GreenDataNet

D3.7 – Smart Energy Management System

FINAL
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Rev 0.4

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REVISION SHEET

Revision Number	Date	Brief summary of changes
Rev 0.1	07/07/2015	Draft for presentation to partners
Rev 0.2	09/07/2015	First version with integration of partners comments
Rev 0.3	13/07/2015	Minor changes
Rev 0.4	15/07/2015	Final version with integration of partners comments

SUMMARY

The SEMS (Smart Energy Management System) software aims to optimize the energy management at Data Center level in order to increase self-production and to avoid buying electricity from the Grid at high electricity prices (peak shaving application).

The IT load optimization part of the SEMS is detailed in the Deliverables 3.2 and 3.3 with the Electricity Consumption Forecasting Tool. This part communicates through XML file (weak interaction) with the SEMS core that integrates the energy optimization of the Data Center. It takes into account the analytical model of the system and receives trough XML files the IT loads consumption forecast, the cooling load consumption forecast, the PV production forecast and the electricity price forecast.

The SEMS software uses C++ language and a Cplex solver.

A User Interface has been designed in order to ease the understanding of the optimization for the next time steps for the user. In this report 23 time steps optimization have been performed (1 day with 1h time steps) but time step could be different and numerous.

The energy optimization results are sent with XML files to the IT load optimization part (SOE and IT load power targets) but also to the reactive layer of the Data Center system, i.e the GreenDataNet UPS prototype. Hence the UPS receive optimal charge/discharge power to be applied to the ESS for the next time step.

2. INTRODUCTION

The model predictive control (MPC) is the core of the Smart Energy Management System for optimizing the global energy management at Data Center level. The smart working of SEMS is based on the possibility to handle the upcoming energy status of the system in order to find its optimal energy management for the next time steps. Hence the forecast information of photovoltaic production (Deliverable 3.4) and IT loads consumption forecasting (Deliverable 3.2) are taken into account.

First the models of the different components (Li-ion storage system, UPS, electrical grid, photovoltaic system, IT loads) of the GreenDataNet prototype, detailed in Deliverable 1.6 are formulated in mixed linear integer programming (MILP).

Then SEMS software, developed for GreenDataNet project, handles the formulation of the problem, solves the optimization problem and sends the optimal solution to Eaton UPS control and also to the Smart Data Centre Energy Controller developed by EPFL and UNITN to optimize the energy and power use at IT level.

3. GREENDATANET FRAMEWORK INTEGRATION

Figure 1 presents the SEMS framework integration for GreenDataNet prototype with all the interactions between components of the SEMS but also the links between SEMS and AEMS, forecasting modules and analytical models.

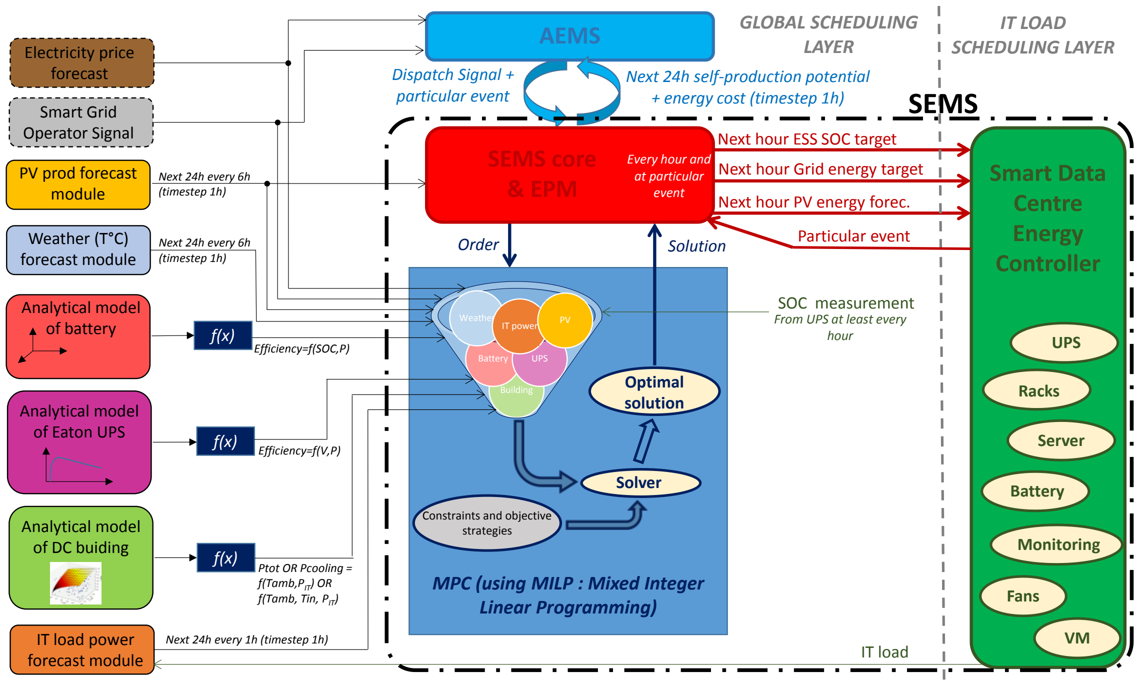

Figure 1- The components of the GreenDataNet Framework

The SEMS core and Energy Planning Module (EPM) [in red] is the part of SEMS software that launches a new optimization calculation regarding the energy management of the DC. The calculation order could be sent to MPC every previously defined period (every 1h or 30min for instance) or regarding a particular event. Such particular event could be generated by the Smart Data Centre Energy Controller (SDCEC) or by the GreenDataNet UPS itself; it could be due to an unexpected change of the system (failure of a part of the battery, malfunction of a part of PV plant …) or to a strong deviation between forecasts and real data. The definition of the generation of particular events due to such strong deviations is a large task and is not part of this deliverable.

The Model Predictive Control (MPC) block [in blue] receives the calculation order and gives as an output an optimal solution of the energy management for the next time steps (for example next 24h). It orders to provide such optimization by taking into account the PV production forecast for the next 24h delivered by the PV production forecast module (developed in Deliverable 3.4) with a time step of 1h or less. The MPC considers also the IT loads consumption forecast for the next 24h with a time step of 1h or less and delivered by the IT load power forecast module (directly linked to the SDCEC). It will also integrate the ambient temperature forecast from a weather forecast service as it impacts the cooling loads of the data center; nevertheless existing temperature forecasts could be strongly impacted by local effects and are not accurate data.

Furthermore the MPC also integrates analytical models of the Li-ion storage system, of the Eaton UPS conversion stages and of the Data Center building regarding the cooling need for IT loads.

Hence the analytical models of the converters within the UPS describe a variation of their efficiencies regarding the output power of each converter; for the moment the efficiency values are constant and have been evaluated by Eaton. But once the prototype will be fully tested values of efficiency that depend on power will be implemented and the MPC is ready to integrate such data.

The analytical model of battery describes the variation of the efficiency regarding the power but also the power limitations (in charge and in discharge) regarding the State-Of-Charge (SOC); Depending on the testing results of the Nissan battery an analytical model of efficiency according to power and SOC could be implemented. The ageing process of the Nissan battery could also be implemented once it will be better identified.

