STORY

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Deliverable 3.4 Streamlined control algorithm for storage integration

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1 Publishable executive summary

Streamlined control algorithm for storage integration has been developed for each demo. Due to the complexity and own characteristics of each STORY demo different algorithms have been developed to comply with the specificities of the demonstration sites. These include national regulatory frameworks and on-site equipment, which influenced the structure, the final architecture of the algorithms and finally also the goal. Nevertheless, the developed algorithms have a shared foundation. They are build up on the Key Grid Challenges in Medium Voltage and Low Voltage levels identified in *Task 3.1 "Identification of hardware solutions for grid challenges"* (for more information please refer to the "*D3.1 Report on hardware solutions for grid challenges*"). The Key Grid Challenges are summarized in Table 1.

Table 1: The role of small-scale storage solutions in KGC mitigation (Source: "D3.1 Report on hardware solutions for grid challenges")

Impact factor / KGC	**Security of Supply**	**Voltage Control**	**Current Congestion mitigation**
Balancing of demand profile	1	1, 2, 3	1, 2, 3
Type of DG	1	1, 2	1, 2
Demand response	1	1, 2	1, 2
Type of network	1	2, 3	2, 3
Voltage control strategy	/	1, 2, 3	/

Legend: 1: Scheduling; 2: Optimal connection location; 3: Reactive power control

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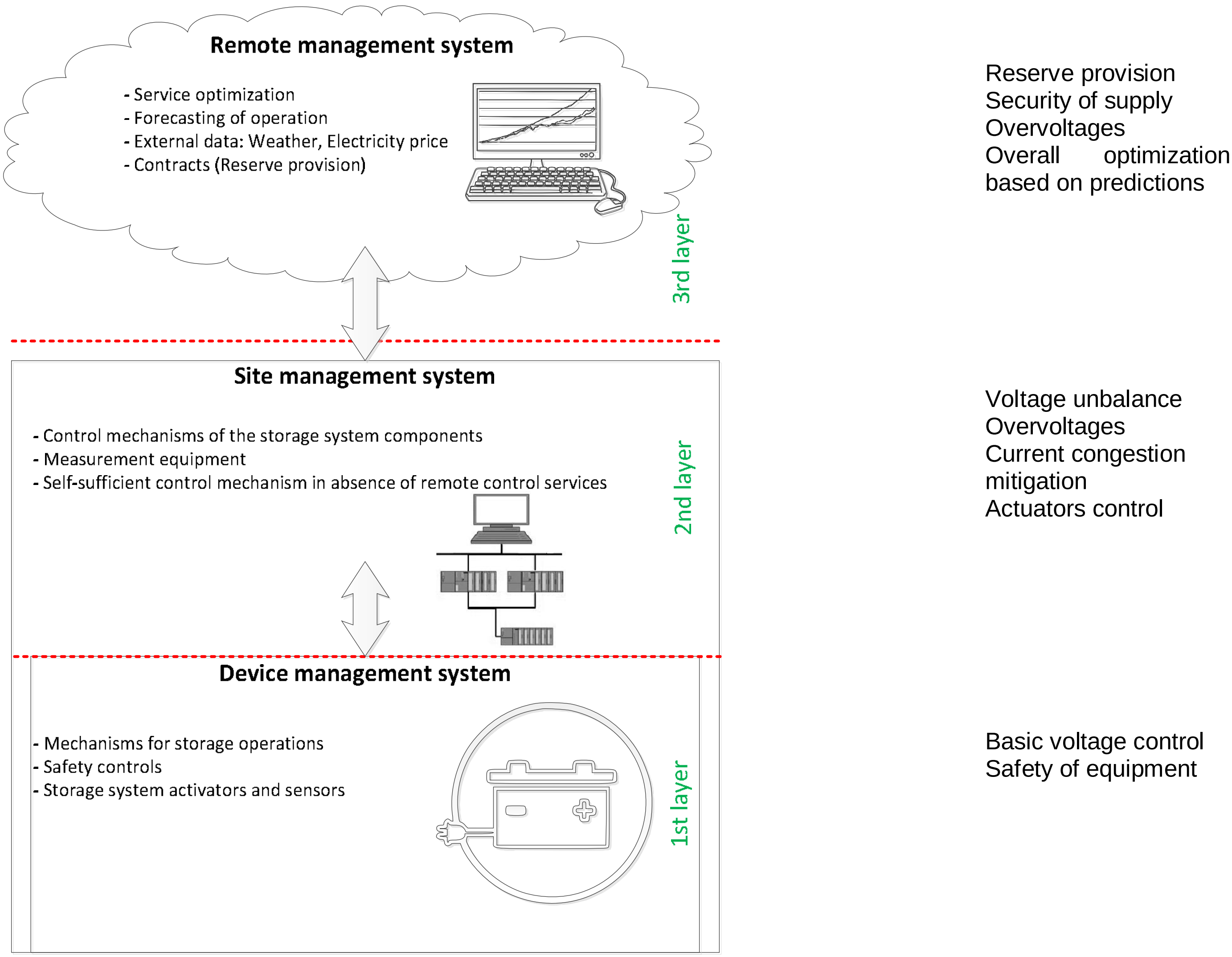

Figure 1: Three-layer control system scheme *(Source: "D3.1 Report on hardware solutions for grid challenges")*

Moreover, the control algorithms base architecture is also common for all the demos and it has also been built upon the three-layered hierarchical structure, proposed in Task 3.1, in demonstration sites are this where relevant (Figure 1). Particularly, as regard the **Demo6**: Demonstration of roll out of private multi-energy grid in industrial zone Olen, Belgium, only the first 2-layers where considered, since advanced control based on overall optimization based on predictions and the other 3rd layer functionalities are not relevant.

- **Demo1: Demonstration at residential building scale- Oud-Heverlee, Belgium**
  - **Demo1: Control for the NZEB building**

The control algorithm has been developed by VTT with the support of THINK, which provided the model of the building, system components technical data, site information and assistance on local regulations.

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- **Demo1: Control for the other buildings in Oud-Heverlee**

The control algorithm has been developed by ACT, Two use cases have been pursued are Minimize grid exchange. & Dynamic pricing.

- **Demo2: Demonstration at residential neighbourhood scale-Oud-Heverlee, Belgium**

ACT has developed the control algorithm

- **Demo3: Demonstration of small scale battery to reduce peak power- Navarra, Spain**

CENER, supported by EXCAL that provided information about the factory energy loads and local regulatory framework, has developed the control algorithms.

- **Demo4: Demonstration in residential district- Lecale, Northern Ireland (UK);**

B9 developed the control algorithms for this demo.

- **Demo5: Demonstration of flexible and robust use of medium scale battery- Slovenia;**

UL, supported by VTT (as regard the creation of the simulation model for testing the control) and EG (as regard requirement and instrumental data of the network), has created the control algorithms.

- **Demo6: Demonstration of roll out of private multi-energy grid in industrial zone Olen, Belgium**

VTT has developed a simulation platform that includes the models of the systems involved in the pilot plant for drawing initial conclusion on the performance of the system and initiating the control algorithm creation. To ensure proper operation, advanced control strategies have been developed by VITO.

The aim of this report is to give an overview on the control algorithms developed per each demo, describing functionalities and aims. The performance of these is described in *Deliverable 3.5 "Report on performance evaluation of control"*.

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2 Control algorithms for STORY demos

2.1 Demo1: Demonstration at residential building scale- Oud-Heverlee, Belgium

2.1.1 Demo1: Control for the NZEB building

The control algorithm is developed by VTT with the support of THINK, which provided the model of the building, system components technical data, site information and assistance on local regulations. The use case, which defines the goals of the control, is defined by both VTT and THINK. In particular, the use case focuses on:

- **increasing renewable energy usage,** rationally maximize the use of renewable energy produced on-site through Energy Storage Systems and
- **minimizing the injection of RES energy** (electricity) to the grid, due to unfavourable local market condition, injecting RES energy (electricity) is not profitable.

The use case has been pursued enabling the following functionalities, which has been considered for building the control algorithm:

- **Peak shaving**
  Energy demand over a threshold will be withdrawn from the ESS (Energy storage system)
- **Demand side management** (Peak shifting)
  Shifting in time the Electric Vehicles load to a convenient time
- **Smart supply scheduling**
  Daily predictive identification of energy supply flows (energy production systems) based on energy/fuel costs and weather data
- **Energy schedule prediction (time shifting**- *intelligent control*)
  Shifting energy (production, storage, consumption) source, considering price and weather forecast, to most convenient time

Overview of the demonstration site and control systems

The demonstration site is located in Oud-Heverlee in Belgium (Figure 2). It is a residential property situated in a natural conservation area. The main components of the energy systems are electricity and heat generation systems (PV/T and vacuum solar-thermal collectors), storages (batteries and both short-term and seasonal thermal storage), and ground source heat pump.

The building has a well-insulated envelope that leads to a low space heating demand. Part of the building foundation piles are thermally activated and used as a shallow geothermal system. In summer time, the building has excess solar energy production. The excess solar thermal energy is stored in the seasonal storages and the excess electricity can either be stored in the battery or exported to the grid. However, at the location of the demonstration site, the electricity feed-in tariff is zero and feeding the excess energy to the grid is not viable.

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Figure 2 - A photo of the demonstration site: the residential building, large array of PV/T panels, three evacuated tube solar collectors and access to underground seasonal heat storages.

Figure 2 shows three vacuum solar collectors and PV/T panels installed on the building roof and the two underground heat storages (hot water tanks) in the demo site. The demo site also has a battery with a total capacity 46 kWh.

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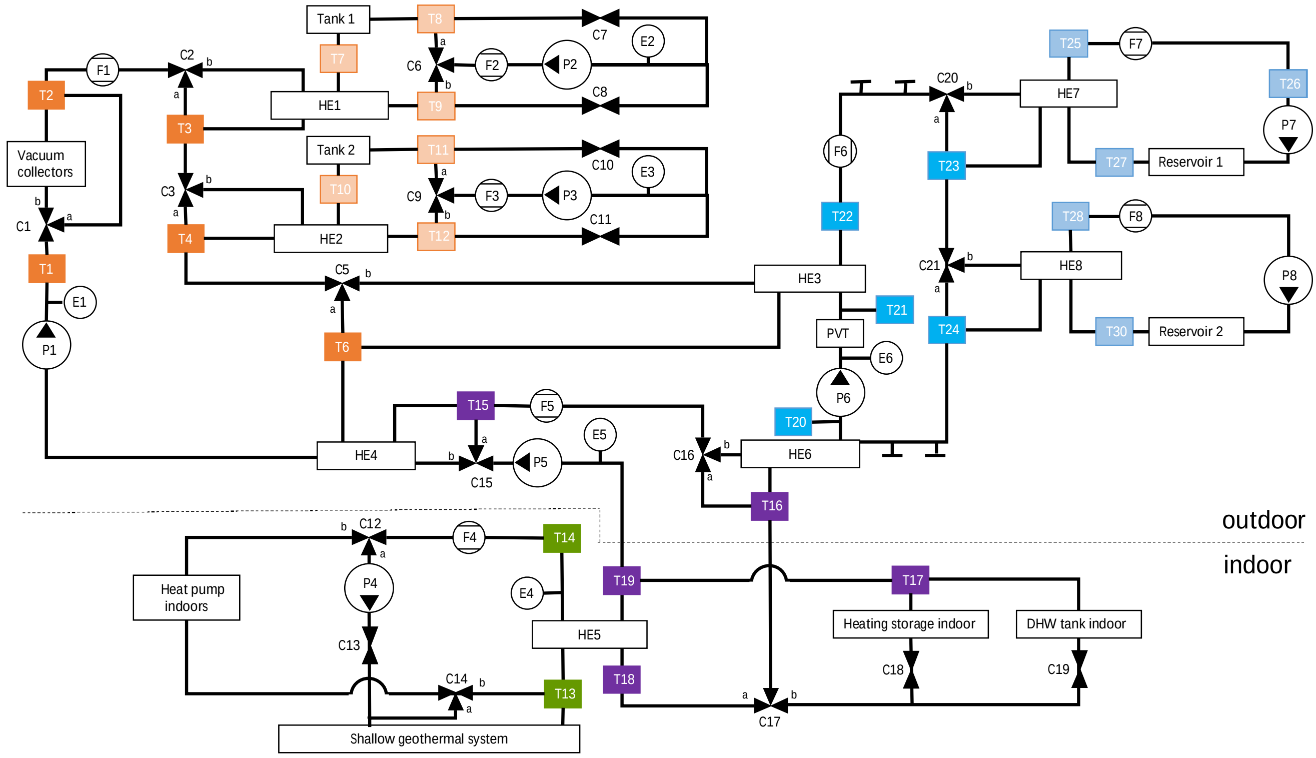

Figure 3 - A hydraulic diagram of the thermal part of the system installed at the demonstration site and showing the circulation pumps (P), temperature (T) and flow (F) meters, heat exchangers (HE), expansion tanks (E) and control valves (C).

The simulation model of the energy system is created by VTT using the Apros software [1] and shown in Figure 3. The model parameters are defined using the data available from technical sheets of the equipment manufacturers as well as available measurements, all provided by THINK. The building model and related building loads are simulated by THINK using TRNSYS software [2]. This data is generated in Task 3.3.1. In addition, weather data, domestic hot water consumption, and electricity (domestic appliances and lighting) consumption profiles are also included in the building model.

In accordance with the control architecture developed in Task 3.1, the model predictive control and the (rational) rule-based controls developed in Task 3.3.3 refer, respectively, to layer 3 and layer 2 of the control hierarchy (Figure 1). Indeed, most of the installed equipment have their own embedded control systems that ensure safety of the devices and maintain operational parameters within safe operation limits. These fall into layer 1 of the control architecture. Layer 2 is related to the control of the whole system including both thermal and electrical components. With regard to the rational rule-based control, the system operation follows pre-defined rules, which allow or prevent energy flows between the system loops and components. These are mainly based on temperature measurements coming from the thermal systems components and outdoor environment. Moreover, the rules are structured in such a way that prioritizes the use of renewable energy generated onsite (self-consumption). Finally, control layer 3 deals with optimization, which

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aims to minimize the operational costs of the system. The optimal controls for the system's operation are derived by an optimizer based on onsite measurements of the current energy status of storages and renewable energy production, built-in predictions of energy system components states, as well as external forecasts of outdoor conditions, non-controllable loads, electricity prices and other factors.

Rational control system

The rational control system at the demo site envisages control decisions that aim at maximizing the use of solar heat for space heating and domestic hot water in order to minimize the electricity consumption of the heat pump. The control decisions are based on temperature measurements of the fluid flow at the outlets of vacuum solar collector and PV/T systems and those of potential sinks: indoor and outdoor tanks and boreholes. In a situation of no fluid flow or similar, the measurement is taken from relevant heat storage. The process of determining whether the heat transfer is possible from a heat source to a heat sink is schematically represented on Figure 4. Heat sources include heat-generating equipment - vacuum collectors, PV/T panels, heat pump and warmer heat storages. Heat sinks are heating and domestic hot water tanks of building, cooler heat storages, including swimming pool and shallow geothermal system.

In addition to temperature gradient based determination of heat transfer possibility, addition checks are in place to maintain operation of different loops of the system within their temperature limits, determined by warranty conditions, materials used and environmental considerations.

As highlighted earlier, priorities are assigned to each rule associated with a specific system operation. Particularly, utilizing the solar heat for indoor space heating and domestic hot water tanks has the top priority while charging the seasonal heat storage tanks has the second priority and ground loop (boreholes) has the third priority. In the PV/T circuit, the objective is to cool down the panels in order to increase their electricity yield. The extracted heat is released into a swimming pool, brook or ground. The heat transfer from the seasonal storages to the indoor tanks takes place when the seasonal storages are warmer and when vacuum collectors cannot produce enough heat, for example during night. The procedure of determination of operating heat transfer paths using priorities is shown on Figure 4.

