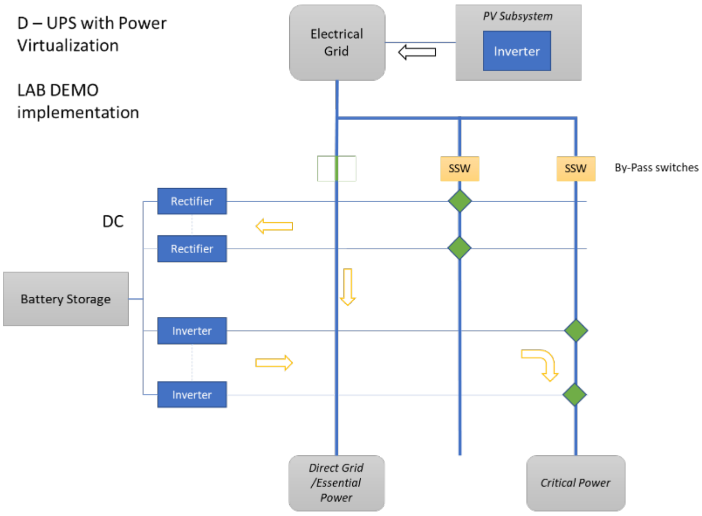


Figure 5.1. The actual implementation of the demonstrator power subsystem. The PV subsystem is connected directly to the Grid.

Figure 5.2. The power subsystem in laboratory testing. The unit is equipped with two power modules (mid position) and a battery management module (bottom position). A single battery string is used (left to the unit), offering 5.4 kWh storage.

For initial testing, the system has been fitted with a battery string consisting of 64 batteries in series connection:

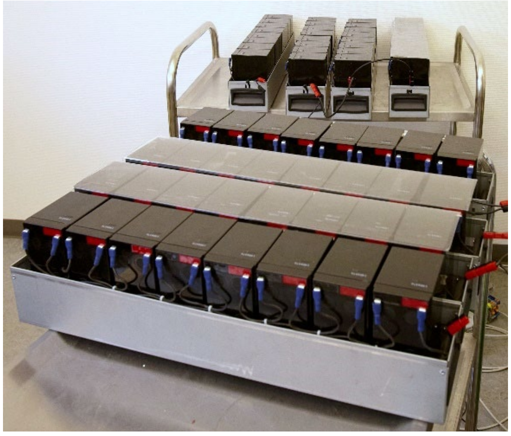


Figure 5.3. A single battery string with 64 units of each 7 Ah/12V – in total this equals 5.4 kWh storage (weight 160 kg).

The battery capacity of the system is scalable. For enhanced studies on Grid Services, a capacity of 15-20 kWh might be suitable, corresponding to e.g.

- A single string with larger battery elements: 64 x 20 Ah/12 V lead acid batteries (15.4 KWh)
- Several strings: 3 strings each of 64 x 7 Ah/12V (16 kWh).

CAUTION: The lab system exhibits voltages up to 1000 V and thus it is extremely hazardous to human life. Furthermore, batteries cannot be switched OFF into a safe state – they are always dangerous, whether the system is in operation or not. Only authorised persons are allowed to work on the unit (L-AUS rules).

The UPS system DC Bus voltage range is from ±346 V (discharged) to ±450 V (charging). Thus, a full discharge is achieved at a battery voltage of 10.8 V (cell voltage 1.8 V), where the system will shut down the outputs/loads.

C. *Implementation of Services*

The actual services are implemented on a dedicated laptop computer comprising

- Communication with the PV subsystem (mainly reading on-the-fly power production data)
- Communication with the modified UPS subsystem (configuring of functions, setting and controlling parameters, reading of parameters)
- Implementation of Grid services (algorithms, control loops).

This solution was chosen to allow for easy access to experiments and continuous developments of Grid Services on a generic development platform (PC) – without the need to modify the UPS subsystem.

(Later, selected services may be embedded into the UPS subsystem Configurator).

The UPS subsystem has been fitted with a function that allows to control the battery subsystem charge state. This is done by commanding the nominal DC Bus voltage of the UPS subsystem. Thus, the UPS subsystem will at any time try to change its power flows such that the setpoint of the DC Bus voltage is achieved.