The analytical model of the DC building is strictly focused on cooling requirement for the building and the data center room considering containment, free cooling, chillers, cooling towers, heat losses … As explained in Deliverable 3.1, this empirical model helps to determine the expected PUE of the data center depending on the ambient temperature values based on weather forecasts, on the target temperature for IT cooling and on the characteristics of Data Center building (free cooling or not, containment or not …). The calculated PUE value is associated to the expected IT load forecast in order to get the forecast of the cooling load for the next time steps (for instance 1h time steps during 24h).

Depending on the first test results on the prototype these different models will be improved if necessary in order to increase the accuracy of the SEMS.

Then it is necessary to formulate the optimization problem with objective and constraints functions (explained in Part 4) before solving it with solvers (see in Part 5.3) in order to find in a short computation time an optimal solution for the system.

This optimal solution is formulated by the MPC in order to be communicated by the SEMS core easily to other components.

Hence based on the optimal solution for the next 24h, the next hour ESS SOC target and the next hour Grid energy target (or IT loads target) are communicated to the SDCEC for the optimal planning of IT tasks. The next hour PV forecast is also communicated to the SDCEC. The SDCEC is detailed in Deliverables 3.2 and 3.3 and is the core of the Electricity Consumption Forecasting Tool (ECFT). The SDCEC is composed by two controllers: the

Green Energy Controller but mainly the IT Infrastructure Energy Controller. The Green Energy Controller permits to anticipate the PV production and ESS use to better optimize the IT loads. Using a VM allocation algorithm, the IT Infrastructure Energy Controller is a powerful tool for dynamic power management of DC to reduce its global power consumption while satisfying QoS requirements. Hence SCDEC permits to find an optimal configuration for reducing IT load power and to deliver the forecast of these powers for the next time steps.

The next hour charge/discharge powers for the Li-ion battery is communicated to the control of the UPS in 'peak shaving' mode and the UPS will apply it as best as possible; the control of the UPS acts as the reactive layer of the SEMS. In the other way some information as real PV production, real SOC value and particular event can be sent by the UPS to the SEMS core.

The communication of the optimal solution to the other components is illustrated in Figure 2.

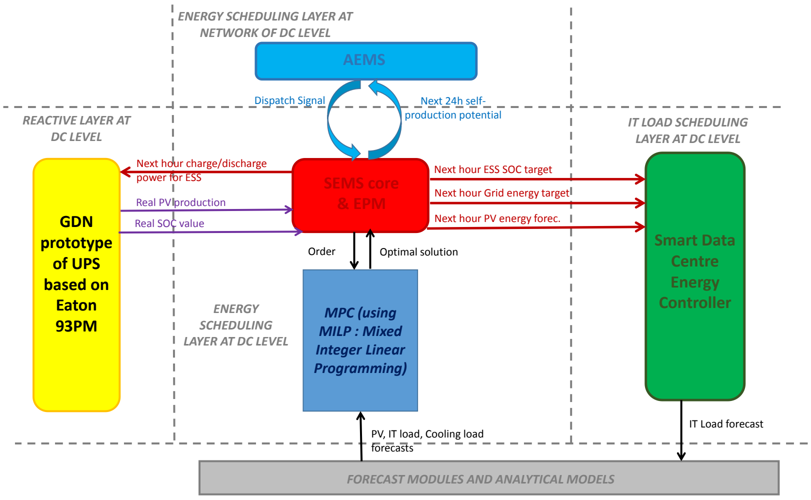

Figure 2- Simplified view of interactions and data exchange between the different components

The SEMS is also designed to exchange information with the foreseen AEMS of GreenDataNet project; it will be developed on the same framework than the SEMS in the next months. The AEMS will be able to consider the next 24h electricity price forecast on the market based on electricity price forecast module; the developed SEMS is also able to integrate this information within the energy optimization calculation in order to have locally an optimized use of storage and renewables from an economical aspect.

The AEMS could also be able to receive signals from grid operator (or smart grid actors) and to adapt the energetic strategy of the Data Centre network.

As explained in this Part 3, the coupling between the SEMS and the UPS in one hand, the SEMS and the AEMS in another hand have been designed to be as simple as possible trough data exchange file. It is also the case between SEMS core and the SDCEC, and between SEMS and the different forecast modules (for PV production, IT loads and temperature). This weak coupling should avoid facing complex issues of compatibility between all the components and should permit a soft working of the energy optimization by the SEMS; indeed whatever the new data are available following a new optimization request, the calculation is always done.

4. FORMULATION OF OPTIMIZATION PROBLEM

The SEMS integrates different elements in the mixed linear integer programming framework. In general, the MILP is characterized by a set of variable x in subject to respect a set of constraint C in order to maximize or minimize an objective. The MILP could be written under general form:

$$\begin{cases} Min\ O \times x \\ subject\ to \\ A \times x \leq B \end{cases}$$

In this formulation, x is variable and it will be determined by solving this problem. $O, A\ and\ B$ are the coefficient matrix. There are two kinds of variables: the continuous variables and binary variables. The continuous variables are classic in linear programming, usually solved by the simplex method. The binary variables are more challenging in optimization process: it will request the use of a Brand&Bound optimization method for an efficient resolution. The complexity of the problem depends on the number of binary variables; in the worst case the computation time could be 2^n where n represents the number of binary variable. To take into account the non-linearity of a system like a variable efficiency, a linearization method has been developed and involved a combination of these two kinds of variables: binary and continuous.

The model of grid is formulated as following:

$$eGrid(k)w \leq EgridMax\ \forall k \in [1, K]$$

The model of PV system is formulated by the next equation:

$$ePV(k) = Epv_{forecast}(k) \forall k \in [1, K]$$

The model of storage system consider that there are two state of battery: charging or discharging

$$SOH(k+1) = SOH(k) + \delta(k) \times eBat_{charge}(k) + \big(1 - \delta(k)\big) \times eBat_{discharge}(k)$$

Energy balancing constraint will be formulated as following:

$$eGrid(k) + ePV(k) + eBat(k) + eDC(k) = 0\ \forall k \in [1, K]$$

5. SEMS SOFTWARE DEVELOPMENT

In this section, the architecture of the SEMS software is presented as well as its input and output interfaces. The software is developed using C++ programming language. The use of C++ programming language allow us to generate easily a Dynamic Link Library (DLL) file and an executable (exe) that can be used and embedded in the global system of GreenDataNet (UPS, AEMS). The interaction with the SEMS software can be realized by using XML files in order to facilitate the integration with other components developed in the project. The use of xml allows us to design a global system with a loosely coupled developed sub parts. The first sub section presents the input XML file format on an example using the set of considered components in a GreenDataNet DC system (Grid, PV, ESS, Invertor, Load, Lad Cooling, Rectifier, Converter and Battery charger). The second sub section presents an example of the output xml file format. Finally, the software architecture and the internal workflow are presented. It is important to note that, in addition to the xml output file, the SEMS software issues the results of the optimization in a web interface UI.

5.1 INPUT XML FILE FORMAT

The Figure 3 shows the electrical diagram of a GreenDataNet DC system as it has been designed in Deliverable 1.6.