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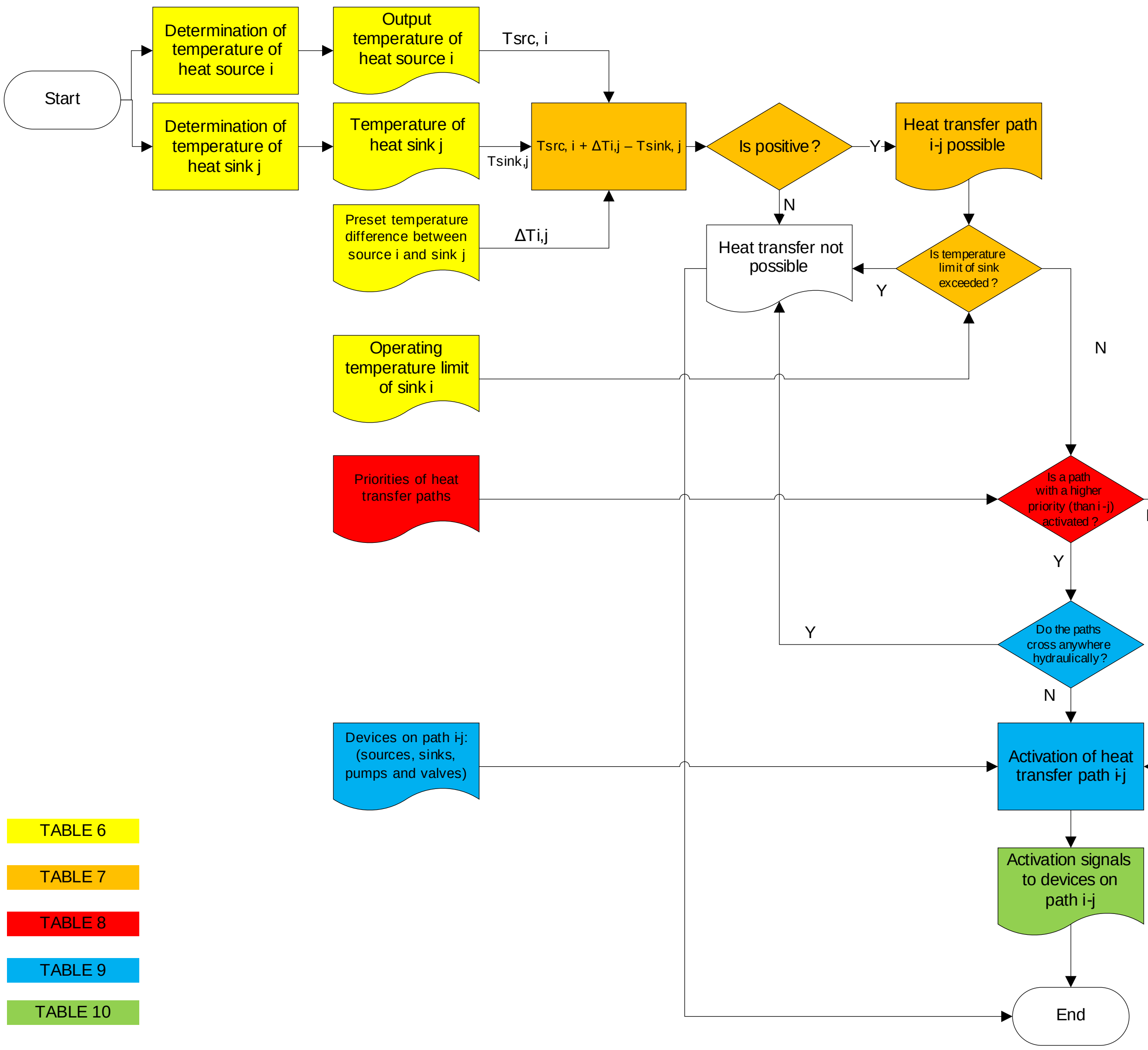

Figure 4: Determination of possibility of heat transfer between sources and sinks and heat transfer paths using priorities.

Out of paths with possible heat transfer (and when temperature or the source does not exceed temperature limits of heat sink), a path having the highest priority is selected to be operated; at the same time the paths, which use the same hydraulic loops and equipment, as the selected path, are excluded.

The detailed description of the rational control in the simulation model is provided in Appendix A. The pre-set rule for the battery storage is to minimize the imbalance between the onsite electricity generation and total electricity load. The excess generated electricity is stored in the battery and in the case of a deficit, the stored energy is utilized to cover the demand.

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Intelligent control with optimization (MPC control)
The model predictive control (MPC) for the energy system of the demonstration site uses a model with simplified physics as an optimal control problem, which is discretized and solved as a mixed integer program. Each component is modelled as a stereotype, consisting of simplified physical equation describing the behaviour of that component. The current implementation uses one-hour time steps and a 24-hour horizon. The MPC controller currently optimizes the net electricity cost and estimated final value of stored heat and electricity at the end of the planning horizon. The MPC control uses hourly indicative prices for buying electricity and a zero price for selling electricity back into the grid. As the model used for predicting the future state utilizes many simplified assumptions and uses discrete time steps, which tend to be longer than the time steps used by rational control, the system under control is very likely to operate better when MPC and rational control complement each other, for example, in situation where rational control could prevent undesired behaviour caused by model mismatches or duration of time steps. For example, timely stopping of circulation, mixing or undesired energy exchanges that might occur during the last time step if the system is operated solely by MPC. In this study, the MPC operated with only two corrections:

1. Battery charge power is the maximum of (i) the MPC command or (ii) excess solar power generation by PV/T over total electric load;
2. Battery discharge power is the minimum of (i) the MPC command or (ii) deficit solar power generation by PV/T over total electric load.

Both corrections aim at avoiding feeding into the grid (at the price of zero). The first correction is to make sure that excess onsite solar energy generation is transferred to the battery first and only then to the grid. The second correction is to avoid discharging more power from the battery than the current electrical load. In such a case, the excess would be exported to the grid.

2.1.2 Control of the NZEB electric system

Optimal control of the whole NZEB energy system proved to be difficult because the system is rather complicated and has several different timescales. In our simulation experiments, MPC is able to gain an advantage over rule-based control mostly by making better use of the in-house battery, and those simulations did not even include electric vehicle charging (we had no data about the EVs at the time). These findings led us to study control of the electric system alone.

The electric system consists of PV/T panels, a power grid connection, a fixed in-house battery, two electric vehicles and various other power-consuming devices (heat pump, home appliances etc.). We consider control of the grid connection (energy export and import) and the batteries state of charge (fixed batteries and EV batteries). Everything else is regarded uncontrollable. For modelling purposes, we assume that the full electrical production capacity of the PV/T panels is always utilised and any surplus is sold to the grid. Unfortunately, the grid operator will not pay for this surplus power. Thus, in practice PV, production capacity is simply left unused in surplus conditions; no more power is drawn than can be used or stored on site. From a modelling perspective, this curtailment of production is equivalent to selling the surplus at zero price. However, in reality it presents a measurement challenge: we can only measure power that is

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actually produced by the panels, not how much they could have produced with more load. This curtailment problem is discussed in the subsection 2.1.3 of the report.

Our control objective is to minimise net energy cost, as in the whole system case. The electricity price is a simple day and night tariff, and as mentioned above, the grid operator does not compensate customers for exporting energy to the grid. This means that the objective is to minimize the imported energy cost. Should this change, our model allows arbitrary time series for both buying and selling prices.

The site battery is modelled as a simple storage with losses: a fixed proportion of charging power is lost, the rest becomes dischargeable energy. Charging and discharging power can be varied freely up to given maxima and minima respectively. EV batteries are modelled as charging tasks: a time window when the car is available for charging and an energy requirement that must be provided during the time window. There is some uncertainty on the amount of control actually allowed by the EV chargers. Therefore, we made two models: One allows charging power to vary freely between zero and a given maximum, as long as the total energy requirement is satisfied. The other requires that, once started, charging proceeds with a fixed power until the energy requirement is met. Only the starting time can be chosen. In any case, the EV batteries are discharged only by driving; we do not consider using them for buffering on-site energy use.

After discretising time (we used 15 min steps for a 48 h planning period), the variable charging power model becomes a linear program, which can be quickly solved with the simplex algorithm. The fixed charging power model yields a mixed integer program, which is a much more difficult problem type. However, in our case the problem is small enough to be easily solvable with standard techniques such as branch and cut.

2.1.3 Handling the effects of curtailment in the input data for MPC

The effects of curtailments are evaluated using a trained machine-learning model, using Gradient boosting ensemble method. The used input data for machine learning have been retrieved from Basen platform. They include yearly series as following:

- PV production data,
- power ac (house total power consumption including EV charging demand)
- SoC data and
- weather station data

In order to detect PV curtailment periods (possible timespans when PV curtailment may occur) along one year, the following conditions are considered:

- full house battery (SoC data values corresponding to 100%) and
- PV production value achieved with machine learning is greater than measured electricity consumption.

The aim is to use machine learnings to filter out the timespans from the measured data where PV production may be curtailed. Thus, in order to properly train and create the machine-learning

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model, only the data segments where curtailment cannot occur are used. This has ensured that the PV production estimations, done by the trained machine-learning model, do not consider potential period where curtailment could have occurred.

2.1.4 Demo1: Control for the other buildings in Oud-Heverlee

ACT has developed the control algorithm. Two use cases have been pursued:

- **Minimize grid exchange.** Peak shaving of the electrical consumption in the neighbourhood is achieved by minimizing the maximum energy exchanged with the grid of a house. This Use case can limit the connection capacity, as limited by the main home fuse power, an end-user has to reserve from its distribution system operator (DSO) and thus reduce costs. Furthermore, it can ensure a neighbourhood with a high penetration of PV does not cope with grid stability issues by scheduling the consumption of heat pumps or batteries during periods of high PV production.
- **Dynamic pricing.** Although many variants of price-based demand response programs exist, most of them can be classified into two subcategories: (i) time-of-use on day-ahead and (ii) real-time pricing. These programs are characterized by time-varying tariff structures that can be based upon short-time wholesale prices. In case of day-ahead time-of-use pricing, each day is divided into 24 different time blocks of one hour to which different electricity prices apply. In this report, this is referred to as Dynamic pricing or DyP. For the DyP case, the tariff structure assumed applicable is an hourly changing price as reported on the day-ahead spot markets. This tariff structure is already present in several of the Northern European countries such as Norway and is expected to be implemented in Belgium together with the rollout of the so-called smart-meter that will measure and communicate the energy exchange with the grid on a fifteen-minute basis. Additionally, the day-ahead spot market price is a good representation of the electricity grid status.

The use cases have been pursued enabling the following functionalities, which has been considered for building the control algorithm:

- **Peak shaving**
  Energy demand over a threshold will be withdrawn from the ESS (Energy storage system)
- **Demand side management** (Peak shifting)
  Shifting in time the Electric Vehicles load to a convenient time
- **Smart supply scheduling**
  Daily predictive identification of energy supply flows (energy production systems) based on energy/fuel costs and weather data
- **Energy schedule prediction (time shifting**- *intelligent control*)
  Shifting energy (production, storage, consumption) source, considering price and weather forecast, to most convenient time

The following Table 2 shows the buildings in the neighbourhood. Particularly, the building indicated with colour (numbers 1, 4 and 7) are part of this section. All these houses are heated by an electric consuming or producing source that can be scheduled by the advanced control (Model Predictive Control) to optimize a defined Use case.

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Table 2: Buildings studied for simulation and the available energy and storage sources

Number	House number	Battery	Heating	Electricity Production
1	143	-	Heat pump	-
2	133	-	Fuel cell	Fuel cell
3		-	Gas-fired burner	-
4	137	Battery possible	Heat pump	10 kWp PV
5		-	Gas-fired burner	-
6		-	Gas-fired burner	-
7	131	Battery possible	Heat pump	-
8		-	Gas-fired burner	3 kWp PV
9		-	Gas-fired burner	-
10		-	Gas-fired burner	-
11		-	Gas-fired burner	-
12	140	Battery possible	Heat pump	11 kWp PV

The four highlighted houses are divided into two levels of complexity:

1. High level of complexity containing a multitude of flexible devices and measurement systems. This level only includes building 12 which is modelled in a very high detail (Demo NZEB building, refer to section 1.1.1)
2. Low level of complexity containing a limited number of flexible devices and measurement systems. This level contains the 3 remaining buildings: 1, 4 and 7.

Using its simulation and control environment, ACT implemented the building (from subtask 3.3.1), boiler and battery models in the neighbourhood for building the control algorithms for running the demo. Using its MPC algorithm, the physical models are continuously optimized based on a mathematical objective that is a translation of the Use case in mathematical terms.
To assess the flexibility and control the relevant electric devices, ACT build component models for the following electrical systems present in the different houses of the neighbourhood as shown in Table 3

Table 3: Electrical systems present in the different houses of the neighbourhood

Model	Electrical device	State variable	Storage capacity	Boundaries
Building house 131, 137 & 143	Heat pump	Inside temperature	The thermal mass of the building structure	Temperature comfort boundaries
Boiler 131	Heat pump	Water temperature	The thermal mass of the water in the boiler	Temperature comfort boundaries

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Battery	Battery	State of charge	The chemical capacity of the battery	No explicit boundaries aside from the physical limitations

In general, a single building can consist of the following components as shown in the Figure 5:

- Battery system
- Heat pump
- PV installation
- Fuel cell
- Hot water storage
- Building thermal mass

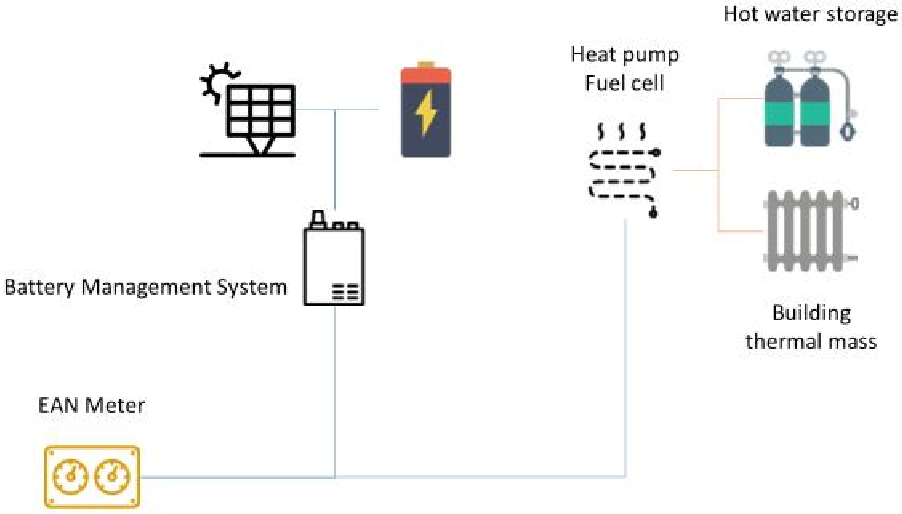

Figure 5: Components in the building

In principle, for a building, the optimization scope is the point of coupling with the grid. Each individual building model has been integrated into the Model Predictive Control (MPC). Mathematically, the MPC is formulated as a mixed integer linear constrained optimization problem that is solved for every time step. An MPC has the following parameters that can be used to tune the he algorithm:

- *Horizon* – Total period over which the optimization occurs.
- *Time step* – Simulation time step for optimization. The control variables are kept constant during every time step.
- *Control step* – Time between two different optimizations.

In general, the following parameters hold for the control of the buildings in the neighbourhood as shown in Table 4.

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Table 4: Parameters for the control of the buildings in the neighbourhood

Horizon	24 to 48 hours
Time step	1 hour
Control step	15 minutes

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3 Demo2: Demonstration at residential neighbourhood scale-Oud-Heverlee, Belgium

To cross optimize the behaviour of different components, the component models are bundled in a single model and optimization scope to be jointly optimized by the MPC, which is different from the one detailed in section 2.1.1. For the neighbourhood, the optimization scope changes from the individual EAN meter to the jointly injected or consumed energy on the point of common coupling, listed as the access point of the neighbourhood in the Figure 6.

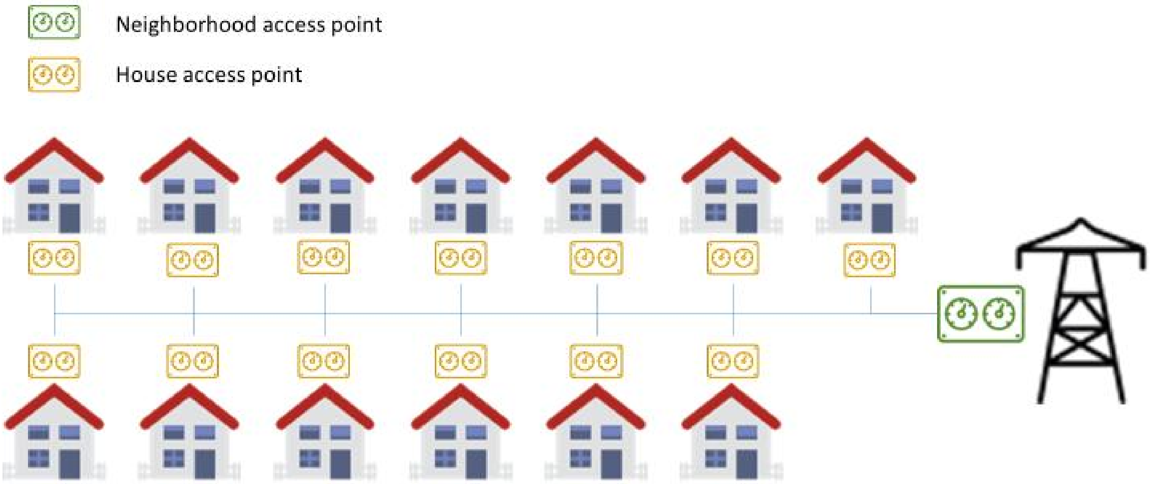

Figure 6: Neighbourhood electrical connections and controls

The access point of the building is measured by an EAN meter that measures both the flexible consumption (heat pump, battery) and the non-flexible production and consumption (lighting, solar production, household appliances.) Only the physical model models the flexible power that can be consumed by a flexibility device. ACT uses a proprietary software infrastructure and architecture to run the MPC in production for the control in real life. The simulation environment is built in Python to be able to quickly change different simulation parameters. After successful testing of the control algorithm in Python, as described in this report, the algorithm is translated to Java in order to run in ThingPark Energy in production and control the flexible devices in real-life.