Note: The UPS subsystem protects the battery lifetime by ensuring that charging current does not exceed the recommended C-rate of the batteries. The C-rate is calculated based on battery size (Ah), and the charging/discharging current is measured by the Battery Management Module.

An Application Programming Interface (API) has been implemented. It is a software interface that enables the Grid Services Console’s reading from and writing to the UPS subsystem.

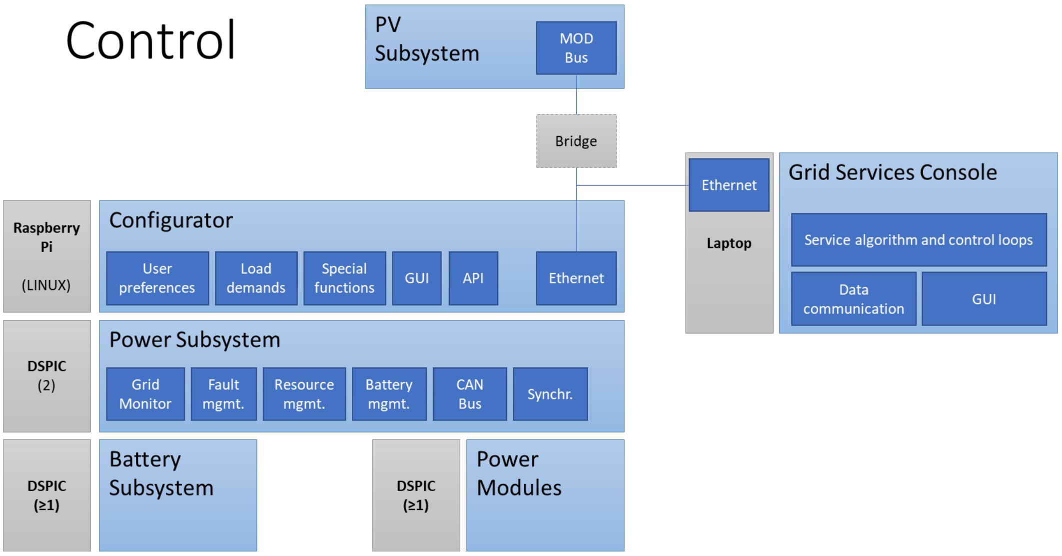


Figure 5.4. Implementation of grid services is carried out based on reading the PV power production, calculating the grid service control loops according to the chosen algorithm, and then commanding a DC Bus setpoint to the UPS subsystem.

Throughout the project it has been an important priority to avoid any modification of the Power Subsystem embedded software (DSPIC environment). This was achieved by exploiting already existing functions of the Power Subsystem: functions that allow the operator to change the battery parameter settings (the battery charging voltage parameter settings varies across battery types).

D. *Functional tests of the power subsystem*

The power system has been fitted with the new controller platform and software.

Functional tests have been successfully implemented verifying

- System initialization and startup/shutdown
- Operation and control of the UPS subsystem
- Management of modules of the power system
- Graphical User Interface (monitoring, data readout)
- API function (read/write of new control parameters).

The laboratory tests were disrupted due to the COVID-19 pandemic. Further testing may be studied in the separate Test Plan.

Due to COVID-19 challenges the development laboratory activities were halted, and it became practically impossible to carry out the following development tasks:

- Final functional testing of the demonstrator
- Development of Grid services interface (PC software)

E. *Ideas and demand for future developments*

a) Grid Export Capability

In cases, where the local consumption is low, it may make sense to be able to export power into the Grid. This development would require

- Grid Parallel control loops (already done within this project)
- Adding Grid Export control loop to the Power Module software (includes vast developments and UPS compliance testing (e.g. EMC, life test, robustness, load sharing))
- Adding functions and capabilities to comply to Grid codes (local production)
- Adding Grid Export function to the UPS subsystem resource management scheme.

b) EV fast charging capability

The Grid capacity is generally not adequate to support local, fast charging of numerous EVs. Furthermore, gigantic investments would be needed to accommodate this kind of peak loads, and the value proposition of such an investment would be questionable.