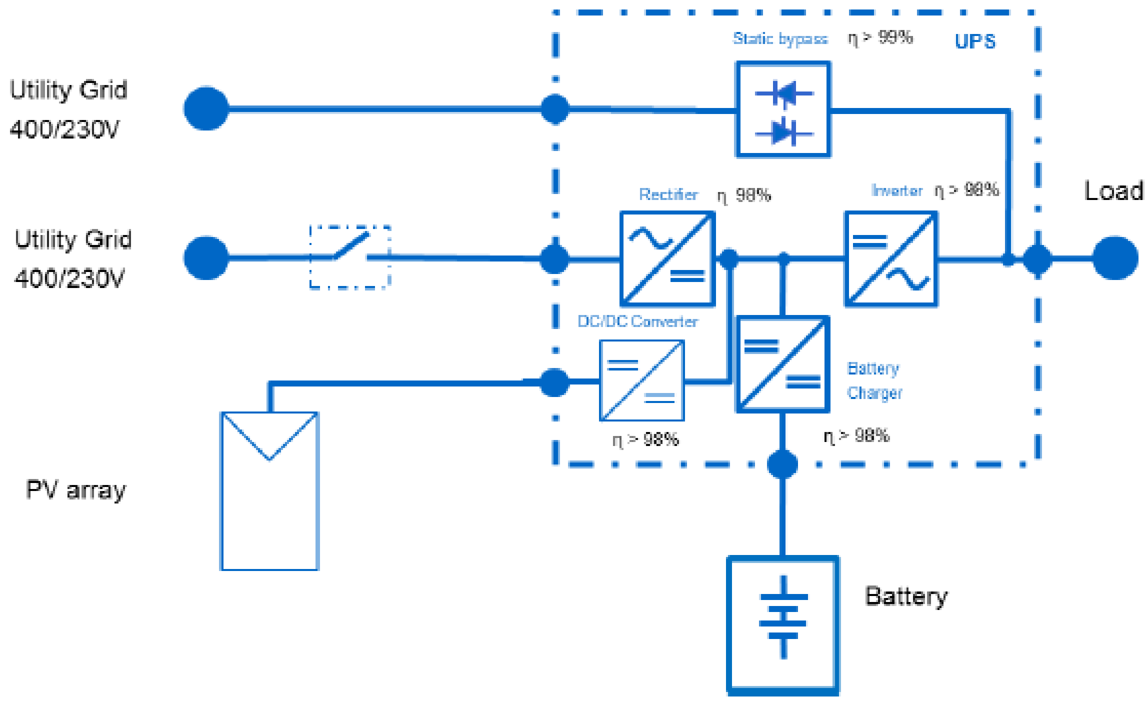

Figure 3- Electrical design of GreenDataNet UPS

The Figure 4 presents the equivalent tree graph of the electrical diagram. A load cooling is added in order to consider the cooling requirement of the UPS and the IT loads (which is not illustrated in Figure 3). Two independent energy storage systems (ESS1 and ESS2) have also been integrated in order to analyze the effects of such configuration on energy optimization; for the moment the GreenDataNet is not designed to have two different ESS, but four Li-ion batteries forming a unique ESS.

The tree graph is used by the SEMS in order to generate an xml representation of the electrical diagram of the system.

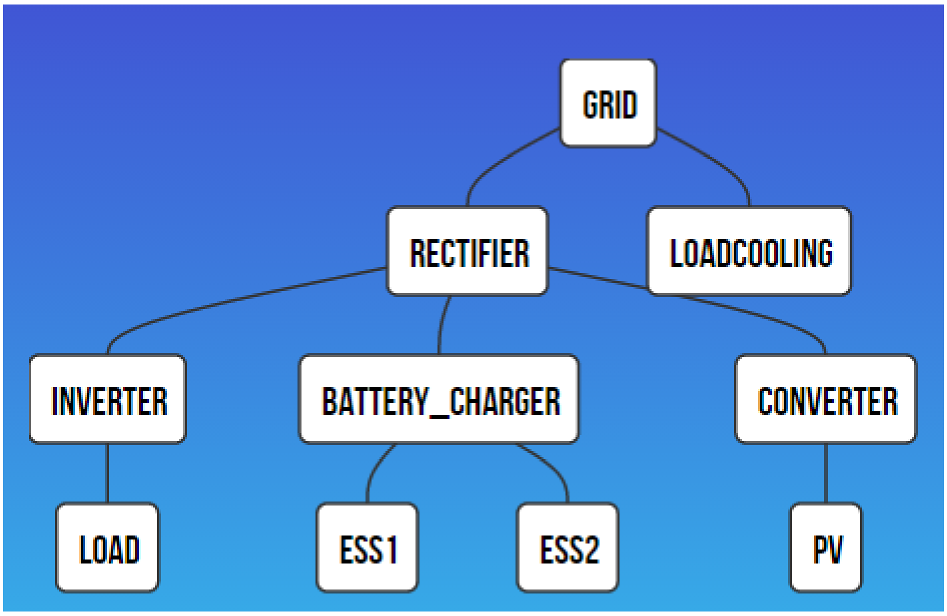

Figure 4- Implemented GreenDataNet UPS system in SEMS

The SEMS input file includes three different parts:

- The system description: includes the set of components and the links between components
- The global optimization parameters
- The data series and parameters of each component

5.1.1 THE SYSTEM DESCRIPTION

The Figure 5 presents the xml representation of the GreenDataNet DC system. The components matches to the tag <ZNode> in the xml file. Each “Znode” has a “nodeRef” attribute that corresponds to the ID of the component, a “type” attribute that corresponds to the type of the component and a “name” attribute used in the output interface.

The ZlinkNodeNode matches to the link between 2 components. Each ZlinkNodeNode has a “LinkNodeNodeRef” attribute that corresponds to the ID of the link, “nodeRef1” attribute that corresponds to the ID of the first linked component, “nodeRef2” attribute that corresponds to the ID of the second linked component.

```xml
<ZNode nodeRef="1" type="GRID" name="GRID" externalControl = "1" />
<ZNode nodeRef="2" type="PV" name="PV" externalControl = "1" />
<ZNode nodeRef="3" type="ESS" name= "ESS1" externalControl = "1" />
<ZNode nodeRef="4" type="TRANSFORMER" name="Rectifier" externalControl = "1" />
<ZNode nodeRef="5" type="TRANSFORMER" name="Inverter" externalControl = "1" />
<ZNode nodeRef="6" type="TRANSFORMER" name="Battery_Charger" externalControl = "1" />
<ZNode nodeRef="7" type="TRANSFORMER" name="Converter" externalControl = "1" />
<ZNode nodeRef="8" type="LOADCONSTANT" name="LOAD" externalControl = "1" />
<ZNode nodeRef="9" type="ESS" name= "ESS2" externalControl = "1" />
<ZNode nodeRef="10" type="LOADCONSTANT" name="LOADCOOLING" externalControl = "1" />

<ZLinkNodeNode linkNodeNodeRef="1" nodeRef1="1" connectorRef1="1" nodeRef2="4" connectorRef2="2"/>
<ZLinkNodeNode linkNodeNodeRef="2" nodeRef1="4" connectorRef1="1" nodeRef2="5" connectorRef2="2"/>
<ZLinkNodeNode linkNodeNodeRef="3" nodeRef1="4" connectorRef1="1" nodeRef2="6" connectorRef2="2"/>
<ZLinkNodeNode linkNodeNodeRef="4" nodeRef1="4" connectorRef1="1" nodeRef2="7" connectorRef2="2"/>
<ZLinkNodeNode linkNodeNodeRef="5" nodeRef1="7" connectorRef1="1" nodeRef2="2" connectorRef2="1"/>
<ZLinkNodeNode linkNodeNodeRef="6" nodeRef1="6" connectorRef1="1" nodeRef2="3" connectorRef2="1"/>
<ZLinkNodeNode linkNodeNodeRef="7" nodeRef1="5" connectorRef1="1" nodeRef2="8" connectorRef2="1"/>
<ZLinkNodeNode linkNodeNodeRef="8" nodeRef1="6" connectorRef1="1" nodeRef2="9" connectorRef2="1"/>
<ZLinkNodeNode linkNodeNodeRef="9" nodeRef1="1" connectorRef1="1" nodeRef2="10" connectorRef2="1"/>
```