For most flexible devices, a direct and an indirect method of controlling the power has been developed. The *direct* method enables the MPC to directly control the power consumption or production of the device, without having to pass through a 2nd-level[1] control device, effectively controlling the power directly. The *indirect* method forces the MPC to route its control signals via, possibly already in-place, a control device that controls the power output of the flexible device. An example of an indirect method is a smart thermostat where the MPC is able to change the set

[1] *D3.1 Report on hardware solutions for grid challenges*

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point temperatures on the thermostat but the thermostat remains the final decision maker to start or stop the heating system based on its internal 2nd level control. Indirect control couples with the current control interface such as a thermostat and tries to change the current control's parameters to influence the power control. It is less efficient but more secure than direct power control where the system can directly control the power output of the device.

As regard the use case of the Demo2, it is the same of the „Demo1: Control for the other buildings in Oud-Heverlee“(for more info see section 1.1.2).

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4 Demo3: Demonstration of small scale battery to reduce peak power- Navarra, Spain

The Spanish demonstrator plant is settled in Marcilla (Navarra, Spain) and belongs to the STORY partner EXKAL S.A that counts with the technical advice of the Navarre Company GREEN RENOVABLES. The main objective of this demo is to demonstrate the management of a Li-ion Battery operation with photovoltaic generation in order to reduce the peak demand charge of the factory. The peak consumptions in the beginning of the project are between 200 and 250 kW depending on the day period, so the contracted peak power is divided in three different periods of 260-270 kW. Moreover, the factory comprises a photovoltaic installation of 112.7 kWp.

CENER, supported by EXCAL that provided information about the factory energy loads and local regulatory framework, has developed the control algorithms.

The **use case** of this demonstrator related to the STORY project is the **reduction of contracted power** by using storage systems with an efficient management.

In particular, it is selected a storage device based on Lithium-ion technology of at least 180 kWh, with its correspondent power converter. Figure 7 shows the initial installation scheme and the components that have been added along the project.

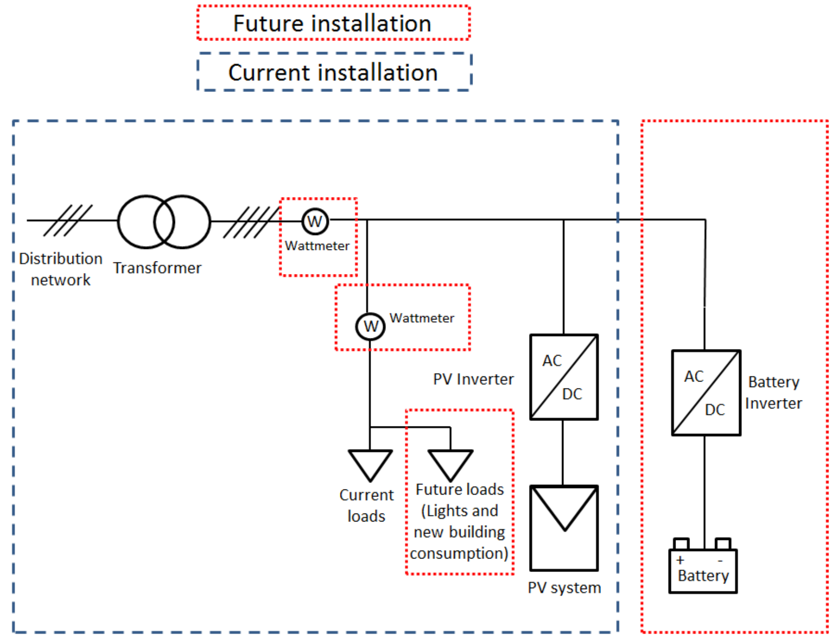

Figure 7: Configuration of the Spanish demo: current and future components (installed during STORY).

The use case of the Spanish demonstrator that define the Energy Management System (EMS) consists of the following:

- Increase renewable energy usage: rationally maximize the use of renewable energy produced on-site through Li-Battery.

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- Daily predictive identification of energy supply flows (energy production systems) based on energy costs and weather data.
- Peak shaving: energy demand over a threshold will be withdrawn from the Li-Battery.
- Energy schedule prediction (time shifting): shifting energy (production, storage and consumption) source, considering price and weather forecast, to most convenient time.

However, the plant must be managed according to the regulatory framework in force and control algorithms should take into account the restrictions from regulation. In the beginning of the project, the regulation in force is the Royal Decree 900/2015 for "self-consumption plants" which is very restrictive regarding the installation and operation of energy storage systems.

Nevertheless, a less limiting legislation is expected in the near future and thus, the control algorithms are developed gradually starting from a simple electric energy balance formulation, called the basic energy management strategy, to a more complex management based on deterministic algorithms' optimisation (like artificial neural networks for forecasting). This last strategy is the advanced energy management strategy. Both referred management strategies are explained in the following subsections.

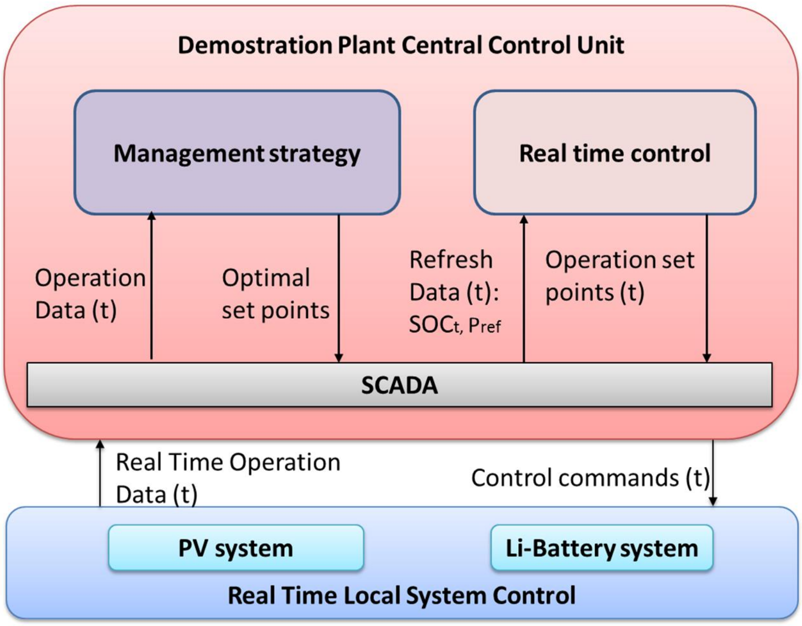

Figure 8: The schematic diagram for EMS of the demonstration plant

The energy management strategy (control algorithms) is developed and implemented in the management strategy module of the simulation platform. Figure 8 shows the control architecture of the EMS design.

The main goals of the control algorithms are:

- Priority of the renewable generation exploitation that can be scheduled to meet the demand.
- Management of the PV and Li-Battery to seek for the minimization of the electricity bill.

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4.1.1 Basic energy management strategy

The basic energy management procedure is explained in (III Congreso smart grids 2016, 2016), where preliminary studies have been carried out. The demo model has been evaluated as a preliminary case of study taking into account the data available from the past periods.

An evaluation of the demo situation and the storage possibilities with renewable generation has been developed. The renewable resources of the region have been evaluated (one synthetic year) as well as the factory loads and the surplus renewable power that is available to store has been quantified.

Constraints of using batteries to store energy:

First: the Li-Battery is not able to store energy from the grid.

Second, in the demo plant, it is mandatory to waste energy if the PV provides more power than the Li-battery is able to store and load can absorb since the regulation does not allow the power injection into the grid. In reality, this is not an issue if the inverter is grid tied.

The management of the SOC of Li-Battery:

The active power reference of Li-Battery depends on the SOC limitations. When the Li-Battery is asked to inject active power, in a discharging process, the SOC must be higher than SOC_{min} and depends on the available capacity. The limit of dischargeable power is defined by the limit of SOC_{max} and the available capacity of discharge.

4.1.2 Advanced energy management strategy

Recent developments in energy management systems (EMS) have been reported multiple methods and algorithms[2], as well as intelligent energy management demand response controller (IEMDC)[3]. In accordance to this, CENER has developed an advanced energy management strategy including forecasts of renewable generation and power demand in standalone hybrid renewable energy systems and grid-connected hybrid renewable systems with storage.

The goal of this specific control algorithm is the reduction of the peak power demand through peak shaving with the minimal cost while giving priority to renewable energy source. In addition, constraints related to budget and reduction of investment could be taken into consideration. Moreover, the commitment methodology applied in this strategy is designed to control the Li-Battery charge and discharge processes. The Li-Battery acts as a buffer for shaving the consumption in peak demand hours, as well as compensate the deviations of renewable generation and demand forecast from real generation and consumptions.

As showed in Figure 8, the control algorithm implemented in the management strategy accounts with the following operational data to perform the computations:

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[2] L. Olatomiwa, S. Mekhilef, M. Ismail and M. Moghawemi, "Energy management strategies in hybrid renewable energy systems: A review," *Renewable and Sustainable Energy Reviews,* no. 62, pp. 821-835, 2016;

[3] Y. Liu and G. Venayagamoorthy, "An Intelligent Energy Management System for a Photovoltaic-Battery System," *IFAC Proceedings Volumes,* vol. 45, no. 21, pp. 115-120, 2012.

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- **Generation forecast:** global irradiance and ambient temperature extracted from CENER meteorological services.
- **Demand forecast:** an Artificial Neural Network (ANN) is trained with the daily temperature in the location and the hourly load demand data of the factory to predict the hourly load profile of the plant.
- **Demand charge reduction:** iterative calculation to determine the power threshold over which the batteries should work
- **Control data delivery in real time**: active power and SOC of the subsystems of the plant.

The methodology applied is schematized by means of functional blocks that describe the management strategy. This structure has been optimized and implemented in the simulation platform for the demo plant is shown in Figure 9.

The energy management strategy based its operation in the handling of the storage system in function of the demand profile predicted and the renewable generation estimation. First, the renewable generation forecast unit is responsible for providing the forecast information data about solar power irradiance and meteorological data at the location of the factory in a specific period. This information is provided by the CENER prediction system based on SKIRON model. The data needed for this module are the horizontal global irradiance and the ambient temperature. These data are combined with the location and solar panel installation data to obtain the incident solar irradiance along the studied period and then, using the PV system simulation model developed by CENER, the solar power generation is estimated. The meteorological data provided by CENER prediction system is also used for the Demand Profile Prediction Module (DPPM).

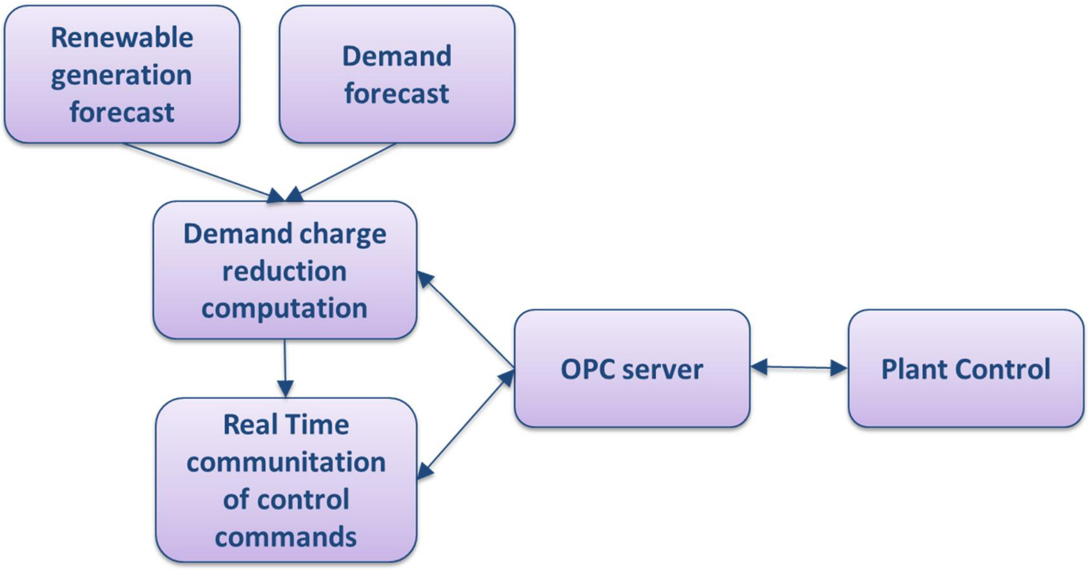

Figure 9: Management strategy of the plant.

Second, the DPPM is fed with historical load data from the factory and the temperature forecast to predict the demand profile of the factory using as backbone an artificial neuronal network (ANN) system. ANNs are metaheuristic methods based in the way that human brain solves a particular

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problem. They are formed with a number of parallel distributed processing units (neurons) highly interconnected which has the ability of store self-learning knowledge and making it available for use. One of the main advantages of ANN is its ability to extract patterns and detect trends that are too complex to be noticed by either humans or other computer techniques. Through a learning process, the ANN developed for the DPPM can automatically infer rules to link consumptions with dates and weather variables, without the need for any functional relationship between loads and weather variables in advance. In addition, DPPM is always implementing a self-learning process, been able to update if internal organization for addressing tendency changes without any intervention from the programmer.

In this project, the ANN is trained with the historical data of the weather in the location of the plant and its electric load demand registers, wherewith the module is able to predict the future electric demand of the plant. The available prediction is extended to seven successive days in advanced, with a reliable level of accuracy.

Third, once the solar power prediction is available and the electricity demand profile is calculated, a Demand Charge Reduction Computation Module (DCRCM) solves, through an iterative process, the optimization problem that consists of finding the optimal active power set point that commands the Li-Battery behaviour to reduce demand charges. Demand charges are based on the highest 15-minute average usage recorded within a given month, depending on the hour of the day (tariff period). In this sense, a day is divided into periods, assigning a demand charge for the peak demand of each period. The demand charge can represent between 25% and 70% of the electricity bill. DCRCM manages the SOC of the Li-Battery, charging it during periods where electricity prices and demand charges are low to cover part of the consumption during the high prices periods.

Fourth, the RT communication of control command module is responsible for the interaction with the available control variables at the OPC (Object Linking and Embedding for Process Control) server in an OPC client communication. Thus, at each communication time during simulation time, the optimal power set points are established (read/write) as the demand charge reduction computation module has commanded, and then, are sent to the storage system. In every computation step, the optimal set points are known and at the specific needed times are communicated to each part of the model as the plant control.

The control algorithms are implemented in a java platform communicating the data through an OPC server-client that interfaces with the simulated demo plant model system on the RT simulation platform.

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5 Demo4: Demonstration in residential district- Lecale, Northern Ireland (UK);

This demo focuses on the development of a Compressed Air Storage to be integrated in the public grid to reduce curtailment in the RES in this district area.
The use case for this project is to operate the machine in such a way that three separate sources of revenue can be realised – these are

i) Arbitrage: buying electricity at night time when the price is low and selling electricity during the evening peak when the price is high,
ii) Load on Demand: providing a balancing load service to avoid the curtailment of local wind turbines and distant wind farms, (load on demand payments are received on the basis of a share of the wind farm revenues preserved), and
iii) Generation on Demand: providing a local generation service to avoid overloading of the 33/11kV substation in the conventional direction, (generation on demand payments are received from the utility on the equivalent basis of a share of the avoided cost of upgrading the 33/11kV sub-station.

The goals of the control algorithms is to fill a gap in the energy market that will allow renewable energy producers to remain in production even when ordered to curtail their production due to lack of need. This will open up various revenue streams that this project can take advantage of.

B9 developed the control algorithms for this demo. Particularly, Figure 10 illustrates the components of the system broken-down into its three constituent modules. The CAES system consists of an Internal Control System as shown by the blue box and the External Controller and Day Ahead Scheduler (DAS) as represented by the green box. These separate control systems are fully integrated within the system to provide a real-time scheduled control of the components based within an Amazon AWS environment.

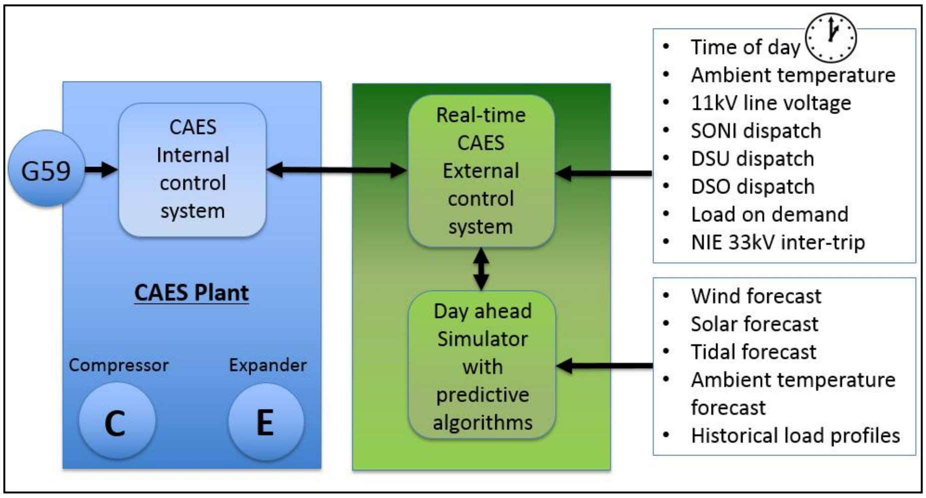

Figure 10: System Model Diagram

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5.1.1 CAES Internal Controller

This module performs the functions of starting and stopping the machine in both compression (load) and expansion (generation) modes and incorporates a statutory hard wired G59 protection input to effect a shutdown and electrical isolation of the machine in the event of a distribution network wide electrical fault. This is for both health and safety and asset protection purposes and a trip will be initiated upon under/over voltage, under/over frequency and ROCOF (Rate of change of frequency)

5.1.2 CAES External Controller

This module provides the interface between the internal control system described above, the day-ahead simulator with predictive algorithms described below and the various connections with outside and remote parties that can ask for control functions to be carried out for various reasons. The basic function of the real time CAES external control system is to firstly follow a current day operational strategy, produced by the day ahead simulator the day before, to inform the internal control system when to start and stop the machine and secondly to always be ready to interrupt normal operations when called upon to do so by prearranged dispatch signals from external third parties. This control system will also compare in real time the actual data on the day with the day ahead profile and make small adjustments accordingly.