A local power subsystem could offer this service without imposing severe constraints on the Grid – if

- The local battery has a size that could cover charging of an EV (i.e. 50-150 kWh)
- The local power solution is capable of – in a cost-efficient manner – to provide the necessary charging power capacity (say 50-300 kW).

A power system based on Power Virtualization would be able to do this.

c) Remote upload of new services

Future use could benefit from becoming able to establish new services and functions – remotely.

In this way, one could define new services, make commercial contracts – and then implement the service without going to the physical site.

5.2 ***Laboratory grid connectivity testing of a commercial integrated PV+STORAGE product***

European Standard () specifies technical requirements for the protection functions and the operational capabilities of micro-generating plants, designed for operation in parallel with public low voltage distribution networks.

A. ***Tests to be performed in lab***

a) NORMAL OPERATING RANGE

- The generating plant shall be capable not to disconnect due to voltage when the voltage at the point of connection stays within the range of 0,85 Un to 1,1 Un.
- The generating plant shall be capable to operate continuously when the frequency at the point of connection stays within the range of 49 Hz to 51 Hz.
- A generating plant shall be resilient to reductions/ increase of frequency at the point of the connection while reducing the maximum power as little as possible.

Table 5.1: Minimum periods for operation in under/over frequency situation

Frequency range	Time period for operation
47,5 Hz – 49 Hz	30 min
51 Hz – 51,5 Hz	30 min

b) REACTIVE POWER CONTROL MODES

The control shall be delivered at the terminals of the micro-generator. The micro-generator shall be capable of operating in the following control modes within the limits stated.

- The fix control mode controls the active factor cos ϕ of the micro-generators output according to a setpoint set in the control of the micro-generator.
- The voltage related control mode Q(U) controls the reactive power output as a function of the voltage. A characteristic curve according to Fig. 5.1 shall be configurable.
- The power-related control mode cos φ (P) controls the active factor cos φ of the micro-generators output as a function of its active power output. A characteristic according to Fig. 5.5 has to be configurable. New set values due to a change of the active power output have to be adjusted within a settling time of 10 s. The rate of change of reactive power should be in the same time range as and synchronised with the rate of change of active power.

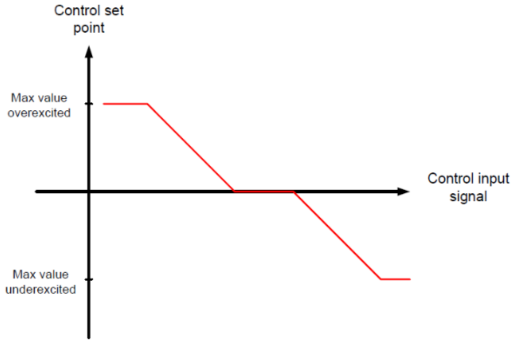


Figure 5.5: Power control characteristic.

c) IMMUNITY TO DISTURBANCES

- **Rate of change in frequency**: With the generating unit operating at nominal power and active factor = 1, connected to a grid simulator set configured as follows. The transition from point to point within each sequence shall be done in 1 second resulting in an average ROCOF of 2,5Hz/s. The time of stable operation at each point shall be at least 20sec or until the output power has stabilised, whatever results in a longer period.
    - Sequence 1
        - Point 1: U = 100% * Un; f = 50Hz.
        - Point 2: U = 100% * Un; f = 47,5 Hz.
        - Point 3: U = 100% * Un; f = 50 Hz
    - Sequence 2
        - Point 4: U = 100% * Un; f = 51Hz.
        - Point 5: U = 100% * Un; f = 48,5 Hz.
        - Point 6: U = 100% * Un; f = 51 Hz.

- **Low voltage ride-through (LVRT):** This procedure aims to provide evidence of the capability of generating units to withstand dynamic low voltage changes. The capability of the generating system to handle Undervoltage events shall be demonstrated for the generating system operating in the full load and partial load range.