Figure 5- XML representation of the GreenDataNet DC System

5.1.2 THE GLOBAL OPTIMIZATION PARAMETERS

The Figure 6 details the global optimization parameters of the system. It is composed of “Data” tags, each data tag has a “name” attribute, the name of the first data tag is of “period Duration” serves to provide the optimization steps to be used; the optimization steps values may not be equal even if in this example there are all equal to 1.

Then, the solver type and the component that carries out the objective function of the optimization (the Grid in this case, i.e. nodeRef=1) are defined.

```xml
<Parameter>
<Data name="periodDuration">
<Sample value="1"/>
<Sample value="1"/>
<Sample value="1"/>
<Sample value="1"/>
<Sample value="1"/>
<Sample value="1"/>
<Sample value="1"/>
<Sample value="1"/>
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<Sample value="1"/>
<Sample value="1"/>
<Sample value="1"/>
<Sample value="1"/>
<Sample value="1"/>
</Data>
<Data name="solveurType">
<Sample value="CPLEX"/>
</Data>
<Data name="OptimizationNodeRef">
<Sample value="1"/>
</Data>
<Data name="OptimizationPortRef">
<Sample value="5"/>
</Data>
<Data name="OptimizationFunction">
<Sample value="MAX"/>
</Data>
</Parameter>
```


Figure 6- Global Optimization Parameters

5.1.3 PARAMETERS OF COMPONENTS AND DATA SERIES

The data series and the parameters associated to a component are also composed of Data tags. Each data tag has a “name” attribute and includes a set of values. The Figure 7 shows the PV component input data. For the PV component, the forecasted power values for the optimization steps are provided in the “Data” tag with the name “forecastedPower” (left column) as provided by the PV production forecast module (Deliverable 3.4).

```xml
<NodeData nodeRef="2">
<Data name="downRatio">
<Sample value="0.3"/>
</Data>
<Data name="forecastedPower">
<Sample value="0"/>
<Sample value="0"/>
<Sample value="0"/>
<Sample value="0"/>
<Sample value="0"/>
<Sample value="0"/>
<Sample value="0"/>
<Sample value="0"/>
<Sample value="0"/>
<Sample value="12"/>
<Sample value="1349"/>
<Sample value="6106"/>
<Sample value="9091"/>
<Sample value="6517"/>
<Sample value="7477"/>
<Sample value="6268"/>
<Sample value="5250"/>
<Sample value="3882"/>
<Sample value="2716"/>
<Sample value="1503"/>
<Sample value="225"/>
<Sample value="0"/>
<Sample value="0"/>
</Data>
<Data name="maxPowerForecasted">
<Sample value="0"/>
<Sample value="0"/>
<Sample value="0"/>
<Sample value="0"/>
<Sample value="0"/>
<Sample value="0"/>
<Sample value="0"/>
<Sample value="0"/>
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<Sample value="5250"/>
<Sample value="3882"/>
<Sample value="2716"/>
<Sample value="1503"/>
<Sample value="225"/>
<Sample value="0"/>
<Sample value="0"/>
</Data>
<Data name="minPowerForecasted">
<Sample value="0"/>
<Sample value="0"/>
<Sample value="0"/>
<Sample value="0"/>
<Sample value="0"/>
<Sample value="0"/>
<Sample value="0"/>
<Sample value="0"/>
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<Sample value="0"/>
<Sample value="0"/>
<Sample value="0"/>
<Sample value="0"/>
<Sample value="0"/>
<Sample value="0"/>
<Sample value="0"/>
</Data>
</NodeData>
```


Figure 7- PV component Data in the XML input file

Similar XML input files are used for the forecasted IT loads power consumption for the next time steps, for the forecasted cooling loads (forecast of PUE value for the next time steps based on ambient temperature forecast and analytical model of DC building multiplied by the forecast of IT loads), and also for the foreseen electricity prices.

5.2 OUTPUT XML FILE FORMAT

Figure 8 shows the output XML file format. The XML contains the output set point for the set of System's components. A component may have one of more set points and data types (Data_Type); here both components have 2 data types and n set points (value) for each data type.

The Figure 9 presents an example of the XML output Data delivered by the SEMS after the optimization process. In this example, the case of ESS data output XML file is presented. Two types of data are delivered for the ESS component: the AC Power and the state of energy (SOE). For these two types of data, a value is given for each of the next 23 steps of optimization. A similar XML output file is generated for the grid component or the IT load component in order to get set points for Grid energy/power or IT loads energy/power. The next AC power set point of the ESS will be used by the GreenDataNet UPS (see Figure 1) whereas next SOE set point will be used by the Smart Data Centre Energy Controller (SDCEC) as well as the next AC power set point of the Grid or of the IT loads.

```
<ComponentName_1>

    <DataType_1>
        <value> value_1 </value>
        ...
        <value> value_n </value>
    </DataType_1>

    <DataType_n>
        <value> value_1 </value>
        ...
        <value> value_n </value>
    </DataType_n>

</ComponentName_1>

<ComponentName_2>

    <DataType_1>
        <value> value_1 </value>
        ...
        <value> value_n </value>
    </DataType_1>

    <DataType_n>
        <value> value_1 </value>
        ...
        <value> value_n </value>
    </DataType_n>

</ComponentName_2>
```

Figure 8- XML output format defined for GreenDataNet

```
<ESS>
<ACpower>
<value> 0</value>
<value> 900.009</value>
<value> -9800</value>
<value> 0</value>
<value> 0</value>
<value> -1733.33</value>
<value> 0</value>
<value> -9800</value>
<value> 7938.08</value>
<value> 0</value>
<value> -9800</value>
<value> 17280.2</value>
<value> -1733.33</value>
<value> 0</value>
<value> -9800</value>
<value> -9800</value>
<value> 0</value>
<value> 0</value>
<value> 0</value>
<value> 17280.2</value>
<value> 0</value>
<value> 0</value>
<value> 0</value>
</ACpower>
<SOE>
<value> 1000</value>
<value> 0</value>
<value> 8820</value>
<value> 8820</value>
<value> 8820</value>
<value> 10380</value>
<value> 10380</value>
<value> 19200</value>
<value> 10380</value>
<value> 10380</value>
<value> 19200</value>
<value> 0</value>
<value> 1560</value>
<value> 1560</value>
<value> 10380</value>
<value> 19200</value>
<value> 19200</value>
<value> 19200</value>
<value> 19200</value>
<value> 0</value>
<value> 0</value>
<value> 0</value>
<value> 0</value>
</SOE>
</ESS>
```