5.1.3 Day Ahead Simulator with Predictive Control Algorithm

This module uses predictive algorithms acting on forecasts of environmental factors and historical load profiles to simulate the best operational strategy for the day ahead and to ensure maximum revenue from specialist services and electricity trading for the least cost.

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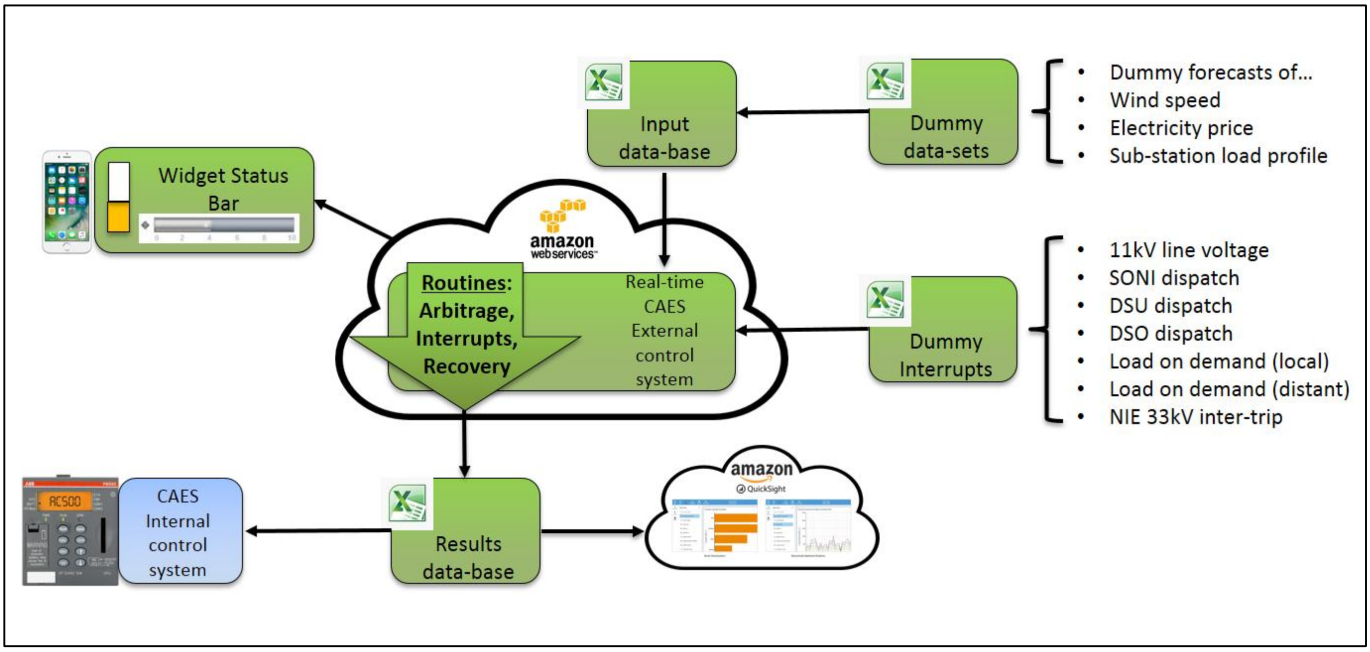

Figure 11: Day Ahead Simulator with Predictive Control Algorithm

Figure 11 shows the architecture of the control system that has been used for development purposes in advance of real time data being available. We have used Excel spreadsheets to represent dummy data sets which are representative of real values for wind speeds, electricity price and 33/11kV sub-station load profiles. We have also used Excel spreadsheets to represent dummy interrupts from the stakeholders listed.

The real-time CAES external control system operates in the cloud and consists of 3 separate routines:

1. Arbitrage Routine: The assumed duty each day is to follow a time based operational profile of compressing air (buying electricity from the grid), storing air and then expanding air (selling electricity to the grid). This is known as arbitrage. Because the round trip electrical efficiency will be in the region of 50% we anticipate 8 hours of compression (load) and 4 hours of expansion (generation). If the day is uneventful in respect of high wind, high load etc. and there are no dispatches from any of the stakeholders then the arbitrage routine is the only algorithm that is used that day.
2. Interrupt Routine: If a dispatch is received from one of the stakeholders then the arbitrage routine is interrupted and the appropriate contracted service delivered as a priority. If more than one dispatch is received then these will need to be prioritised and tested for conflict.
3. Recovery Routine: On completion of the interrupt routine, an attempt is made to return to the arbitrage profile. This is called the recovery routine. If successful then the day continues as planned with the remaining portion of the arbitrage profile. If the recovery is not successful then the arbitrage plan is abandoned and recovery extends into the following day.

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6 Demo5: Demonstration of flexible and robust use of medium scale battery- Slovenia;

The model is based on the data provided by ABB and includes measured charge/discharge curves and efficiency of battery. UL, supported by VTT (as regard the creation of the simulation model for testing the control) and EG (as regard requirement and instrumental data of the network), has created the control algorithms. Storage components are shown in Figure 12. Initial model is designed in MATLAB Simulink, and based on that model, MATLAB code is written to represent faster model of the Storage unit. Code model is suitable for other software environments and will be used as a model in RTU on demo location for quick calculations of the storage operation.

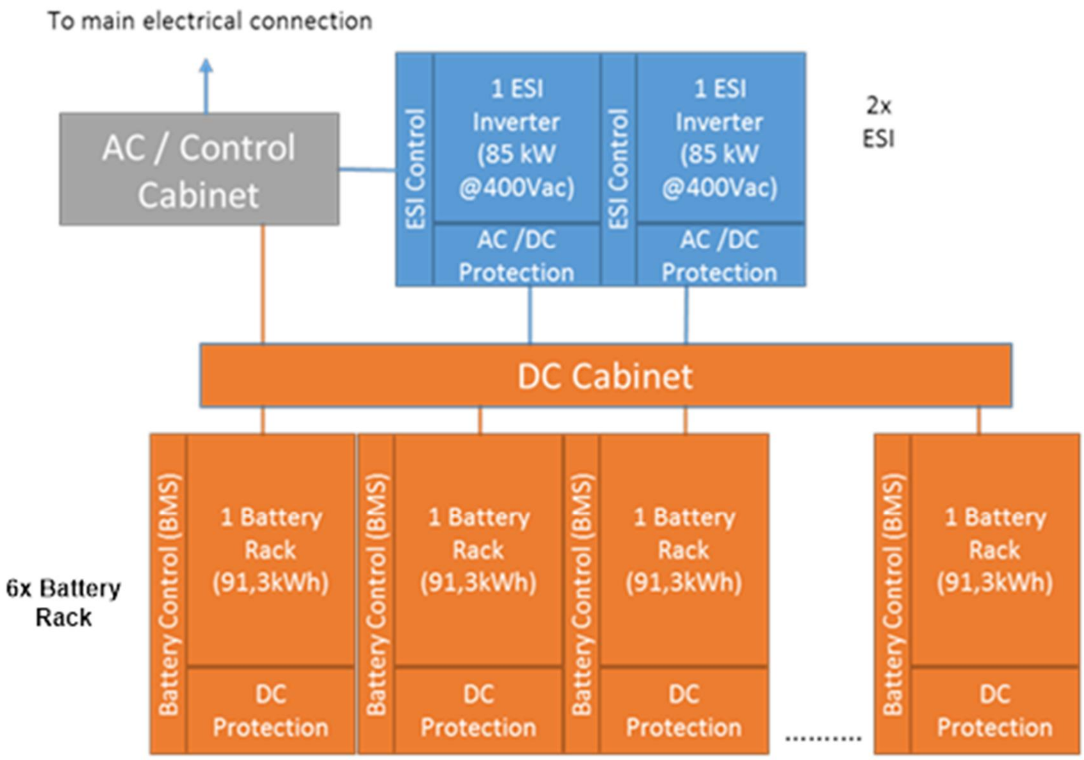

Figure 12: MV/LV substation battery example, used in EG demo cases

The main functionality of the storage and the key reason for implementation are the prevention of the reverse power flows in the electricity grid and mitigation of PV impact. With implementation of 170 kW/ 320 kWh Li-ion storage, we aim to store surplus of 210 kWp PV produced energy during the day, which is later discharged back to the grid in morning and evening peak demand intervals. For this functionality, we designed Peak Demand Control Algorithm as one of the storage functionalities. Additionally, Tertiary reserve provision demonstration is also designed together with Zero Load provision, where islanding operation of the network is maintained. From discussion with the DSO and result from analysis, algorithms are updated, storage unit factory test also presented several storage operation properties and some upgrades are newly possible

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In this section, we describe the background and the structure of individual strategy and control algorithm. All of the controls are performed in real time; peak demand control has additional updating calculation functions. As regard this demo, three different control algorithm packages have been created. They are triggered based on the network conditions and specific needs. These control algorithm packages control algorithm packages refer to:

- *Peak demand control algorithm*
- *Zero load provision*
- *Reserve provision*

6.1.1 Peak demand control algorithm

Purpose of peak demand control is to reduce peak level of active power flows, caused by peak values of local consumption and surplus generation in intervals with low consumption. With received forecast of solar irradiation for area of the network, we determine how much solar power plants will produce and what transformer power flow of active and reactive power will be. Predefined transformer profiles are stored in database, created with analysis of yearly measurement data.
Based on the solar irradiation data and transformer measurements for 2017 new database is created. It presents expansion from 16 available profiles to yearly database of 360 transformer profiles shown in Figure 13. Based on the received solar irradiation forecast, the most similar day in the database is selected with method of least square root deviation from the forecasted profile. The transformer profile database now allows for more accurate selection of the profile and thus for better-expected storage operation. In Figure 13 we can see historical trends of active power flows in the grid. When PV units are producing at highest rates, the consumption of energy in the grid is low and as a result, we experience reverse power flows of the energy, which we aim to mitigate with this peak demand control, which control peaks of consumption and local production.

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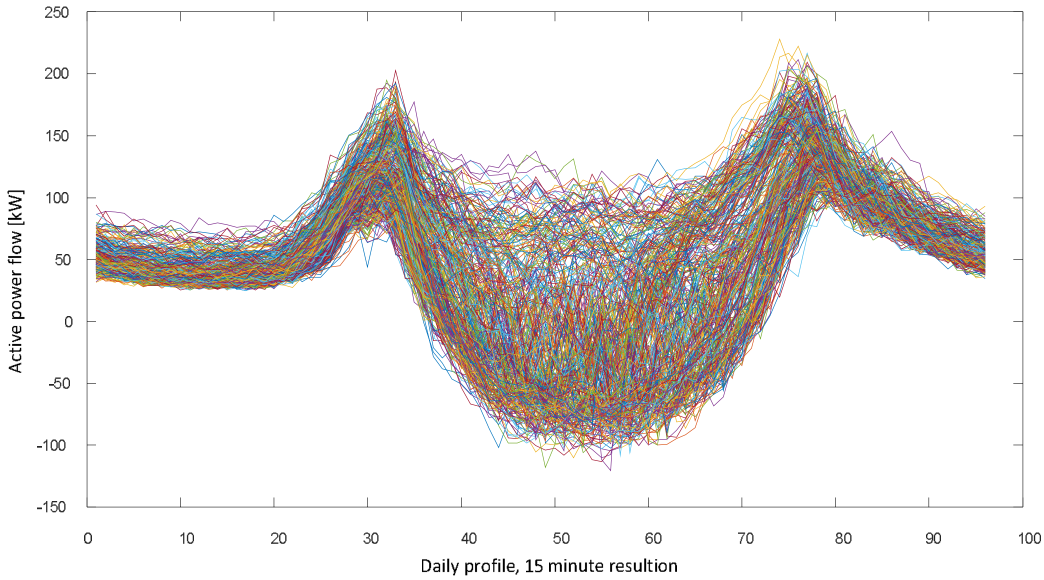

Figure 13: Yearly profile database of active power flows

On Figure 14 we present the first phase of the control. From the Slovenian weather agency ARSO, a solar irradiation forecast is received, and from historical database of measurements, the most similar dataset of irradiation is identified, together with corresponding transformer profile.

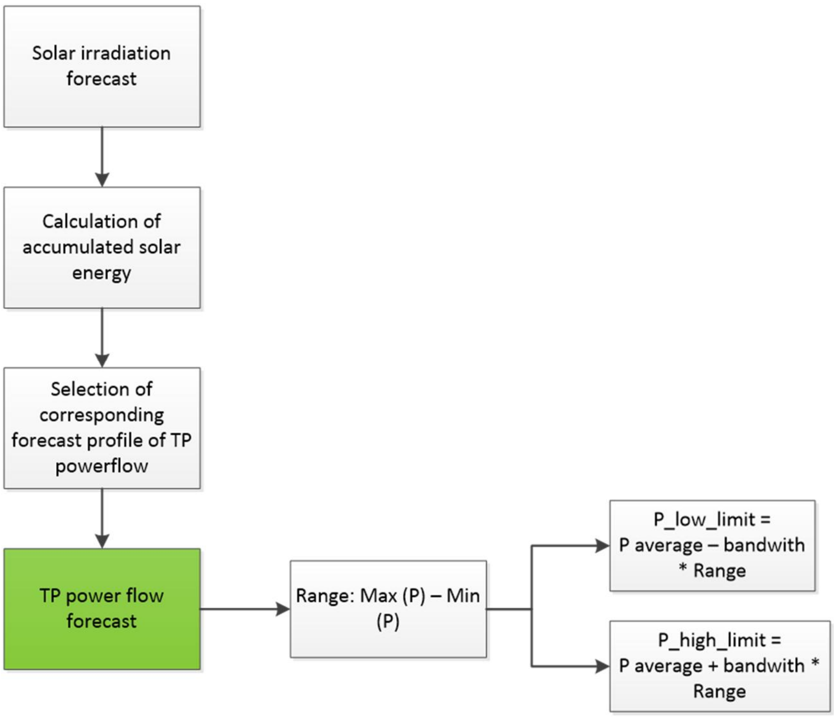

Figure 14: Initial part of control activation - Profile selection

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After power flow profile is selected, the storage control calculates set points. These trigger activation of the storage, which will consequentially lower power flow levels. After creation of transformer power flow profiles database, an algorithm is designed for peak demand control activities. When the solar forecast is received and profiles selected, threshold levels are determined for 24-hour interval or until the next forecast is received. When the profiles are selected, they are used in an iterative process shown in Figure 15 to determine threshold levels for storage operation.

As seen on the figure, the measurement of the active power through transformer (P(t)) is compared to the set lower (P_low_limit) and upper allowed threshold (P_high_limit) of the power flow of active power. This threshold is set to minimal levels of storage charging and discharging and is iteratively increased in increments, defined in the algorithm, for each threshold, the algorithm check if the State of Charge (SoC) is in allowed bandwidth (between SoC_min and SoC_max) and if it allows operation of charging and discharging. Storage charges and discharges with the difference between the defined threshold and actual active power.

The goal of the process is to achieve the lowest power levels on the transformer level while still taking into account storage limitation, such as the allowed SoC levels (seen in Figure 17) and the time resolution of operation. The process is limited to 50 steps and the final threshold levels shown in Figure 16 are determined, applied to real time operation of the storage for interval until the next update is performed. Initially, the threshold levels are updated once per day; in later versions, they are updated hourly.