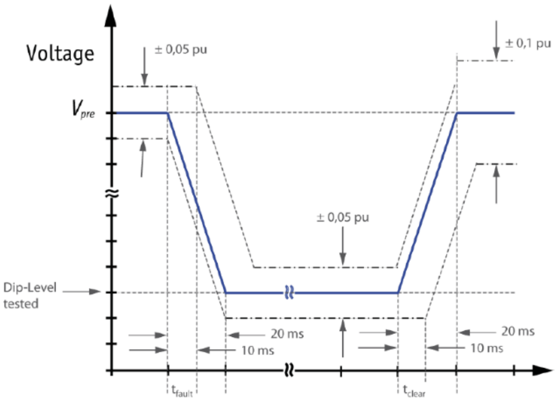


Figure 5.6: Tolerances of the positive sequence voltage for the undervoltage event.

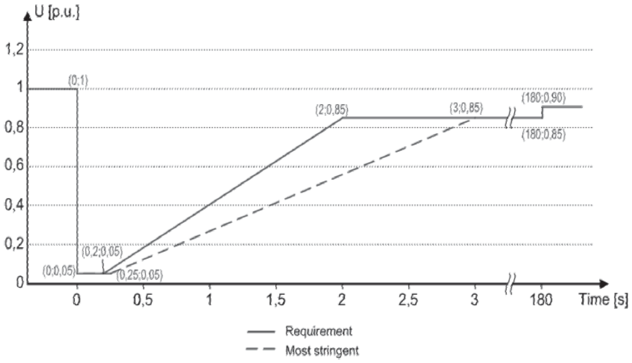


Figure 5.7: Low voltage ride through capability for converter technology connected generating unit.

- **High voltage ride through (HVRT):** This procedure aims to provide evidence of the capability of generating units to withstand dynamic overvoltage changes. The overvoltage tests are optional (depends on test equipment and possibility). It is up to the manufacturer to define the overvoltage event capability chart for the generating system specification to be verified by the overvoltage test.

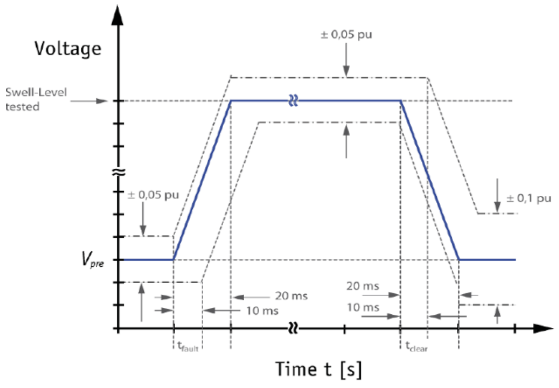


Figure 5.8: Tolerances of the positive sequence over voltage event.

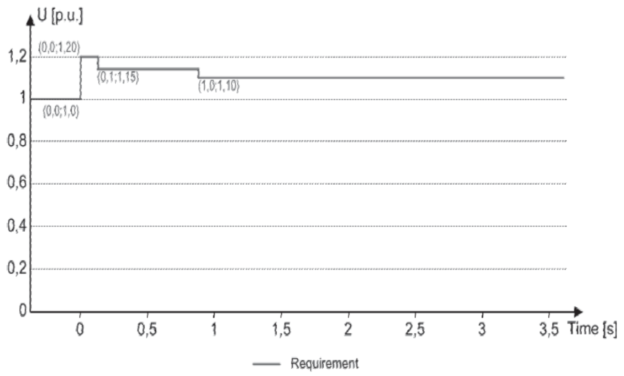


Figure 5.9: Example of an overvoltage capability curve.

d) ACTIVE RESPONSE TO FREQUENCY DEVIATION

- **Power response to over-frequencies:** The two sequences of measures A and B of Fig. 5.10 are performed starting from a power P>80% of the nominal power (sequence A) and starting from a power P between 40% and 60% of the maximum active power Pmax (sequence B). The Fig. 5.10 refers to the droop of 2.4%.

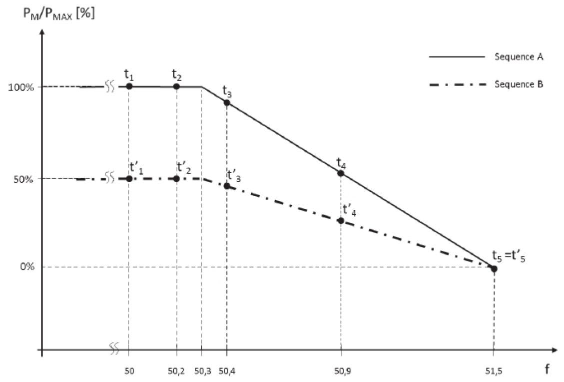


Figure 5.10: Active power response to over-frequency.