Figure 9- Example of the ESS output XML file after SEMS optimization

5.3 SOFTWARE ARCHITECTURE

The SEMS is coded in object oriented C++ language for improving the execution speed and robustness, which are important characteristics for 'industrial' deployment. This software is organized in three main packages as explained hereafter and illustrated in Figure 10:

- Input/output package: this package is composed of different classes for handling the input XML file into C++ object. The analysis and the validation of input XML file are also developed in this package. The output of SEMS is also under XML format as seen in previous part. The output web interface (html files) with integrated interactive graph for illustration and debug process is a library of this package.
- Optimization package: for solving the MILP, different solvers can be used. In the current version of SEMS developed for GreenDataNet, the IBM Cplex solver is used. Cplex is one of the most advanced solvers in the market and its performance fully fulfill to GreenDataNet requirement. The driver of the solver is implemented by using the library C++ of ILog-Cplex in order to minimize the time of construction of the optimization problem. C++ Ilog-CPLEX library enables us to design models of optimization problems and to call the Cplex solver in C++ projects.
- Component package: this package contains the library of components. Each component is characterized by the set of variables, constraints and objectives.

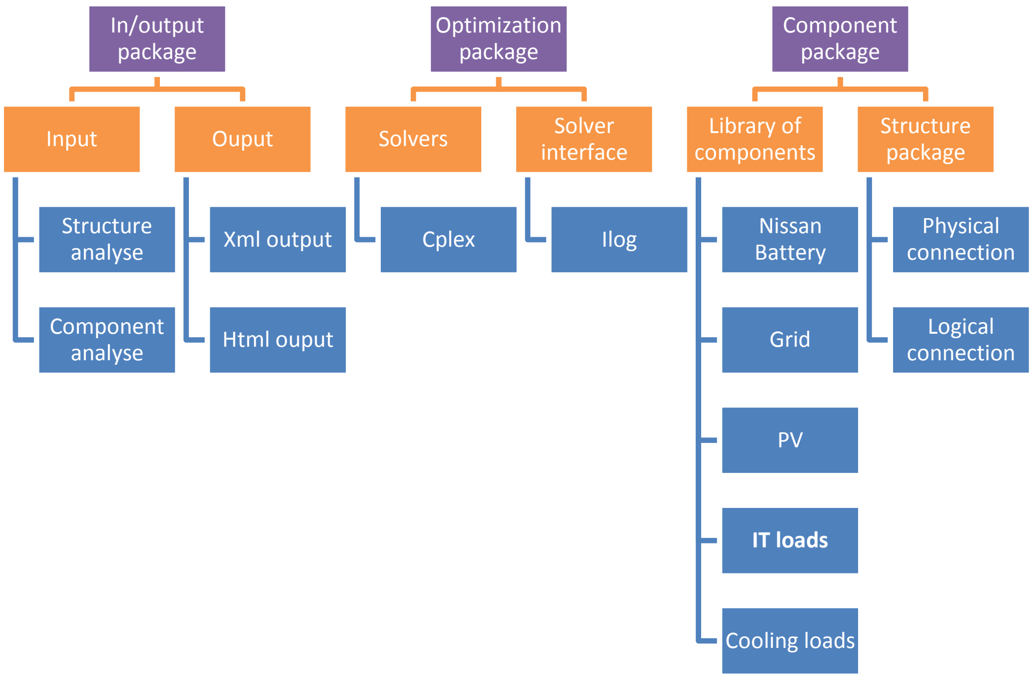

Figure 10: The structure of the SEMS software

6. INTERNAL WORKFLOW OF SEMS

In order to setup the optimization problem, the SEMS software will process different steps as described in Figure 11 and detailed here below.

1. Step 1: XML input parser: XML parser module analyze and validate the xml file and recover all necessary data for the formulation of optimization problem. If the input xml file is not valid, the error "invalid xml file" will occur.
2. Step 2: The structure of system is a part of the XML file which contains the list of components and how they are connected together. This structure is analyzed in order to make sure that all the components are formulated in the connected graph.
3. Step 3: The construction of the problem is done based on the components' models. A data base of components is already integrated to the SEMS software, a verification of the list of included components is realized in this step. An error of the type "unknown component" is handled when a component cannot be detected.
4. Step 4: The structure of the system, the models of components and the objective function are formulated in this step. The optimization problem is then ready to be communicated to the solver. At this stage, it is not possible to be sure that the problem is feasible or solvable in limited time.
5. Step 5: The verification of feasibility of the problem is checked through the relaxation of the binary variables, it's considered as linear variable. If infeasibility is detected, the "Infeasible problem" error is handled. In general, the solving time limit is fixed to 60 seconds. If the solver cannot found an optimal solution, the best possible solution is selected.
6. Step 6: There are three states of solving the optimization problem: infeasible, optimal, non-optimal solving. Based on the SEMS first tests, the optimal solution is generally always found in few seconds.
7. Step 7: The two kinds of output of SEMS model predictive control are the XML file and the output web interface (html files). The XML file is used for sending optimal data to SCDEC (that manages servers and racks) and to the UPS (for managing the energy storage system). The html file with dynamic chart is useful for user interface and the system supervision.
8. Step 8: The outputs of SEMS model predictive control (xml file, html files …) as well as the XML input file are saved in the SEMS Archive Database.

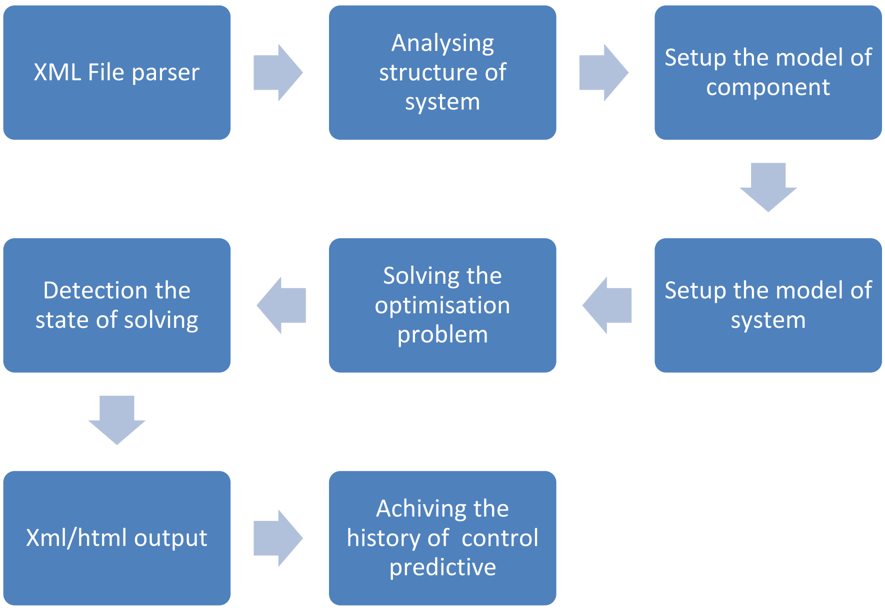

Figure 11: The steps of SEMS process

7. TEST RESULTS OF SEMS

The results of the optimization done by the SEMS software are presented in this section. A 50kW UPS system has been considered with a 10kW PV input, two 20kWh batteries, and IT loads power almost constant at 20kW; this configuration is the design of the GreenDataNet project with up to 4 batteries. The issues of the SEMS software are provided by the GreenDataNet SEMS web interface UI.