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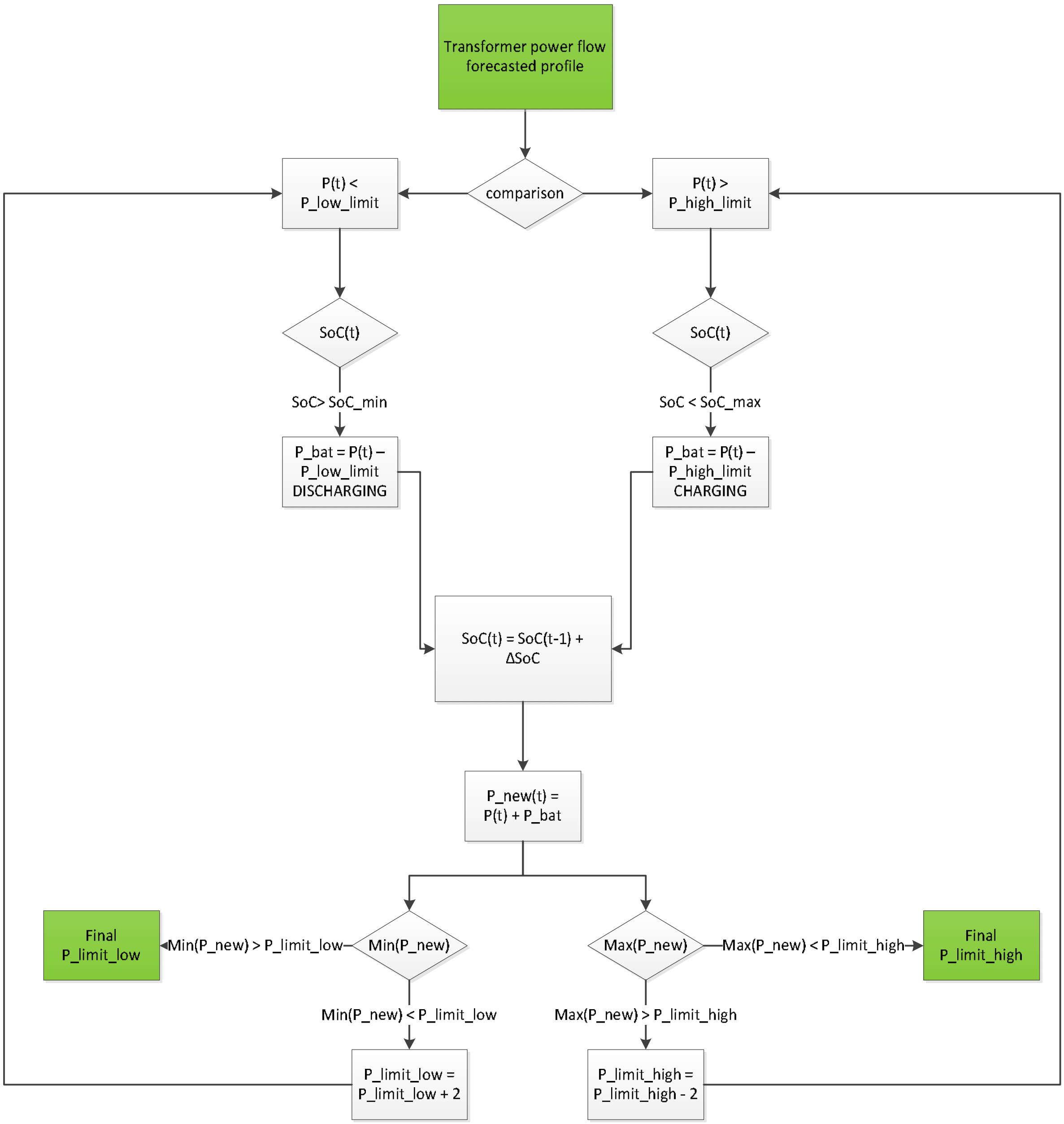

Figure 15: Scheme of iterative process of determination of threshold power levels

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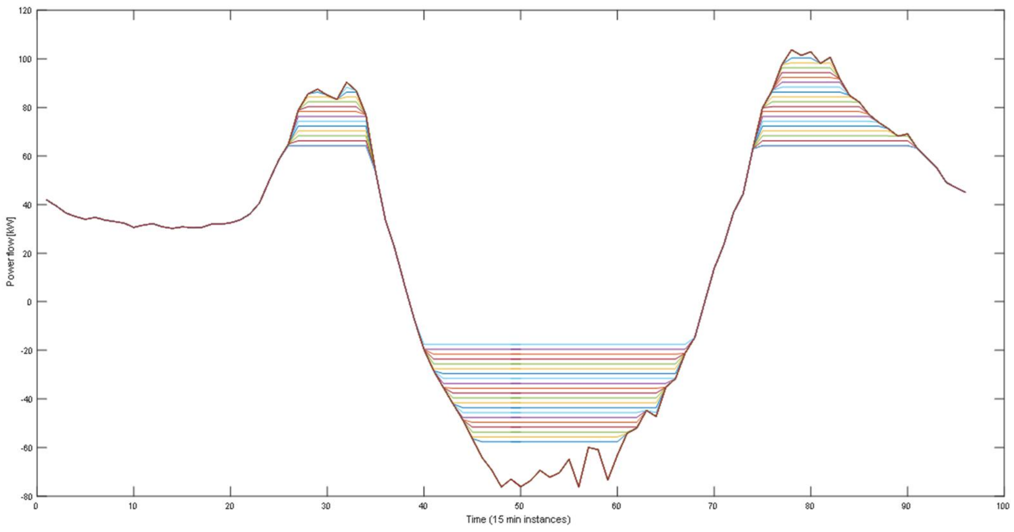

Figure 16: Definition of threshold levels in iterative process, with final threshold levels (inner light blue)

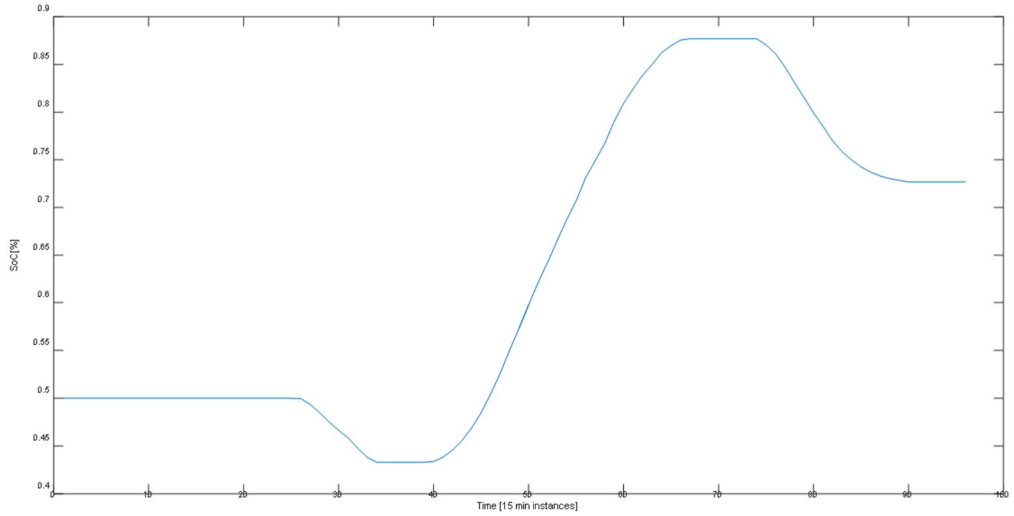

Figure 17: SoC levels determined for 24-hour interval, with allowed levels from 40% up to 95% SoC level

Once the threshold levels are calculated, they are applied in real time control of storage unit. Based on real transformer measurements of active and reactive power, storage control is activated every 1 minute and power rates for charging and discharging of the unit are calculated and applied.

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On Figure 18, a real time part of the algorithm is presented. Transformer active power reading (P(t)) is checked against lower and upper active power set points. If the power flow exceeds defined limits, the SoC check is performed to see if storage can charge or discharge. If the SoC levels are within allowed ranges, storage begins charging and discharging with surplus of the power flow above or below the threshold.

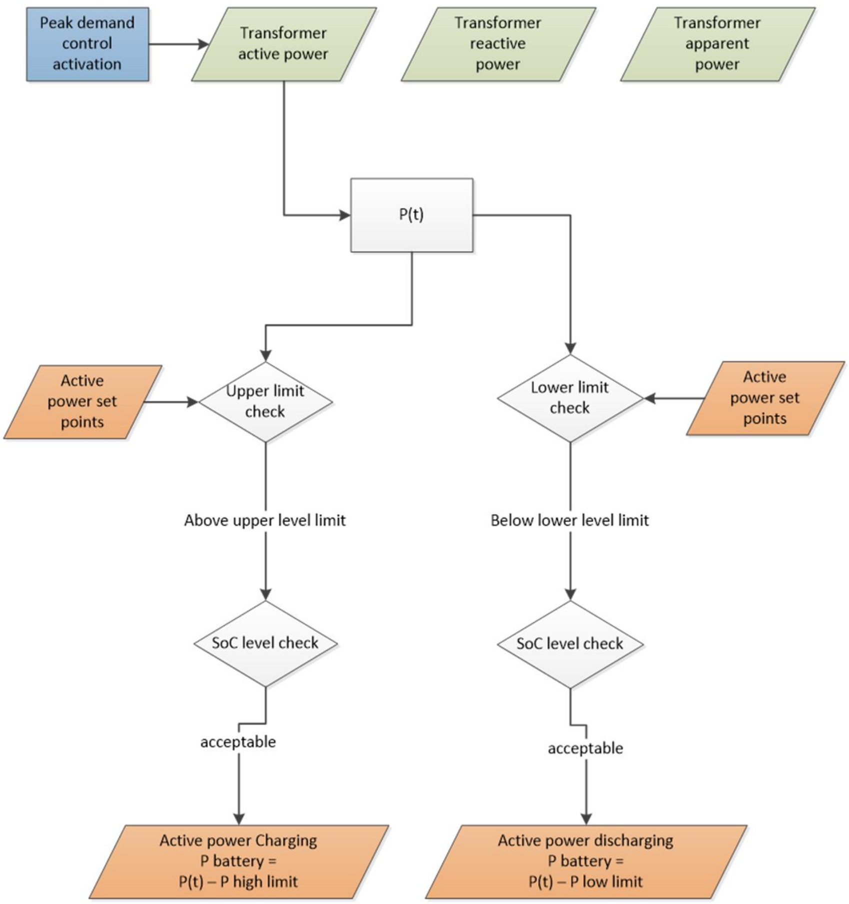

Figure 18: Real time control of storage unit

The algorithm is developed in stages, and each brought additional features into the operation of the storage:

- **Forecast interval of 36 hours**
  After the initial 24-hour forecast interval, 36-hour forecast is used. Based on this long period, daily profiles are determined at midnight for coming day and day ahead. This brought additional calculation factors into the algorithm. Based on the expected solar energy in the following day, a morning discharge is calculated. This discharge allowed storage unit to charge from PV production surplus of energy during the day. Before the evening peak storage is full or at least sufficiently charged from PV and reallocated SoC in the storage. Based on the expected evening peak, and day-ahead profile, thresholds for

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evening discharge are calculated. In addition to these threshold levels, operation levels for day ahead are calculated as well. This version of the algorithm is activated at midnight and it calculates the storage operation threshold levels for 2 days ahead, as shown in

Figure 19. This approach allows for a reserved and more planned storage operation, wherein expectance of cloudy days, SoC levels are preserved for operation in days, where no charging is allowed.

Figure 19, the advanced planning of charging and discharging is presented. Based on the updated weather forecast and SoC measurement we calculate if PV production will cause reverse power flows or it will be locally consumed entirely. If we have low rates of PV production, defined percentage of energy is preserved for evening peak demand interval. In case of sunny day, battery is charging from the PV production and based on the expected amount, similar percentage of stored energy is still preserved for evening peak or it is discharge fully in the morning, if we expect more than 60% energy charge from the PVs during the day. This way we ensure that we have more than half of the capacity prepared for the evening peak, which is larger in amount compared to the morning peak demand interval. Iterative process of threshold definition is still applied to calculation of morning discharge limit value, daily charge level and evening discharge level.

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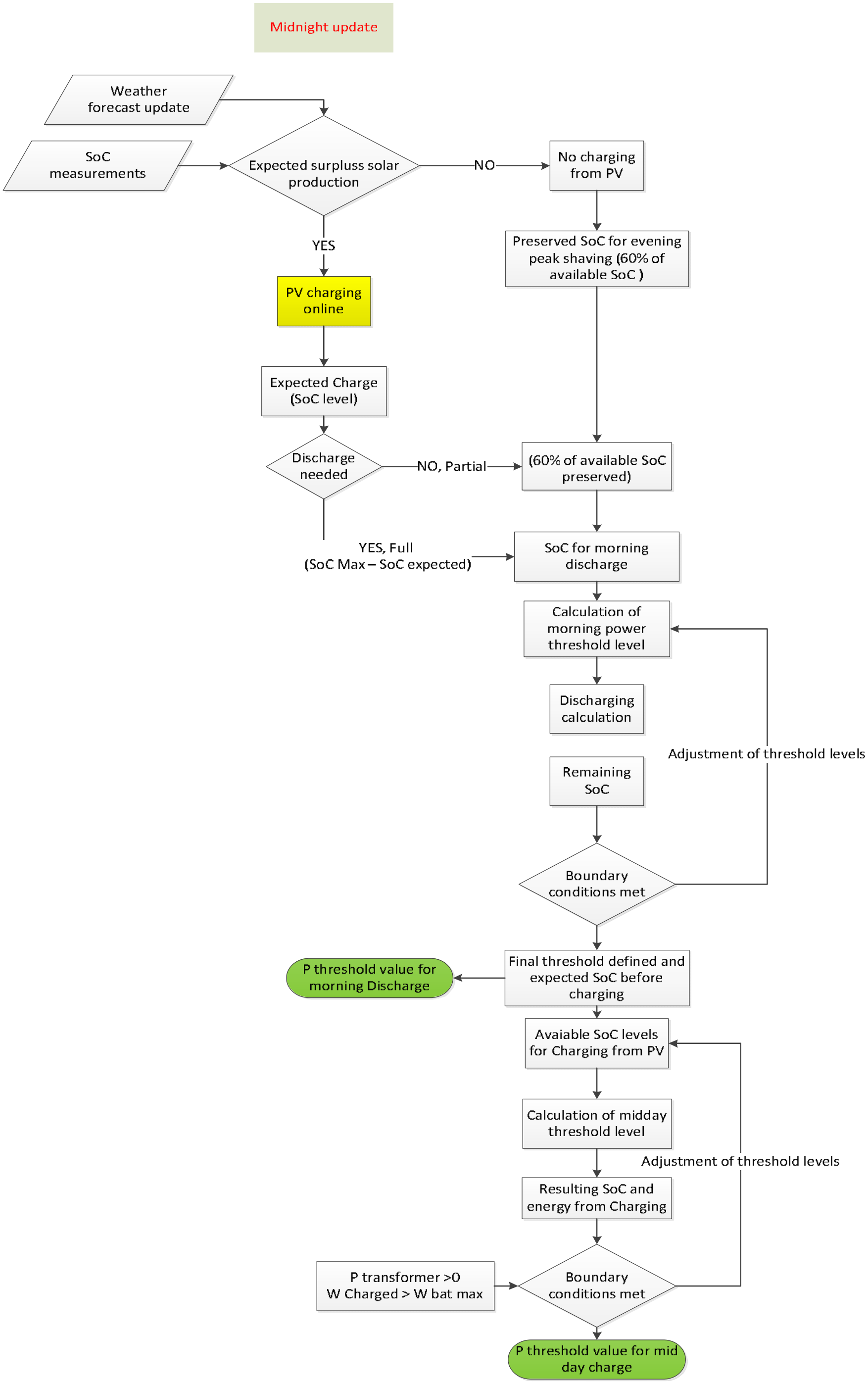

Figure 19: Midnight calculation for 2 days

- **Addition of night charging**

  In addition to Storage being charged from the surplus of PV generation, night charging has been added as an option for days with lower PV production rates. The storage utilizes the night interval, where electricity prices are lower and demand in the network is low, to store

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enough energy for the next day. With this measure, it has been assured that enough SoC is stored for incoming morning peak and daily operation.

- **6-hour update of the weather forecast**
  Due to the deviation between the weather forecast and an actual weather condition, the update frequency is increased. The accurate solar irradiation forecast is crucial for a precise storage operation. With the weather forecast being available every 6 hours, 6 hours update of forecast and transformer profile is introduced.

- **AC power factor and hourly updates**
  Newly discovered impact of AC power consumption has been implemented in the algorithm as well. Power consumption directly affects storage operation since the storage consumption from the grid point of view is not equal on the battery cell point of measuring. Additionally, the SoC parameter of the storage has been considered as well. Due to the deviation between the forecast and the actual profile of active power flow through the transformer, storage did not charge-discharge to the calculated level in situations with less accurate forecast. With the hourly recalculation of the threshold levels, this impact has been mitigated. Based on the SoC measurement, each hour storage calculates how much it can charge, or discharge based on the expected profile. The storage unit is now hourly updated with the measurement of available SoC level, and based on that value, the thresholds levels are recalibrated, and the storage unit is more efficiently utilized.

As being recorded by remote control SCADA system, an example of storage daily operation is shown of the Figure 20. Algorithm calculations and predictive diagrams are shown on the lower part of the figure, while real time Battery Energy Storage System (BESS) measurements are depicted on the upper half. The comparison of prediction to real time of individual BESS parameters reveals a high curves match, which proves the quality of control algorithm. It is important to have good weather forecast, however, deviations are mitigated to some extent with hourly updates, which recalculates the storage operation based on real SoC reading.

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Figure 20 Storage real time daily diagram, upper window are measured values, forecasted values are presented in the lower part

6.1.2 Zero load provision control algorithm

Storage unit is operating in island-like state of the network, where goal is to achieve minimal power flows through the transformer station. Storage unit, which is located next to the transformer station, operates based on real time measurements of power flows in transformer station. Unit is charged to predefined SoC level in order to be able to provide energy to the network.

The algorithm checks and detects the need for the island mode operation, and if storage is available and sufficiently charged above predefined threshold SoC levels, storage is activated for zero load provision. As seen in Figure 21 based on the transformers measurements of active and reactive power flows, storage charges and discharges at rates required for compensation of power flows and on the predefined boundaries for SoC level, dedicated for the island mode needs.