Table 5.2: Test parameters for active power response

Droop (%)	Threshold freq. (Hz)	t1 (Hz)	t2 (Hz)	t3 (Hz)	t4 (Hz)
2.4	50.3	50.2	50.6	50.9	51.2
2	50.5	50.4	50.7	51	51.4
12	50.3	50.2	51.2		

- **Power response to under-frequency:** The two sequences of measures A and B of Fig. 5.11 are performed starting from a power P>80% of the nominal power (sequence A) and starting from a power P between 40% and 60% of the maximum active power Pmax (sequence B). The Fig. 5.11 refers to the droop of 2.4%.

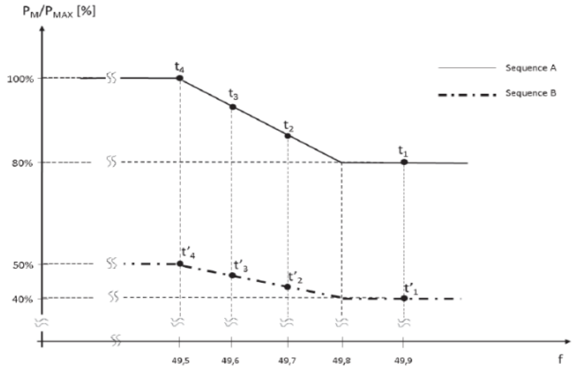


Table 5.3: Test parameters for active power response

Droop (%)	Threshold freq. (Hz)	t1 (Hz)	t2 (Hz)	t3 (Hz)	t4 (Hz)
2.4	49.8	49.9	49.7	49.6	49.5
2	49.8	49.9	49.7	49.6	
12	49.8	49.9			49.5

Figure 5.11: Active power response to under-frequency.

B. *Test system*

The compliance of the specific PV inverter in the laboratory at PowerLabDK, with the Danish grid codes, can be investigated through the design of several test situations and the establishment of an experimental test platform. An overview of the laboratory setup is shown in Fig. 5.12.

To realize the designed test situations, specific voltage profiles at the terminal of the inverter, including different unbalanced and fault conditions must be generated. The 150 kVA power amplifiers in Fig. 5.12 allow this by forming a three-phase controllable grid connected to the PV inverter through lab cells represented by the switchboard in Fig. 5.8. An ELSPEC meter is installed at the terminals of the inverter to measure the output from the inverter and save the measurements on the dedicated server. During the fault condition test, the output voltage and current are also measured by NI CompactDAQ (cDAQ). Since the output from real PV modules is intermittent and directly dependent on the irradiance level and ambient temperature, a programmable DC power supply shown in Fig. 5.8 is used instead of the PV modules, to get a more stable input into the inverter and increase the controllability of the testing platform.

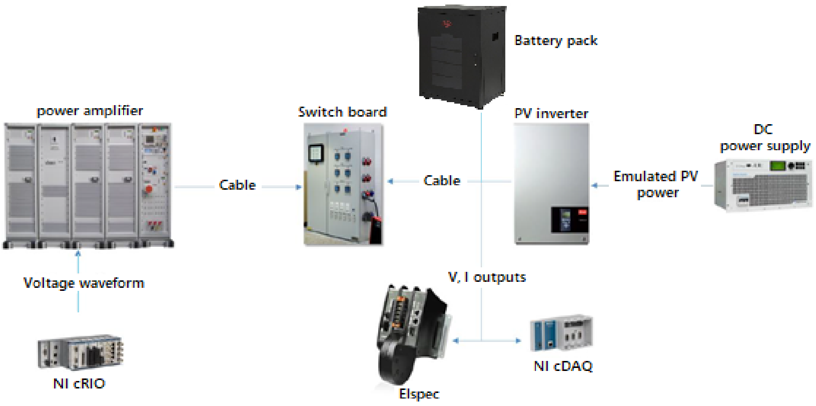
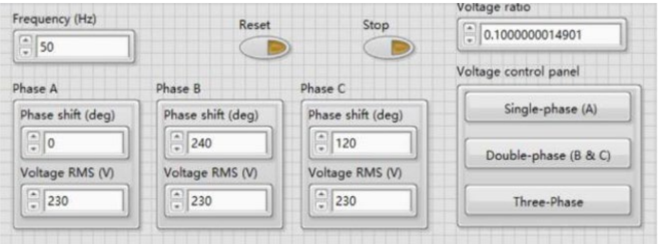


Figure 5.12 PowerLabDK PV inverter experimental platform overview.