The Figure 12 shows the tree graph representation of the GreenDataNet DC System in this output interface of the SEMS software.

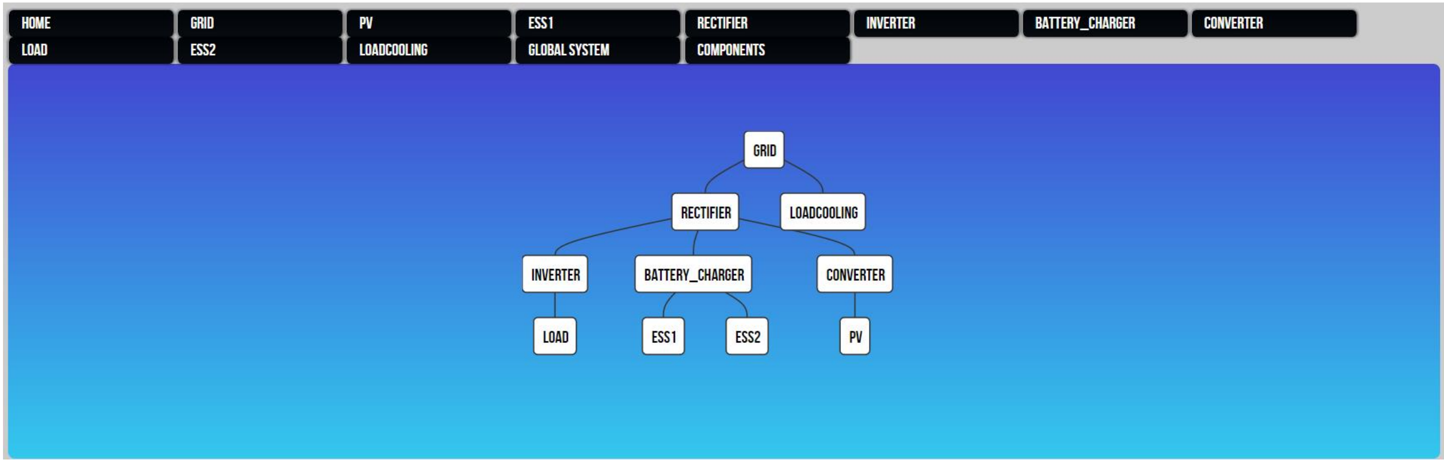

Figure 12- Components organization within the GreenDataNet DC system and represented by the output web interface of the SEMS software

Figure 13 presents the global data and set points for the components of the system. The UI allows to enable and to disable the display of data associated to a component.

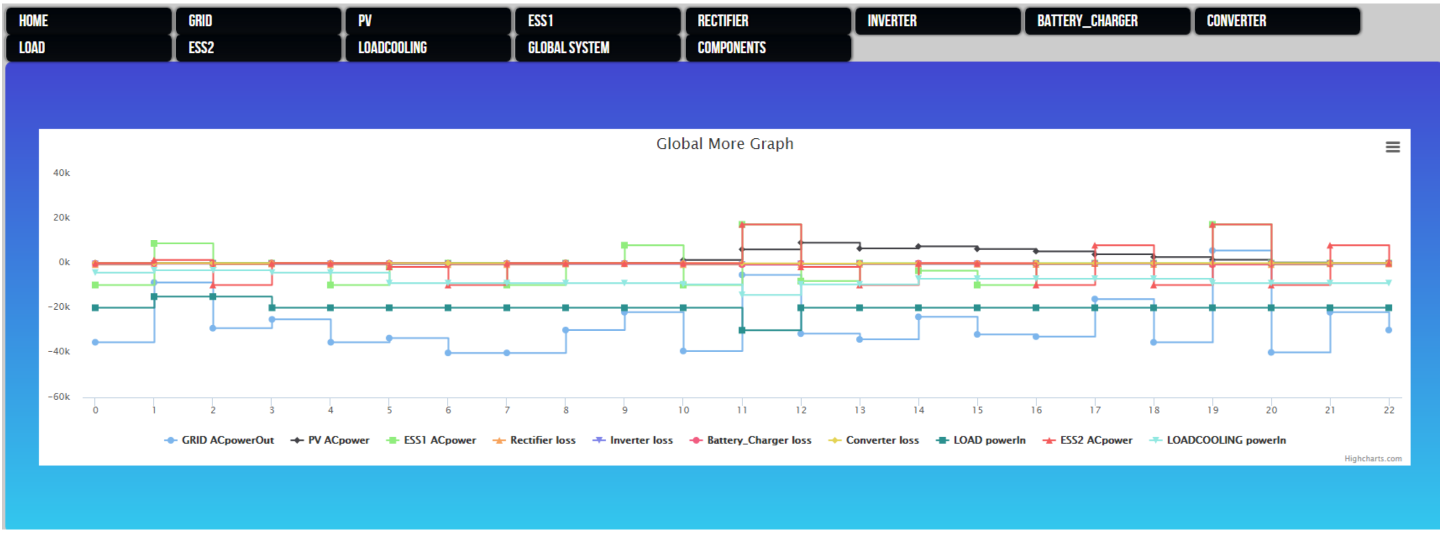

Figure 13- The global set point results of the system for the next 23 time steps following the solving of the optimal energy management

The different data can also been shown component by component.

Figure 14 shows the optimized AC Power (as output) and the electricity price variations (as input) for the Grid component. The electricity price profile used in the example is variable during the optimization period; this variable price should be later provided by the electricity price forecast module and it should depend on the electricity market. It can be observed that the power flow of the grid is almost always negative (the Grid supplies power to the system) because the power of the PV system (10kW) is lower than IT loads power (20kW with 15kW and 30kW periods in this example). It can also be underlined that low power consumption from the Grid or injection periods occur at high electricity price time (in red circles).

Figure 14- The AC Power (output) and the Electricity prices (input) of the Grid component

Figure 15 presents the forecasted PV power during the optimization period; values will be provided by the PV production forecast module (Deliverable 3.4).