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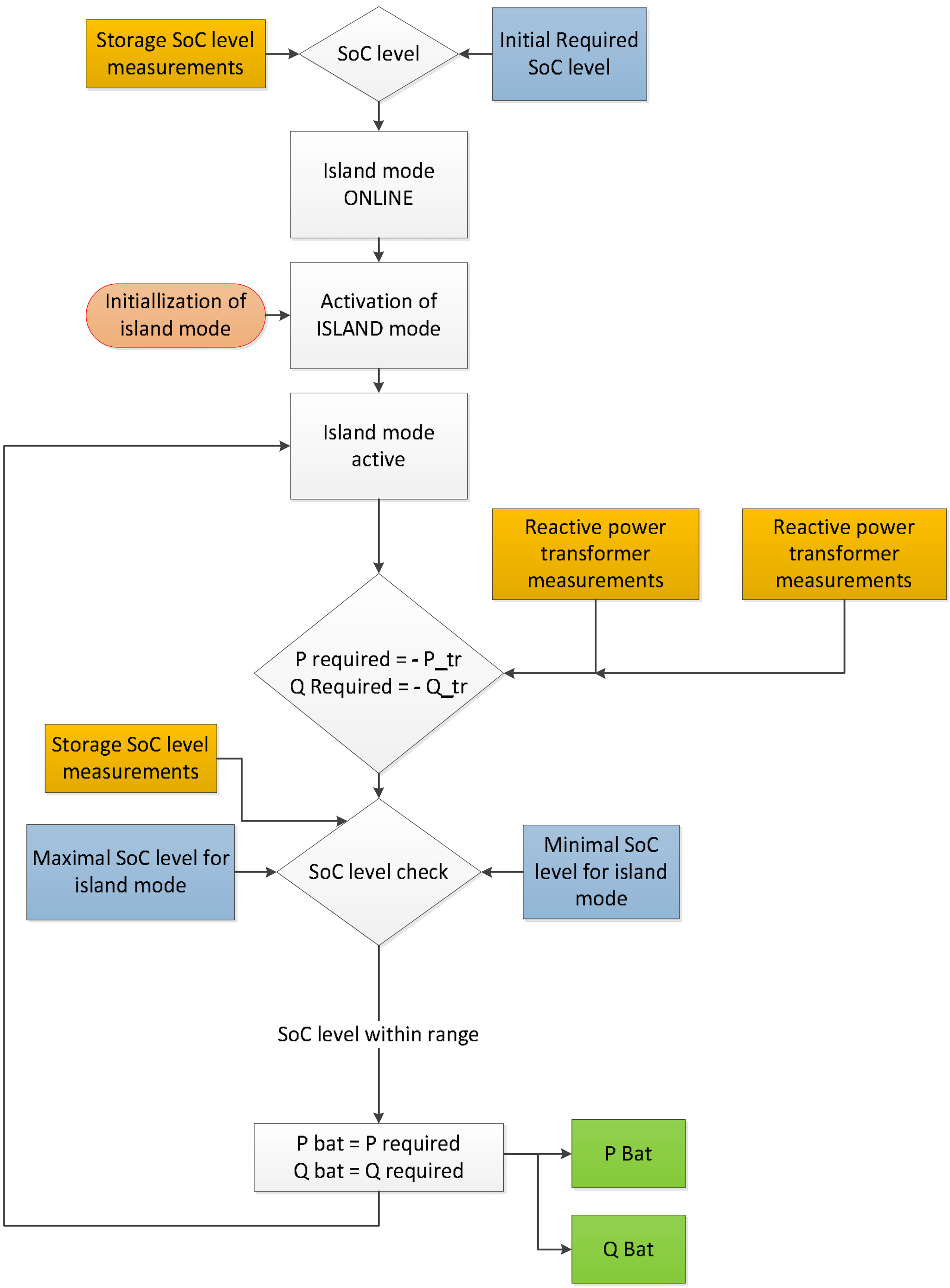

Figure 21: Algorithm flowchart

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6.1.3 Reserve provision control algorithm

In order to provide tertiary reserve provision of active power, a contract between network operators, which could be DSO or TSO and the battery owner. In the contract, they define the rated power of storage output and length of the interval, in which storage is supplying the energy, seen in Figure 22. When the contract is in action, the amount of energy provided in the contract needs to be available for any possible activation. Storage operator can achieve this with rising the lower boundary for normal operation of the battery. For example, if storage is running load demand control duty throughout the day, and reserve needs 20% SoC for the contract, the peak-shifting algorithm operates with SoC levels between 100% and 60% if the lower security threshold of allowed discharge is 40%. This way the required energy for reserve provision is always stored and available for activation. When the DSO sends the signal for activation of reserve activation, storage discharges stored energy at agreed rate of power for defined time instance.

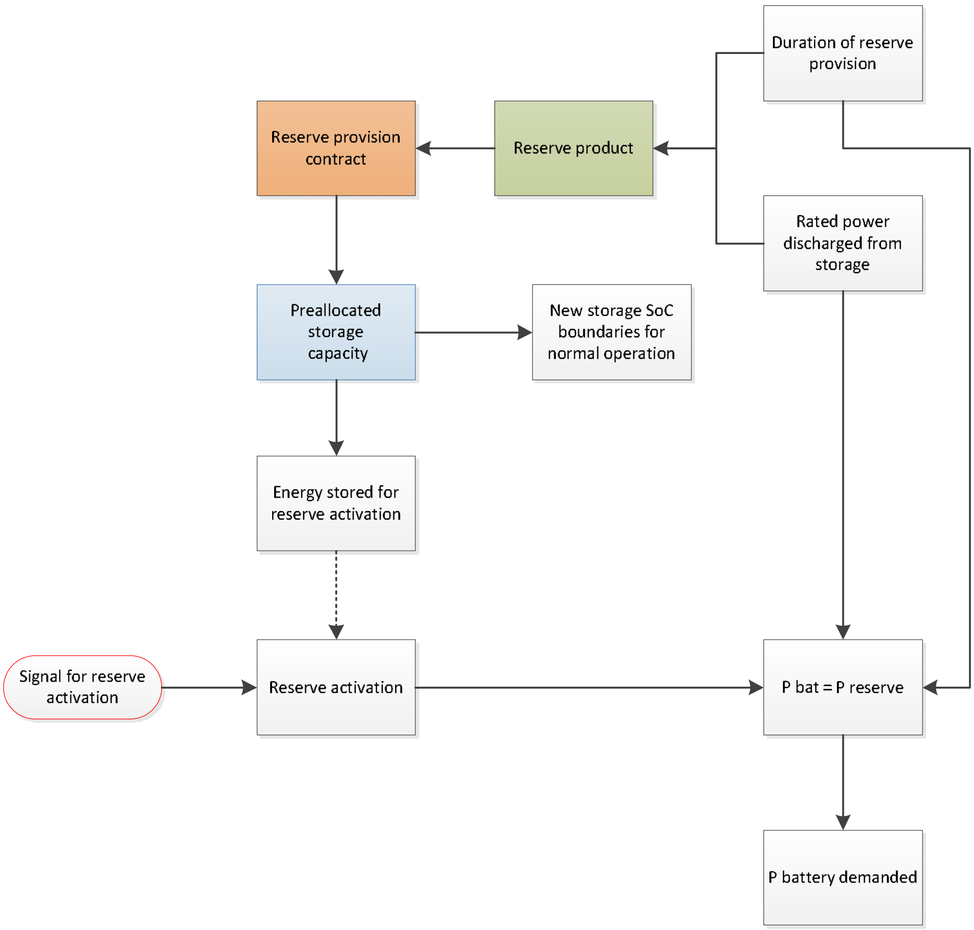

Figure 22: Reserve provision procedure and eventual night charging

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7 Demo6: Demonstration of roll out of private multi-energy grid in industrial zone Olen, Belgium

In the present case a Belgian SME, Beneens (BEN) joined the STORY consortium to provide a demonstrator suitable for roll-out of a private multi-energy grid in an industrial area. The site itself is located around a joinery that is itself a large source of waste wood and requires a considerable amount of heat for certain processes. Additionally, SMEs in the neighbourhood could also benefit from heat surplus by connecting to the newly installed multi-temperature heating grid.

Electricity is produced on-site using an Organic Rankine Cycle (ORC) from low-temperature heat produced by the waste-wood boiler. The inclusion of thermal storage, at two different temperature levels, allows generating flexibility in the energy system by decoupling thermal demand and production. Additionally, it enhances the efficiency of the ORC.

The objective of the demonstrator is to use this waste-wood on site to generate both electricity and thermal energy for on-site use, as well as providing services to neighbouring SMEs by the roll-out of a private multi-energy grid. Electricity is produced by an ORC powered by low-temperature heat provided by the 1.6 MW waste-wood boiler. Thermal storage in the form of 20 and 50 m^3 storage units generates flexibility in the system.

The goal of this demonstrator is to show the benefit of thermal and electrical energy storage to:

- increase the efficiency of the ORC
- reducing the peak power demand in the thermal network and the electricity grid
- reducing the losses in the district heating network by the optimal use of the local heating grid using two temperature regimes.

As mentioned before, the 1.6 MW waste-wood boiler will provide thermal energy for the entire system. Heat can be delivered to both the ORC (1.0 MWt) and high-temperature storage unit with a volume of 50 m^3 at a regime of 90°C/70°C (1.6 MWt). The boiler is designed to deliver the heat at a temperature of 145 ℃ (130 ℃ return) and interaction with both the storage and ORC are done using heat exchangers of 1.0 MW for the ORC and 1.6 MW at the storage side. The electric efficiency of the ORC is about 10% and the remaining 900 kW are connected to the low-temperature heating grid with a temperature regime of 40/30 □. The low-temperature storage unit of 20 m^3 (H=328cm, Diameter=280cm) is connected to this circuit to balance supply and demand. In this way, electricity can be generated in the absence of (sufficient) heat demand.

The 90°C/70°C-temperature circuit is mainly used for processes and this heat can be directly delivered by the heat exchanger separating this circuit from the production side as well as by the high-temperature storage of 50 m^3 (H=585cm, Diameter=380cm)

Extensive monitoring is present in the entire system to keep track of energy flows and temperatures in all the parts of the installation as well as to serve as input for the control algorithms.

In order to approach these kinds of studies and improvements, VTT has developed a simulation platform that includes the models of the systems involved in the pilot plant for drawing initial conclusion on the performance of the system and initiating the control algorithm creation.

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To ensure proper operation, advanced control strategies are required and have been developed by VITO and implemented by BEN. The control strategies also require accurate knowledge on the state-of-charge (SOC) of the thermal storage units. These methods have also been developed by VITO.
The development of the algorithm can be broken down into two blocks. Firstly, there is the development and testing of the SOC determination algorithm used to quantify the flexibility. Secondly, there is the overall control of the energy system.

7.1.1 SoC algorithm

Two methodologies for the SoC estimation are explored. Both of them can provide the temperature evolution in time at different heights of the storage units. Methodology 1 is based on [3,4] while methodology 2 in reference [5].
All storage tanks are modeled as n layers of water (i = 1,… n) . Each layer has a uniform temperature and a known volume calculated from the total volume and the number of layers. Both methodologies consider thermal losses, conduction and mixing effects.

While for methodology 1 there is no need to have historical data to calibrate the model, methodology 2 takes advantage of the existence of historical data to estimate some of the models' parameters, which are triggered by hand on methodology 1.
For both methodologies the required data are: the initial conditions (temperatures at different heights of the buffer); information about the flow rate and temperature of the water being injected or withdrawn from the storage tank in each time step, the amount of heat injected or withdrawn from the storage tank in each time step and other tank specifications (such as the heat loss coefficient, in case of methodology 1, and dimensions of the storage tank).

In methodology a), the method returns the state of charge (SoC) in the form of a percentage and it is derived from the m temperature measurements, where n is not necessarily equal to m. To do so, a reference point defining when the storage tank is fully charged is used. A fully charged tank means that all water stored has a temperature of at least T_{max}. Accordingly, the reference energy content of the buffer is equal to the energy content of the buffer when all water is uniformly at T_{max}. The state of charge of the buffer can therefore be calculated as described in [3,4] and using equations (1-3). The meaning of the abbreviation is shown in Table 5.

$$SOC = 100\left[1 - \frac{3600(E_{max} - E_{min})}{4.186(T_{max} - T_{min})V_t}\right] \quad (1)$$

, where

$$E_{max} = \sum_{i=0}^{n} \frac{4.186Vi(T_{max} - T_i)}{3600} \quad (2)$$

$$E_{min} = \forall j(j: 0 \rightarrow n, T_j < T_{min}) \rightarrow \sum_j \left[\frac{4.186V_j(T_{min} - T_j)}{3600}\right] \quad (3)$$

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Table 5: Definition of symbols used for SOC calculations

Symbol	**Meaning**
SOC	State of charge (in %)
T_{max}	Maximum temperature of the storage tank
T_{min}	Minimum outlet temperature
T_j	Temperature of layer j $(j: 0 \rightarrow n, T_j < T_{min})$
V_i	The volume of layer i
V_t	The total volume of the tank, i.e., $V_t = \sum V_i$
E_{max}	Energy required to fully charge the tank, i.e., $\forall i: T_i = T_{max}$
E_{min}	Energy required to get all water at minimal T_{min}

If more information is needed or if a reference point cannot be defined (e.g., there is no upper limit previously defined), the temperature distribution along the height of the storage units can provide more insights concerning the status of the tank.
In methodology b), the first step is to use historical data to estimate the unknown. After having those parameters, the model performance is evaluated in an out-of-sample dataset (crosscheck data). The problem is modelled in `python` using the mathematical modelling framework `CasADi` [6] and is solved using the interior point solver IPOPT**Error! Bookmark not defined.**. As mentioned before, the code is based on [5]. All formulas and explanations are depicted in that reference.

7.1.2 Overall control of the energy system

The control principles, as discussed in this document, are focussing on the control of the high temperature control side of the Beneens setup and the high temperature buffer tank control that requires an active control strategy.

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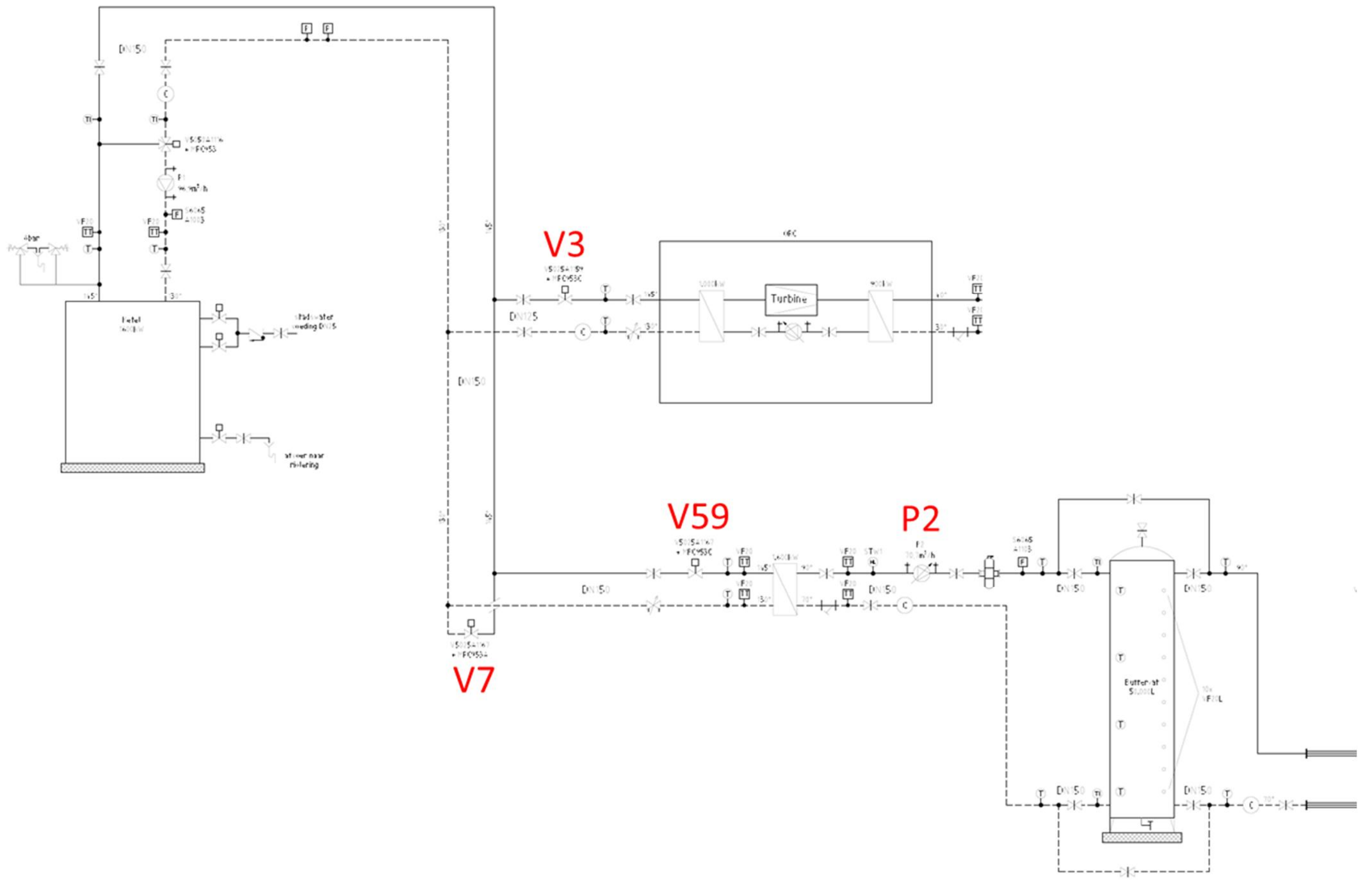

Figure 23: High temperature schematic of the Beneens setup

Figure 23 shows the main control elements that will be discussed further in this document:

- V3: valve which controls the flow going to the ORC
- V59: valve which controls the flow to the high temperature circuit (HTC)
- V7: Bypass valve that opens when the flow towards the ORC and HTC circuit is limited. The valve prevents pressure build-up in the primary circuit.
- P2: pump that controls the flow at the secondary side of the HTC heat exchanger. 3 situations:
  - flow P2 = sum of all flows of heat users: HTC buffer is not altered
  - flow P2 > sum of all flows of heat users: HTC buffer is charged
  - flow P2 < sum of all flows of heat users: HTC buffer is discharged
- Wood burner power is automatically adjusted in order to maintain the target temperature. From safety point of view, it is convenient that the wood burner is self-controlling, but as shown later in the document, it is quite inconvenient when it has to be integrated in a larger control scheme.