C. *Signal generation*

The input voltage, both magnitude and phase angle, of each phase, is controlled by National Instruments (NI) CompactRIO (cRIO) in Fig. 5.12. The NI cRIO is programmed in NI LabVIEW and made capable of controlling the magnitude and phase angle of three analog output channels of the NI-9269 voltage module, through the human-machine interface (HMI) shown in Fig. 5.13. Here "voltage ratio" is defined as the per-unit value of the desired voltage, namely the ratio between desired voltage and inverter nominal voltage. The value is entered in the text box on the right side of Fig. 5.13 and by clicking on of the buttons in the middle, the fault or unbalanced conditions are applied to the corresponding phase(s). The frequency is controlled by entering values in the text box in the top left corner of Fig. 5.13. Since the power generation from PV power plants is usually high when the demand is low and due to the over-frequency support requirements in TR 3.2.1 only over-frequency conditions are tested in the experiments.



Frequency (Hz): 50
Voltage ratio: 0.1000000014901

Phase A
Phase shift (deg): 0
Voltage RMS (V): 230

Phase B
Phase shift (deg): 240
Voltage RMS (V): 230

Phase C
Phase shift (deg): 120
Voltage RMS (V): 230

Figure 5.13: cRIO control panel as human-machine interface.

6. STANDARDIZATION

6.1 *Input to the upcoming technical requirement on DER performance in Denmark*

There is a lack of consensus on how to restrict the impact of harmonics components generated by the RES on the electric power system [18]. Some grid codes worldwide only have limits for the generated current [19], and therefore the local utility is responsible to maintain the voltage harmonics within the limits. While some grid codes just address limits for the voltage harmonics, and the minority of then have limitations for both [20], current and voltage harmonics. Although, in the last case, these two requirements are not always related to each other, and also, they normally do not take into account the background distortion.

6.2 *Input to the EU working groups on PV+STORAGE performance*

Based on PVST testing, some of the suggestions on the inverter functionality are,

- With high penetration of PV+STORAGE expected in the future distribution grid, high-level access to the optimization objective of the PV+STORAGE should be provided to the users, which could be changed in recommendation with the utility, hence forming a mechanism that helps both supplier and the prosumer.
- A time based manual battery charge/discharge functionality must be made available via the battery inverter. This could help prolonging the life of the battery when potential problems arise.

6.3 *IEC standardization working group on microgrid protection*

The test results are quite useful as input to the Technical Specification “IEC TS 62898-3-1: Microgrids - Part 3-1: Technical requirements –Protection and dynamic control”, which is being developed by IEC standardization TC08, SC01, working group 7. DTU is part of the working group. In the specification battery system is key to keep the voltage stability and provide short circuit power to the microgrid. However, the tests of the battery system show that the system protection scheme will need to consider the component level protection settings, where the current in the overvoltage and undervoltage conditions from the battery system can be exploited as input to the project system, which means the protection of the battery system may be relaxed so that the battery can stay sufficiently long during a system event.

7. DISSEMINATION

Publications	Journal Publications	Status
	Peng Hou, Guangya Yang, Junjie Hu, Philip J. Douglass, Yusheng Xue, “A Novel Transactive Energy Operation Mechanism Integrating Distribution	Submitted

---

[18] E. Troester, "New German Grid Codes for Connecting PV Systems to the Medium Voltage Power Grid", 2nd International Workshop on Concentration Photovoltaic Power Plants: Optical Design, Production, Grid Connection.

[19] IEEE Std 1547-2003, "Standard for Interconnecting Distributed Resources with Electric Power Systems", IEEE, June 2003. ISBN 0-7381-3720-0 SH95144.