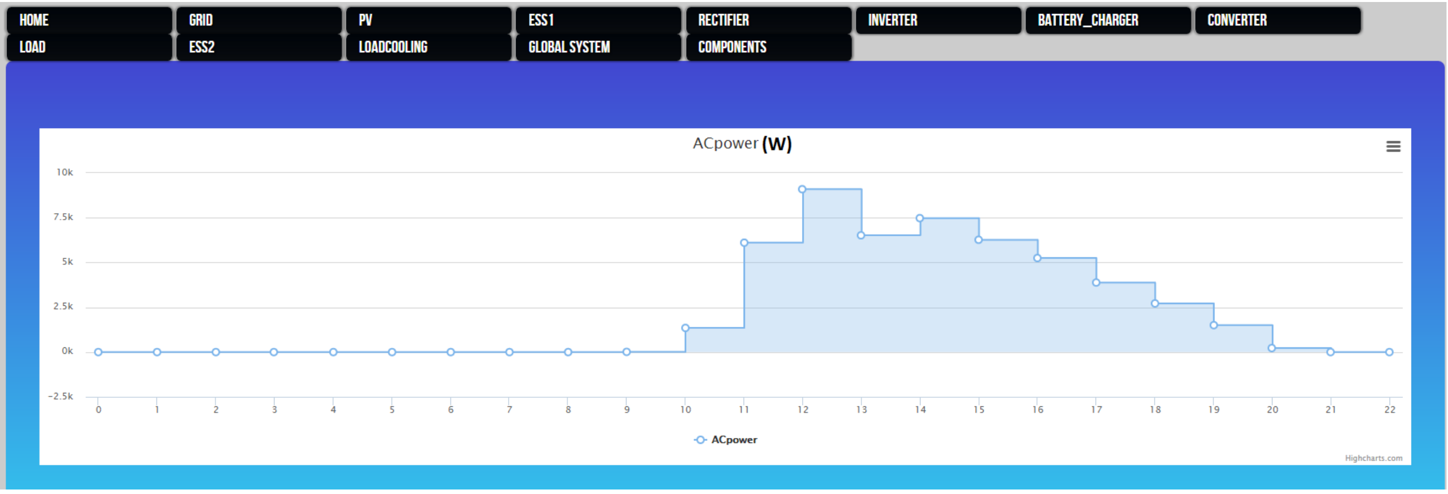

Figure 15- The AC Power for the forecasted PV production (input)

Figure 16 and Figure 17 illustrate the AC power and SOE of the ESS1 and ESS2 that are outputs of the optimization solving. The two batteries discharge energy during the steps with the highest electricity prices and recharge them during the period of maximum PV production; it is the foreseen behaviour for increasing PV local use and for having peak shaving ability. Two independent ESS have been implemented in the SEMS even if only one ESS (with up to 4 batteries) is expected to be connected to the GreenDataNet prototype; it permits to observe the higher flexibility of such configuration regarding different objectives. The ESS2 plays the role of the energy buffer. Many recharge and discharge periods occur for it according to the electricity price variation. The ESS1 is tried to be charged/discharged as less as possible due to the consideration of an arbitrary battery ageing criteria.

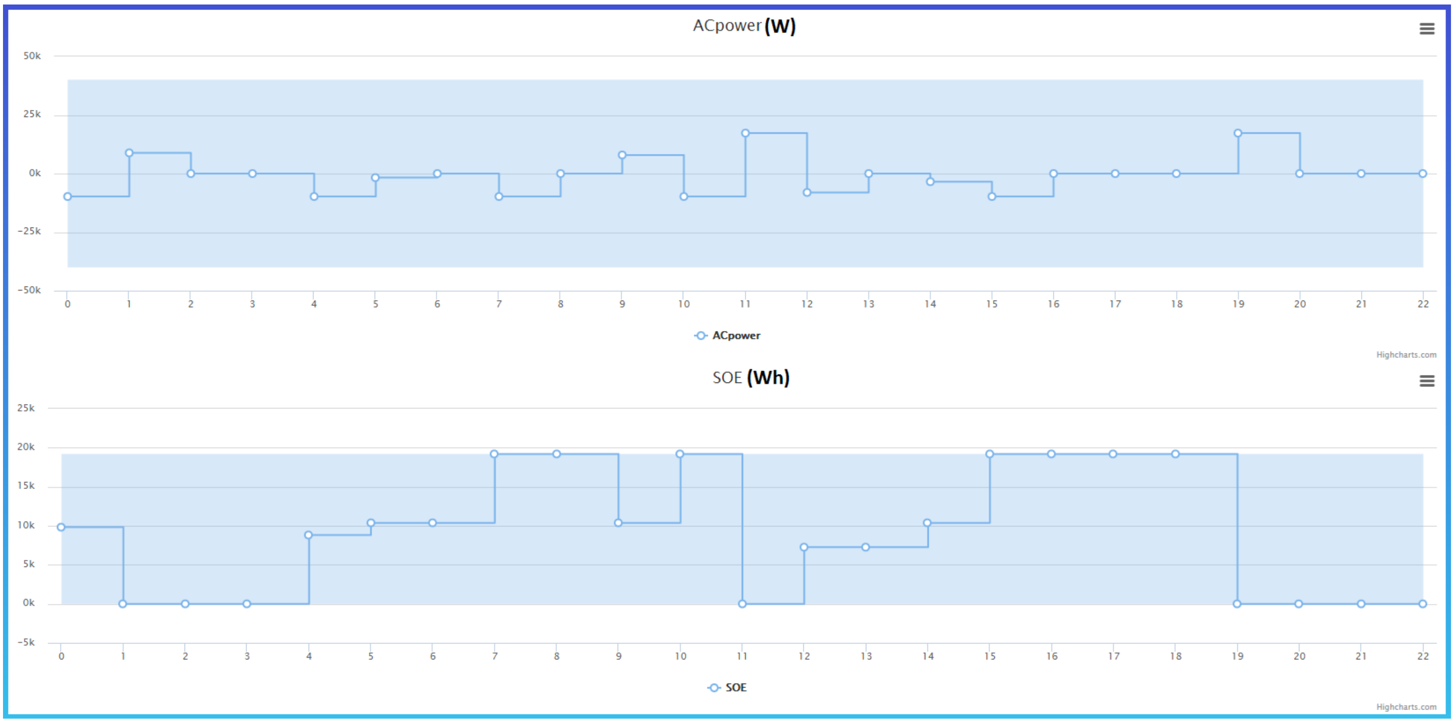

Figure 16- The AC power and the SOE for the ESS1 (outputs)