7.1.2.1 Challenges in the current control scheme

In the current control scheme, the valves are controlled directly to adapt the power towards the ORC or the high temperature circuit in an uncoordinated way.

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Example 1: opening V3 in order to increase the power towards the ORC not only increases the flow to the ORC, but also reduces the flow towards the high temperature circuit
Example 2: changes in the bypass valve influence flow to the HTC and the ORC

Further, the uncoordinated approach makes it very difficult to get the pressure in the primary circuit under control. In order to prevent pressure build-up and in order to avoid opening of over pressure valves, the bypass valve V7 is kept quite open for security reasons that makes the controllability of the system difficult.

7.1.2.2 Levelled control approach

This document describes a control approach in 4 control levels:

- Valve control level: The valve control level receives flow target set points for the flows to the ORC and the and the high temperature circuit heat exchanger. It is responsible to control the flows while maintaining a constant pressure in the primary circuit
- Power control level: The power control level is responsible for translating power target values for the ORC and HTC circuit in flows
- Power target calculation level: This power target calculation level is needed in order to handle the power control of the wood burner. In case direct power control of the wood burner would be possible, this level would not be needed.
- Scenario control level: the scenario control level makes a planning for the ORC and the HTC buffer based planning information, weather information, forecasts, etc.

scenario control level is responsible for the profitable integration of the storage tanks is the system.

7.1.2.2.1 Valve control level

The valve control level receives flow target set points for the flows to the ORC and the and the high temperature circuit heat exchanger. It is responsible to control the flows while maintaining a constant pressure in the primary circuit.

The major issue to get the valve control level right is the lack of flow meters. In the current setup, there are only 2 flow meters in the primary high temperature circuit:

- Main flow meter: measures the total flow going through the wood burner
- ORC flow meter: measure the flow going towards the ORC primary heat exchanger

Consequently, the flow towards the HTC heat exchanger and through the bypass valve is unknown.

Recommendation 1: Add flow meter towards the HTC heat exchanger or alternatively on the bypass circuit in order to know all flows in the circuit. In the rest of this section, it is assumed that the flow towards the HTC heat exchanger can be measured.

Recommendation 2: The bypass valve (V7) is mainly present to avoid pressure build-up in the primary circuit in case the valves towards the ORC and the HTC heat exchanger are both closing. However, there is no real time pressure measurement in the primary circuit that makes it very difficult to keep the pressure under control. Adding a real time pressure measurement will highly

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improve controllability and safety of the primary circuit. In the rest of this section, it is assumed that a primary pressure measurement is available.

Terminology:
ORC_Q_target: target flow towards the ORC
ORC_Q_measured: measured flow towards the ORC
HTC_Q_target: target flow towards the high temperature circuit heat exchanger
HTC_Q_measured: measured flow towards the high temperature circuit heat exchanger
PP_target: primary circuit target pressure
PP_measured: primary circuit measured pressure
V3: valve setting for the flow going to the ORC
V59: valve setting for the flow to the high temperature circuit (HTC)
V7: valve setting for the flow in the bypass circuit

Control architecture
Under the assumption that and additional flow measurement and primary pressure measurement are added, the control is quite straightforward with 3 actuators (V3, V59, V7) which have to control 3 system variables: ORC_Q, HTC_Q and PP. Due to the very non-linear relationships between flows, pressures and valve settings, the bandwidths of the different controllers have to be small and will never result in a fast response. Better performance can be achieved by adding a feedforward circuit. Figure 24 shows the control flow diagram and logic.

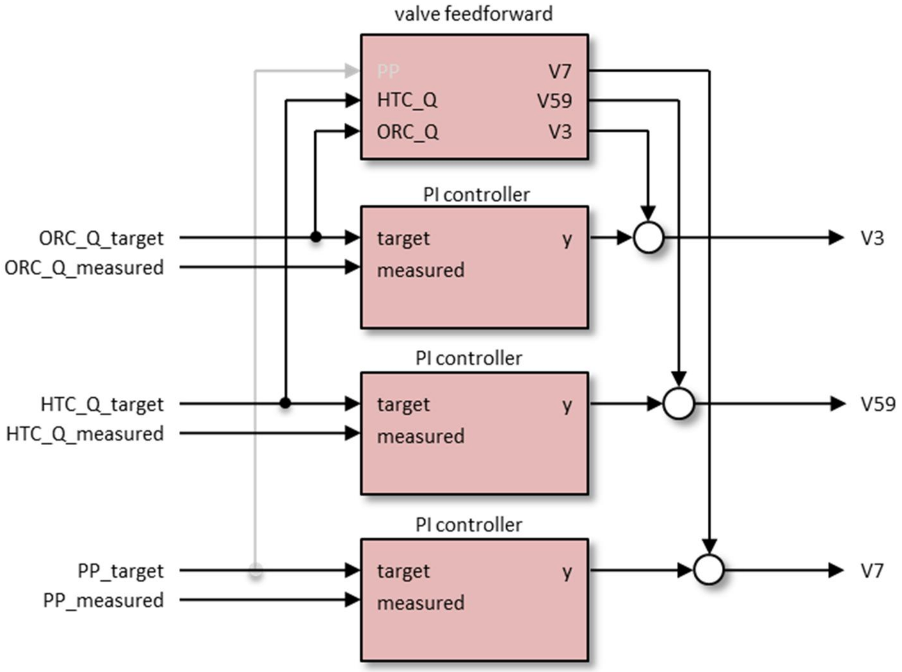

Figure 24: Valve control implementation with 3 independent PI controllers and feedforward circuit

In principle the valve, feedforward block contains calibrated tables (based on measurements) which know he relationship between the valve settings and the target flows. In case the calibrations are performed well, every flow target change results immediately in the correct valve

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setting. The PI controllers only have to correct for (small) calibration errors. In principle, the valve feedforward calibration only has to be performed for the target primary circuit pressure that simplifies the valve feedforward block.

7.1.2.2.2 Power control level

The power control level is responsible for translating power target values for the ORC and HTC circuit in flows.

7.1.2.2.3 Power target calculation level

The power target calculation level is responsible for executing a planning for the SOC of the HTC buffer and a planning for the ORC, taking into account the actual heat demand of the Beneens plant. In takes care that sudden heat demand changes or abrupt change requests are handled properly by the buffer without large temperature variations at the primary side.

Terminology:

In the terminology 2 different setpoint types are used:

- *_planned: the "_planned" setpoints are setpoints which the top level controller actually would like to have at this right moment.*
- *_target: the "_target" setpoints are setpoints which are actually used by underlying controllers which might be different from the actual planning. E.g. at some moment in time, the planning was to run the ORC at 900kW, but due to high heat demand in the HTC circuit and the buffer tank empty, the actual target power to the ORC will be reduced to 700kW.*

Calculation of the required power for the HTC buffer

The control mechanism tries at all times to keep the HTC buffer state of charge at a planned SOC (SOC_planned) which can deviate from the actual SOC (SOC_actual). In case the actual SOC deviates from the planned SOC, additional power will be planned to correct the SOC to the correct value. Proposal is to do this with a proportional controller:

HTC_buffer_P_planned = (SOC_planned – SOC_actual)*K

Example 1: The actual state of charge is lower than the planning:
K = 500, SOC_planned = 50%, SOC_actual = 40%
HTC_buffer_P_planned = 0.1*500 = 50kW will be planned for charging the buffer

Example 2: The actual state of charge is higher than the planning:
K = 500, SOC_planned = 50%, SOC_actual = 80%
HTC_buffer_P_planned = -0.3*500 = -150kW will be planned for discharging the buffer

Planned boiler power calculation

Based on:

- The planned power for the ORC (ORC_P_planned)
- The actual heat demand of all the HTC circuits (HTC_P_demand)

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- The planned charging/discharging of the HTC buffer (HTC_buffer_P_planned)
- The estimated system losses (P_losses)

the boiler power can be calculated:

Boiler_P_planned = ORC_P_planned + HTC_P_demand + HTC_buffer_P_planned + P_losses

Example: At a certain moment in time, the ORC is planned to run at 1MW and the actual heat demand of all the HTC circuits is 250kW. Based on a difference between the actual SOC and the planned SOC of the HTC buffer it was calculated that the buffer must be discharged with 150kW. Further is assumed that the system losses are estimated at 100kW. Under these conditions it is clear that in ideal circumstances, the boiler should produce:

Boiler_P_planned = 1000 kW + 250kW -150kW + 100kW = 1200kW

7.1.2.2.4 Scenario control level

The ideal scenario

In an ideal scenario it would be possible to use Boiler_P_planned as a setpoint for the wood burner. Since the boiler has a large thermal inertia, sudden changes in the boiler power are impossible and the actual boiler power (Boiler_P) can significantly deviate from the planned boiler power (Boiler_P_planned).

In order to avoid large temperature variations in the primary circuit, it is important that the actual heat offtake does not deviate from the actual produced power.

Example: Suppose the Boiler_P_planned = 1200kW (see previous example) while the actual boiler power Boiler_P = 1400kW. In order to give the wood burner the time to reduce its actual power from 1400kW to 1200kW, the planned powers to the different users are adapted. In the above example it makes sense to temporarily absorb the excess power in the buffer. This would allow smooth power changes without any temperature variations in the primary circuit.

The real scenario

In practice, however, the wood burner has its internal controller which controls the wood burner target outlet temperature of 145deg. As long as the target temperature is on target, the wood burner keeps running at the same power. For that reason, a control strategy is needed which creates a mismatch between the produced power and the actual demand to make the wood burner controller react. It is important, however, that the primary temperature does not deviate too much from the target temperature.

In this section, the difference between Boiler_P_planned and Boiler_P_target will be explained. Boiler_P_target will be calculated in 3 steps:

Step 1: calculate the actual power of the wood burner:

Boiler_P = Boiler_Q*(Boiler_Tout – Boiler_Tin)*4186/3600

Step 2: calculate the temperature deviation:

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delta_T = Boiler_Tout_target – Boiler_Tout

Step 3: calculate the adapted target power offtake:
Boiler_P_target = Boiler_P_planned – (Boiler_P_planned - Boiler_P)*delta_T/delta_T_ref

By means of some examples, it will be explained how this principle avoids a temperature collapse at the primary side.

Situation 1: Wood burner power should actually increase but the outlet temperature is still OK. Suppose Boiler_P = 1MW and Boiler_P_planned = 1.2MW, Boiler_Tout_target = 145deg and the actual Boiler_Tout is also 145deg.

delta_T = 145 - 145 = 0
Boiler_P_target = Boiler_P_planned – (Boiler_P_planned - Boiler_P)*delta_T/delta_T_ref
Boiler_P_target = 1MW – (1MW – 1.2MW)*0/10 = 1.2MW

Boiler_P_target is the target power which will be used by the underlying power controllers for the offtake of power. Since the wood burner runs at 1MW and the actual power offtake is 1.2MW the temperature will start dropping resulting in an increased power of the boiler and that is what should happen.

Situation 2: Wood burner power should increase but temperature is getting lower. We are in the same situation as in situation 1, but in the meanwhile the outlet temperature of the wood burner is dropped to 140deg.

delta_T = 145 - 140 = 5
Boiler_P_target = Boiler_P_planned – (Boiler_P_planned - Boiler_P)*delta_T/delta_T_ref
Boiler_P_target = 1MW – (1MW – 1.2MW)*5/10 = **1.1MW**

Although the planned power offtake is 1.2MW, the real power offtake from the primary circuit will be reduced in order to avoid a complete temperature collapse.

Situation 3: Wood burner power should increase but the primary water temperature is getting at the lower acceptable limit and is dropped to 145deg.

delta_T = 145 - 135 = 10
Boiler_P_target = Boiler_P_planned – (Boiler_P_planned - Boiler_P)*delta_T/delta_T_ref
Boiler_P_target = 1MW – (1MW – 1.2MW)*10/10 = **1.0MW**

Since the temperature is too low (135 instead of 145), the wood burner will increase the power. The offtake of the primary circuit, however, is the same as the actual power of the wood burner. This means that all the additional power will be used to warm up the HTC circuit. This mechanism avoids a further collapse of the temperature.

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Correction
In case the target heat offtake deviates from the planning, this means that the wood burner power is slowly adapting to the correct power, but in the meanwhile the power offtake is adapted to avoid a temperature collapse.
In this section it is described how this difference will be handled in 5 different situations:

1. Boiler_P_planned > Boiler_P_target, SOC > SOC_min
The heat demand is larger than the boiler can deliver at the moment, but there is still hot water in the HTC buffer tank. The difference will be extracted from the buffer and the ORC can run at the planned power:

ORC_P_target = ORC_P_planned
HTC_buffer_P_target = Boiler_P_target - ORC_P_target – P_losses - HTC_P_demand

Example:
- The buffer is at 50%, ORC_P_planned = 1 MW, HTC_P_demand = 200kW, P_losses = 100kW so Boiler_P_planned = 1000+200+100 = 1300kW
- Boiler_P_target = 1100kW
- ORC_P_target = 1000kW
- HTC_buffer_P_target = 1100kW – 1000kW – 100kW – 200kW = -200kW

2. Boiler_P_planned > Boiler_P_target, SOC <= SOC_min, ORC running
The heat demand is larger than the boiler can deliver at the moment and there is no hot water in the HTC buffer. In this situation, the power of ORC will be reduced.

ORC_P_target = ORC_P_planned – (Boiler_P_planned - Boiler_P_target)
HTC_buffer_P_target = 0

Example:
- The buffer is at 0%, ORC_P_planned = 1 MW, HTC_P_demand = 200kW, P_losses = 100kW è Boiler_P_planned = 1000+200+100 = 1300kW
- Boiler_P_target = 1100kW
- ORC_P_target = (1000kW – (1300-1100)) = 800kW
- HTC_buffer_P_target = 0kW

3. Boiler_P_planned > Boiler_P_target, SOC <= SOC_min, ORC not running
The heat demand is larger than the boiler can deliver at the moment, there is no hot water in the HTC buffer and the ORC is not running. In this situation there is no other choice than reducing the power over the HTC heat exchanger.

4. Boiler_P_planned < Boiler_P_target, SOC_actual <= SOC_max
In this situation the heat demand of the system is lower than the wood burner delivers at this moment. Since the buffer tank is not full yet, it makes sense to store the excess heat in the HTC buffer tank and the ORC can keep running at its planned setpoint:

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ORC_P_target = ORC_P_planned
HTC_P_demand_corrected = HTC_P_demand
HTC_buffer_P_target = Boiler_P_target - ORC_P_target – P_losses - HTC_P_demand

Example:

- The buffer is at 0%, ORC_P_planned = 1 MW, HTC_P_demand = 200kW, P_losses = 100kW Boiler_P_planned = 1000+200+100 = 1300kW
- Boiler_P_target = 1500kW
- ORC_P_target = 1000kW
- HTC_buffer_P_target = 1500 - 1000 – 100 – 200 = 200kW

5. Boiler_P_planned < Boiler_P_target, SOC_actual >= SOC_max

In this situation the heat demand of the system is lower than the wood burner delivers at the moment. The excess heat cannot be stored in the buffer tank because it is full. This is an emergency situation where it must be tried to evacuate the excess heat into the buffer at a higher temperature than the target temperature.