[20] Elkraft, Eltra, Regulation TF 3.2.6, "Wind turbines connected to grids with voltages below 100 kV", May 2004.

	Systems Operators, Aggregators and Prosumers”, submitted to IEEE Transactions on Smart Grids.	
	Peng Hou, Guangya Yang, Philip J. Douglass, Koen Kok, “Rolling Optimization of EV Aggregator considering V2G via Transactive Energy Approach”, IEEE Access, 2019.	Published
	Junjie Hu, Guangya Yang, Ziras Charalampos, Koen Kok, “Aggregator Operation in the Balancing Market Through Network-Constrained Transactive Energy”, accepted by IEEE Transactions on Power Systems, Special Issue on Transactive Approaches to Integration of Flexible Demand and Distributed Generation.	Published
	ETIP-PV working group, “The inverter as multi-purpose control element: a review”, EU PVSEC 2019.	Published
	João Martins, Dezso Sera, Sergiu Spataru, Abderezak Lashab, “A Ramp-Rate Control Algorithm for PV with Energy Storage Systems based on linear controllers”, IEEE Transactions on Sustainable Energy.	Published
	Conference Publications	
	Philip J. Douglass, Peng Hou, Guangya Yang, Sebastian Martens, “Technical and Economic Impact of Residential BESS on Distribution Systems Under Alternative Tariff Regimes”, CIRED, Madrid, Spain, 3-6 Jun 2019.	Published
	Peng Hou, Philip J. Douglass, Guangya Yang, Arne Hejde Nielsen, “Optimal Scheduling of PV and Battery Storage at Distribution Network considering Grid Tariffs”, APSCOM 2018, HongKong, China.	Published
	Sergiu Spataru, João Pedro Rodrigues Martins, Daniel-Ioan Stroe, Dezso Sera. “Test Platform for Photovoltaic Systems with Integrated Battery Energy Storage Applications.” 7th World Conference on Photovoltaic Energy Conversion. IEEE Press, 2018.	Published
	Tools developed	
	Cost benefit analysis tool in excel for private PV and storage investors	Finished
	New functions in products	
	Communication software and hardware platform of the UPS system are upgraded for better data connectivity	Finished
	Frequency response is developed.	Finished
	Ramp-rate control function is ready for adoption.	Finished
Contribution to research based education	**Course projects and finishing date**	
	Generic Consumption Profile Development Incorporating Distributed Energy Resources (jan 2019)	

Applying data mining methods to incorporate energy storage in household solar PV plants (feb2019)

Design and management of electric energy storage for residential solar PV integration (Sep 2018)

Design of experiments in LV network for inverter testing (Jul 2019)

MSc thesis

Economic assessment of solar PV and storage technologies in Denmark (Dec 2019)

8. UTILIZATION OF PROJECT RESULTS

The WP1 results of the project have been implemented in the software (converter control and system communication) of the battery system developed by Livingpower. The WP4 lab testing results of the battery system are used for the IEC standardization work. The WP2 PVST consumer operation model developed will be used to plan a sufficient energy system of Bornholm. In WP3 the load profile developed for PVST consumers is to be used as input to Net-pro programme developed by Danish Energy for Danish DSOs grid planning. Power Virtualization is a unique solution (patent held by LivingPower A/S, Denmark).

8.1 *Business Innovation based on Services and Contents*

During the last decade, the most obvious trend in the energy arena is a vast transition from classic physical product offerings towards new business models based on services and contents.

Similar evolutions have been seen in other arena – e.g. in telecommunication, where key business focus for many years was conservatively maintained on copper wire transmission, then replaced by optical fibre transmission, then mobile communication – whereas nowadays money are earned mainly within services and contents (e.g. apps, streaming of movies etc.).

Within the power products industry, earnings have for many years been threatened, and the catalogue of defensive measures has been growing:

- Consolidation – Acquisition of competitors
- Cost reductions, including outsourcing of manufacturing to low-wage regions
- Focus – narrowing the product offerings and leaving certain business areas for good…

Today, the remaining giants have realized, that

- They are not able to create or sustain a viable product differentiation
    - A strong and very representative example is the rather costly quest for "leading power efficiency" – where the results are very predictable: Nobody will exceed 100%, and they all will lump together just below that fundamental limit.
- They must become able to master cross-fertilization – expanding their traditional business into the Digital business
    - "Today, we are a software company", as some of them say.