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8 Appendix A - Description of rational control system

8.1.1 The structure of the detailed model

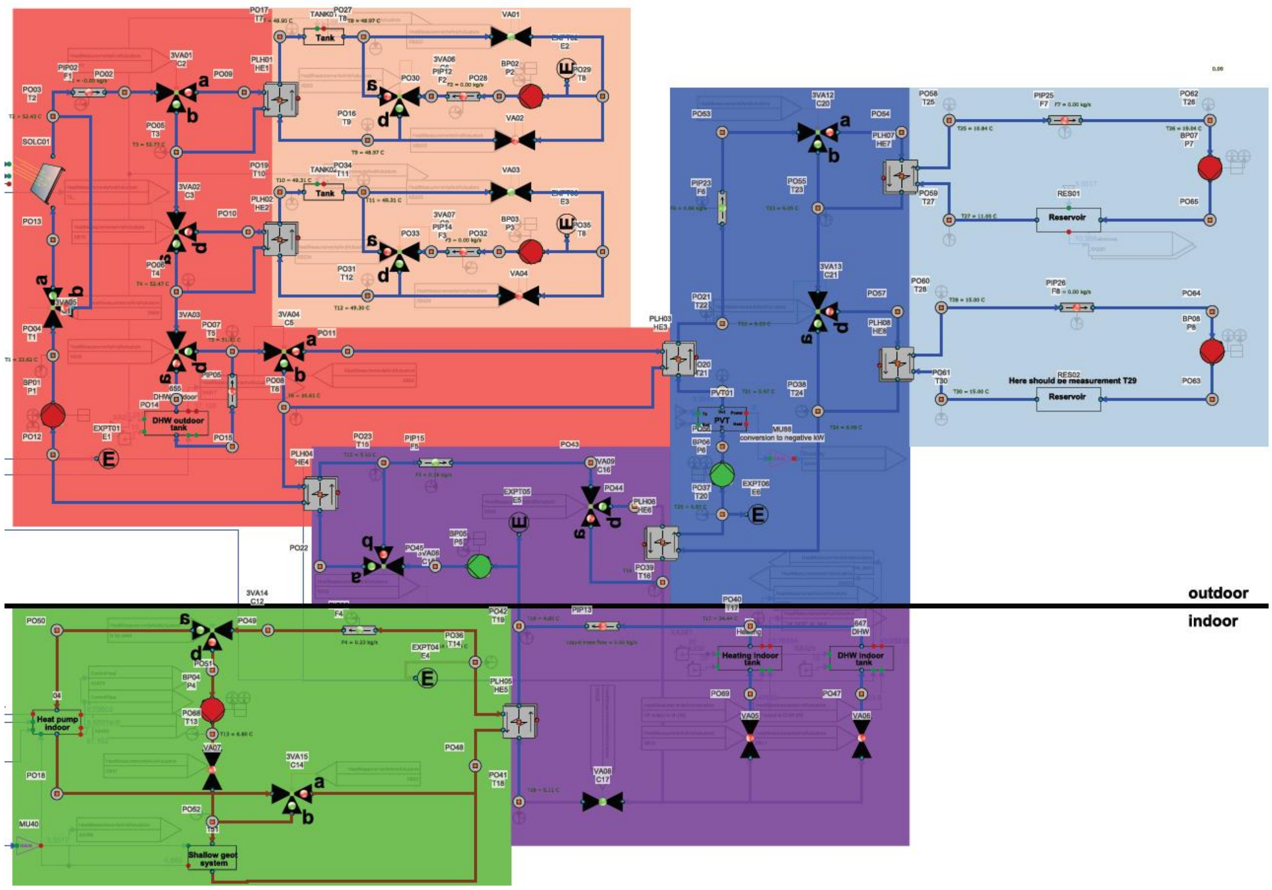

Figure 25: The controller flow diagram

The control model shown in Figure 25 may be controlled by a so-called rational control automation, which is described in this Appendix. The rational control automation system consists of three main blocks. The first block mainly obtains logical signals using measurements of temperature levels across the parts of the system. The aim is to define possible heat transfer directions and prevent operation outside of allowed temperature limits. For example, “is temperature of vacuum collector greater than temperature of indoor space heating storage tank with a margin”, or “is temperature at the inlet to shallow geothermal heat storage lower than allowed”.

The second block uses these outputs of the first block and implements the hierarchy of priorities for operating the loops of the model. The outputs of the second block are logical signals defining the operation mode, i.e. the directions of heat transfer. For example, “is vacuum collector heating

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indoor domestic hot water tank", "is heat transfer possible from PV/T loop to the loop of shallow geothermal system".
The third block translates the operation mode signals received from the second block into switching configuration and operational state of circulation pumps. The outputs are commands sent to the actuators of valves and circulation pumps.

The temperature and other measurements utilized by the rational control system (inputs to the first block) are summarized in the Table 6.

Table 6 - Temperature and other values used as input data for the temperature level checks

Abbreviation	Location of temperature measurement
T1	Before vacuum collectors bypass
T2	Vacuum collectors (when idle) or T2 (when there is flow)
Tdhw_out	Outdoor DHW tank (mean value)
T_top_tank1	Top of seasonal storage tank 1
T_bot_tank1	Bottom of seasonal storage tank 1
T_top_tank2	Top of seasonal storage tank 2
T_bot_tank2	Bottom of seasonal storage tank 2
Tpvt	Outlet of PVT system (T21)
Tres1	Reservoir 1 (mean value)
T_top_dhw_tank	Top of indoor DHW tank
T_bot_dhw_tank	Bottom part of heating coil of indoor DHW tank or bottom of tank
T_top_sh_tank	Top of indoor DHW tank
T_bot_sh_tank	Bottom part of heating coil of space heating tank or bottom of tank
Tsoil	Indicative temperature of shallow geothermal storage (ground)
T14	Temperature after heat exchanger HE5 in the geothermal loop
T_to_geo	Temperature at the inlet to shallow geothermal system
	Other outputs and assumptions in the simulation model
dT	Temperature spread (assumed 5Kelvins)
T_top_dhw_max	Maximum temperature at the top of domestic hot water tank (70°C)
T_top_sh_max	Maximum temperature at the top of space heating tank (50°C)
Tres1_max	Maximum mean temperature of reservoir 1 (25°C)
T_inlet_geo_max	Maximum inlet temperature to shallow geothermal system (23°C)
T_top_tank1_max	Maximum temperature at the top of seasonal storage tank 1 (90°C)
T_top_tank2_max	Maximum temperature at the top of seasonal storage tank 2 (90°C)
T_sp_sh_tank	Heat pump set point temperature for space heating (35°C)
Tlb_sp_dhw_tank	Heat pump lower bound set point temperature for DHW (45°C)
Tub_sp_dhw_tank	Heat pump upper bound set point temperature for DHW (50°C)
is_heating_season	Logical value which is False between April and October (1.0368e7 and 2.30796e7 seconds elapsed from beginning of year)
is_dhw_outdoor_tank_enabled	In the simulation was always False (no heat exchange with outdoor domestic hot water tank)
T_dhw_out_max	Maximum mean temperature of outdoor DHW tank (70°C)

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is_PVT_producing_heat	Logical value from simulation[4]

Processing of the listed temperature measurements by the first block, results in the following logical signals (Table 7).

Table 7 - List of binary signals resulting from processing temperature measurements

Outputs of processing temperature measurements	Interpretation when the output value is True
is Tdhw_out > T_bot_dhw_tank + dT	Heat transfer from outdoor DHW tank to indoor DHW tank is possible
is Tdhw_out < T_dhw_out_max	Outdoor DHW tank may be heated
is T2 > Tdhw_out + dT	Heat transfer from vacuum collectors to outdoor DHW tank is possible
is vc producing (is T2 > T1)	Vacuum collectors are generating heat
is T_top_tank1 > T_bot_dhw_tank + dT	Heat transfer from seasonal heat storage 1 to indoor DHW tank is possible
is T2 > T_bot_tank1 + dT	Heat transfer from vacuum collectors to seasonal heat storage 1 is possible
is T_top_tank1 < T_top_tank1_max	Seasonal heat storage 1 may be heated
is T_top_tank2 < T_top_tank2_max	Seasonal heat storage 2 may be heated
is T2 > T_bot_tank2 + dT	Heat transfer from vacuum collectors to seasonal heat storage 2 is possible
is T_top_tank2 > T_bot_dhw_tank + dT	Heat transfer from seasonal heat storage 2 to indoor DHW tank is possible
is Tres1 < Tres1_max	Reservoir 1 may be heated
is T_top_dhw_tank < T_top_dhw_max	Indoor DHW tank may be heated
is T2 > T_bot_dhw_tank + dT	Heat transfer from vacuum collectors to indoor DHW tank is possible
is T_top_tank1 > T_bot_sh_tank + dT	Heat transfer from seasonal heat storage 1 to space heating tank is possible
is T_top_tank2 > T_bot_sh_tank + dT	Temperature difference allows heat transfer from seasonal heat storage 2 to space heating tank
is T_top_sh_tank < T_top_sh_max	Space heating tank may be heated
is T2 > T_bot_sh_tank + dT	Heat transfer from vacuum collectors to space heating tank is possible
is (Tsoil + dT) < T2 < T_inlet_geo_max	Heat transfer from vacuum collectors to shallow geothermal system is possible and is safe for pipes of geothermal system

[4] This signal is used to start circulation in PVT loop. Its value can be derived from on-site measurements of outdoor temperature combined with irradiation measurements (e.g., True, when Irr>350 W/m2), or state of pvt panels (temperature inside panels or their electrical output).

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is (Tsoil + dT) < Tres1 < T_inlet_geo_max	Heat transfer from reservoir 1 to shallow geothermal system is possible and is safe for pipes
is Tpvt > Tres1 + dT	Heat transfer from PVT system to reservoir 1 is possible
is (Tsoil + dT)< Tpvt <T_inlet_geo_max	Heat transfer from PVT system to shallow geothermal system is possible and safe for pipes
is T_inlet_geo < T_inlet_geo_max	Temperature at inlet to geothermal loop is safe. T_inlet geo = min {T14; T_to_geo}

There are eight priority levels defining the operation modes of the system. They are described in order in the following list:

1. Vacuum collectors are heating indoor DHW tank;
2. Vacuum collectors are heating indoor space heating tank;
3. Outdoor DHW tank is heating indoor DHW tank (not simulated);
4. Seasonal heat storages 1, 2 are heating indoor DHW tank;
5. Seasonal heat storages 1, 2 are heating indoor space heating tank;
6. Vacuum collectors are heating outdoor DHW tank;
   6.1. PVT is heating shallow geothermal system, or
   6.2. Reservoir 1 is heating shallow geothermal system;
7. Vacuum collectors heating seasonal heat storages 1, 2;
8. Vacuum collectors are heating shallow geothermal system.
9. PVT system is operating simultaneously with 1-8, except 6.1 or 6.2:
   9.1. PVT is heating reservoir 1, or
   9.2. PVT is heating reservoir 2.
10. (or, priority zero) Heat pump starts whenever temperatures in indoor tanks drop below set lower boundary value. The state of heat pump only has effect on the circuit of shallow geothermal system

The above hierarchy of operation is implemented according to sufficient conditions described in Table 8.

Table 8 - Priorities of operation with rational control system. output signals defining operation modes and sufficient conditions

Priority number	Output signal	Sufficient condition (all must be True):
1.	is vc heating dhw_in	is T_top_dhw_tank < T_top_dhw_max
		is T2 > T_bot_dhw_tank + dT
		is vc producing
2.	is vc heating sh_tank	is not priority 1 executed (NOT is vc heating dhw_in)
		is T_top_sh_tank < T_top_sh_max
		is T2 > T_bot_sh_tank + dT
		is_heating_season
		is vc producing
3.	is dhw_out heating dhw_in	is not priorities 1 or 2 executed
		is T_top_dhw_tank < T_top_dhw_max

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		is Tdhw_out > T_bot_dhw_tank + dT
		is dhw outdoor tank enabled
4.	is tank1 heating dhw_in	is not priorities 1 or 2 or 3 executed
		is T_top_dhw_tank < T_top_dhw_max
		is T_top_tank1 > T_bot_dhw_tank + dT
4’.	is tank2 heating dhw_in	is not priorities 1 or 2 or 3 executed
		is T_top_dhw_tank < T_top_dhw_max
		is T_top_tank2 > T_bot_dhw_tank + dT
5.	is tank1 heating sh tank	is not priorities 1 or 2 or 3 or 4 or 4’ executed
		is_heating_season
		is T_top_tank1 > T_bot_sh_tank + dT
5’.	is tank2 heating sh tank	is not priorities 1 or 2 or 3 or 4 or 4’ executed
		is_heating_season
		is T_top_tank2 > T_bot_sh_tank + dT
6.	is vc heating dhw_out	is not priorities 1 or 2 or 3 or 4 or 4’ or 5 or 5’ executed
		is Tdhw_out < T_dhw_out_max
		is T2 > Tdhw_out + dT
		is dhw outdoor tank enabled
6.1.	is pvt heating soil	is not priorities 1 or 2 or 3 or 4 or 4’ or 5 or 5’ executed
		is (Tsoil + dT)<Tpvt<23
6.2.	is res1 heating soil	is not priorities 1 or 2 or 3 or 4 or 4’ or 5 or 5’ executed
		is not pvt heating soil
		is (Tsoil + dT) < Tres1 < T_inlet_geo_max
7.	is vc heating tank1	is not priorities 1 or 2 or 3 or 4 or 4’ or 5 or 5’ or 6 executed
		is T_top_tank1 < T_top_tank1_max
		is T2 > T_bot_tank1 + dT
7’.	is vc heating tank2	is not priorities 1 or 2 or 3 or 4 or 4’ or 5 or 5’ or 6 executed
		is Ttank2 < T_top_tank2_max
		is T2 > T_bot_tank2 + dT
8.	is vc heating soil	is not priorities 1 or 2 or 3 or 4 or 4’ or 5 or 5’ or 6 or 7 or 7’ executed
		is (Tsoil + dT) < T2 < T_inlet_geo_max
9.1	is pvt heating res1	is not pvt heating soil or res1 heating soil (no heat transfer between pvt loop and central loop)
		is Tpvt > Tres1 + dT
		is Tres1 < Tres1_max
9.2	is pvt heating res2	is not pvt heating soil or res1 heating soil (no heat transfer between pvt loop and central loop)
		is not Tres1 < Tres1_max
		is Tpvt > Tres1 + dT
10’.	is hp in use (hot water)	is T_top_dhw_tank < Tlb_sp_dhw_tank AND T_top_dhw_tank > Tub_sp_dhw_tank

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		(heat pump starts when T_top_dhw_tank drops below lower bound set point and operates until it exceeds upper bound set point)
10''.	is hp in use (heating)	is_heating_season
		is T_top_sh_tank < T_sp_sh_tank
10.	is hp in use	is hp in use (hot water) OR is hp in use (heating)

Intermediate signal values derived from the signals described above are useful for later formulation of commands sent to actuators of pumps and valves. Table 9 summarizes these signals.

Table 9 - List of intermediate signals

Intermediate signals	Signal value True when:
is tank1 charged	is vc heating tank1
is tank2 charged	is vc heating tank2
is tank1 discharged	is tank1 heating dhw_in OR is tank1 heating sh tank
is tank2 discharged	is tank2 heating dhw_in OR is tank2 heating sh tank
is HE6 in use	is pvt heating soil OR is res1 heating soil
is HE6 not used	NOT (is pvt heating soil OR is res1 heating soil)
is HE4 in use	is vc heating dhw_in OR is vc heating sh tank OR is dhw_out heating dhw_in OR is tank1 discharged OR is tank2 discharged OR is vc heating soil.
is sh tank charged from vc loop	is vc heating sh tank OR is tank1 heating sh tank OR is tank2 heating sh tank.
is dhw_in charged from vc loop	is dhw_out heating dhw_in OR is vc heating dhw_in OR is tank1 heating dhw_in OR is tank2 heating dhw_in.
is geo in use	is hp in use OR is res1 heating soil OR is vc heating soil OR is pvt heating soil
indoor tanks not charging	NOT (is sh tank charged OR is dhw_in charged)

The Table 10 lists the valves and pumps to which the rational control system sends logical True/False commands. The True signal sent to a three-way valve indicates that the valve should be open in the direction "a". When True signal to a close valve, then the valve should be open and if True signal is sent to a pump, the pump should be on. The valves and pumps can be identified using the structure of model shown in section 8.1.1.

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Table 10 - Logical signals defining the positions and states of valves and pumps

controlled valve or pump	control signal name	control signal value
C1	is vc loop flow through vc	is vc producing
P1	is vc loop pump running	is tank1 charged OR is tank2 charged OR is HE4 in use
C2, P2	is loop of tank1 in use	is tank1 charged OR is tank1 discharged
C3	is loop of tank2 not in use	NOT (is tank2 charged OR is tank2 discharged)
C4	is dhw_out in use	is dhw_out heating dhw_in OR is vc heating dhw_out
C5	is HE3 used	False
C6, C8	is tank1 not charged	NOT is tank1 charged
C7	is tank1 charged	is tank1 charged
C9, C11	is tank2 not charged	NOT is tank2 charged
C10	is tank2 charged	is tank2 charged
P3	is loop of tank2 in use	is tank2 charged OR is tank2 discharged
C20, P7	is res1 used	is pvt heating res1 OR is res1 heating soil
C21	is res2 not used	NOT is res2 used
P6	is pvt loop pump on	is res1 used OR is res2 used OR is pvt heating soil OR is pvt producing
P8	is res2 used	is res2 used
C15	is HE4 in use	is HE4 in use
C16	is HE6 not used	is HE6 not used
C17	is HE5 in use	is vc heating soil OR is indoor tanks not charging
C18	is sh tank charged	is sh tank charged
C19	is dhw tank charged	is dhw tank charged
P5	is central loop exchanging heat with vc loop or with pvt loop	is HE4 in use OR is HE6 in use
C12	is hp in use	is hp in use
C13, P4	is not hp in use	NOT is hp in use
C14	is not hp operating with geo	is hp in use AND is geo in use

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8.2 References

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