However, inviting digitization is a difficult challenge, often leading into pitfalls like

- Establishing "Digital Business" as a new, independent (isolated) business column

    - In some cases, this is done with no relation to neither traditional offerings and technologies, nor existing organization – so it is genuine entrepreneurship, a discipline that they not at all embrace
- "Augmenting their traditional product with digital capabilities" – an addition to their existing hardware products – an exercise that may take decades, as it is driven by the existing organization, often with a rather narrow knowledge in business development and services and contents. Often the classic products are just fitted with a "digital section" that is capable of radiating enormous amounts of data – job done… – until someone realize that the most important job is to use the data to create value to the customer.

From this project, we have chosen this approach:

- The starting point is a classic product area, the Uninterruptible Power Supply (UPS). The UPS creates value to the customers by cleaning the power consumed from the electrical grid and that is protecting the consumers loads against grid power outages
- Furthermore, we have chosen a product implementation that is already born with "digital capabilities" – a unique, interactive solution that we have upgraded to support
    - Simple (and remote) addition of new services and functions
    - On-the-fly, dynamic control.

This approach envisages a go-to-market strategy focusing on UPS-customers, adding PV clean energy as well as digital services (Grid Services, in this case) on top of a hardware offering with its traditional scope.

Selling points are

- From a business case point-of-view
    - Except for an increased battery capacity, the on-site installation is already-paid-for in terms of the UPS functionality
    - The grid Service solution opens for revenue generation
    - Uptime is improved (enhanced battery capacity)
- The customer becomes a green solution.

8.2 *End User solutions and trade-offs*

The End User characteristics mainly concern his local consumption – like

- Basic load behavior (constant loads, peak loads, load variations)
- The demand for power availability ("uptime") will vary like
    - Direct Grid power quality
        - Typically, 23 minutes of accumulated downtime per year at its best (power plant level, Denmark), further degradation is very likely to appear depending on geographical location, local distribution capacity, neighboring user behavior etc.
    - Short-Break power
        - This corresponds to traditional "generator protected" power – accordingly, the power supply is kept running, but there will be short outages when switching between the Grid and the alternative source (e.g. a generator)
        - Applications: Mostly for applications that are critical (like safety), but that tolerates minor/limited duration outages (lighting, pumps, refrigeration, climate control, actuators, doors, elevators…).
    - No-Break power (Critical Power)

        - Loads are protected by a local uninterruptible power supply solution (UPS) that can bridge all outages up to a given duration
        - The bridging capability is denoted “runtime”
        - Typical runtime is from 10 minutes to several hours
- Demand for other services
    - On-demand High Peak consumption
        - Fast charging of EV – anytime
        - Starting of certain industrial processes (e.g. heating up)
        - Starting of large high-inrush motors and actuators (e.g. pumps)
        - Important step-loads. Typical example: Datacenters compressors when the active cooling takes over from free cooling (happens when outdoor temperature passes say 12-14 degrees C).

From this project, we also include

- A local power production subsystem (PV)
- A local electrical energy storage (battery) to be used basically to smoothen the dynamic net load on the Grid according to various algorithms (Grid service).

Note: The energy arena is likely to develop in the coming years, influenced by factors like

- The Grid capacity will be substantially challenged due to EV charging
- Peak consumption needs to be scheduled to save on capacity investments
- The energy price (price per kWh) will in some cases be replaced by services that you pay for – like
    - High availability
    - Instant peak power
    - High peak/average ratio
    - Zero carbon footprint

This evolution may co-exist in a fruitful manner with local solutions capable of high peak power and high availability – independent of the Grid.

9. PROJECT CONCLUSION AND PERSPECTIVE

During the project, the impact of PV+STORAGE has been studied from a technical and economic viewpoint for both grid operators and market retailers. Also, the interoperability and efficiency of PV+STORAGE system is enhanced for better operational and market value.

This project is one of the first to attempt to assess large-scale PV and storage in the distribution networks, for residential consumers. The project brings valuable results to Denmark in the field of distribution system operation, smart grid technologies, retail market development and enhances the knowledge in this field.