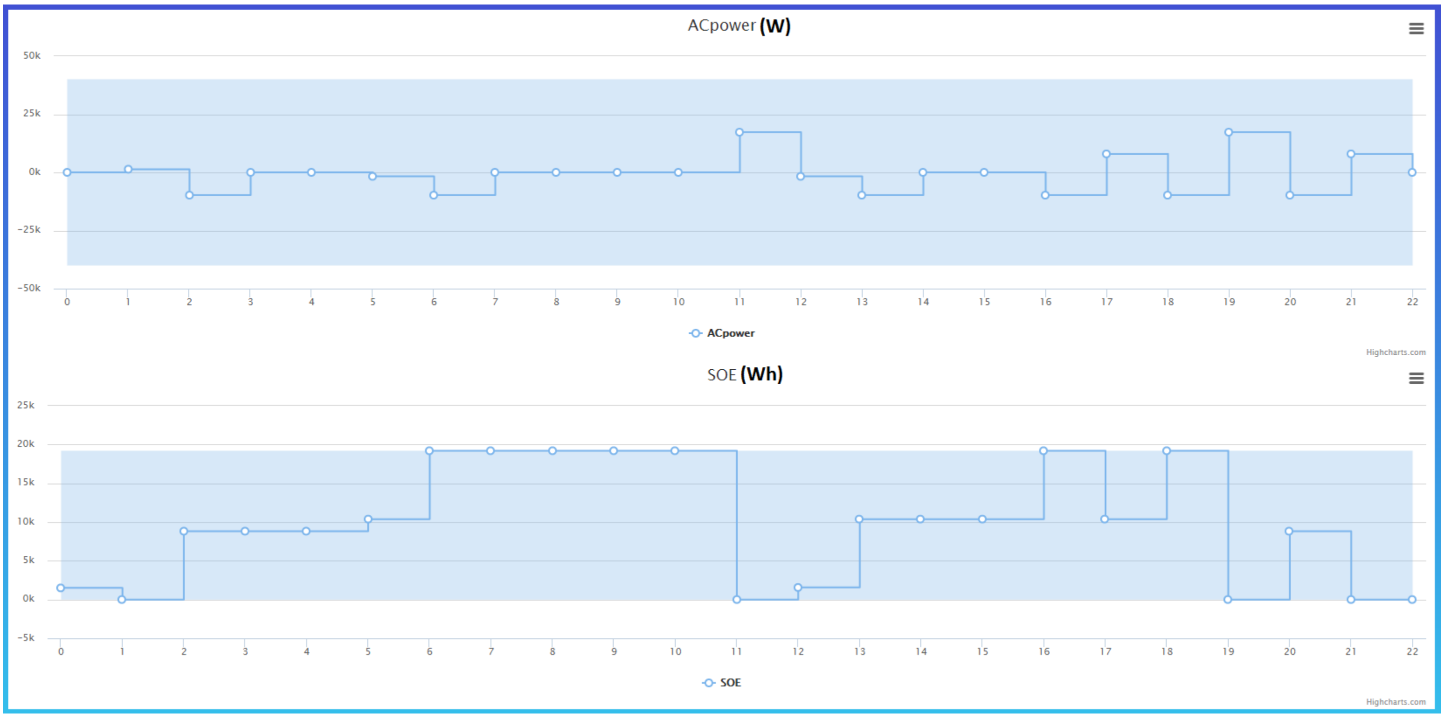

Figure 17- The AC power and the SOE for the ESS2 (outputs)

As explained in Part 3, the AC power targets of ESS1 and ESS2 are sent by the SMES core to the UPS (i.e. the reactive layer) in order to charge and discharge the batteries. The optimal SOE targets of ESS1 and ESS2 are used by the SDCEC (i.e. IT load scheduling layer).

Figure 18 and Figure 19 show the forecasted IT Load power (20kW for all the time steps excepting 2 time steps at 15kW and 1 time step at 30kW) provided by the electricity consumption (for IT loads) forecasting tool (Deliverable 3.2) and the forecasted associated cooling load power according to the DC building thermal analytical model (Deliverable 3.1).

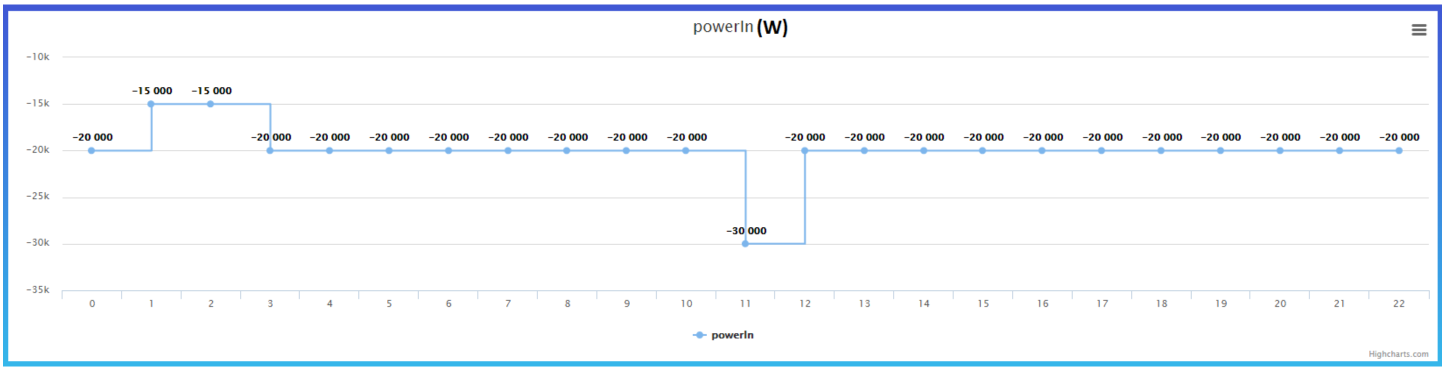

Figure 18- The forecasted IT load power for the 23 next time steps (input)

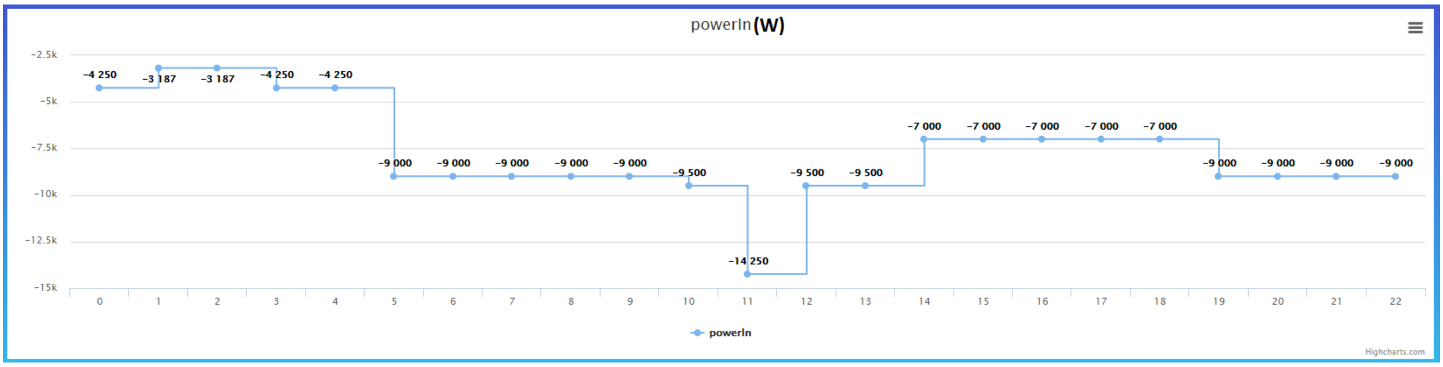

Figure 19- The associated cooling load for the next time steps (input)

As detailed in Part 3, from the forecasted ambient temperature time series, forecasted PUE values are determined considering DC characteristics and IT cooling temperature. These forecasted PUE values are associated to the forecasted IT loads powers in order to get the forecasted cooling load powers. Then in Figure 19, the variations of expected cooling load powers during periods with constant IT load power are due to expected PUE variations because of change of ambient temperature and activation/deactivation of free cooling mode. It can also be observed that a variation of forecasted IT load (-5kW to 15kW in time steps 1 and 2, and +10kW to 30kW in time step 11, see Figure 18) has a proportional impact to the forecasted cooling load powers if the same PUE conditions are expected.

Not only optimal power flows at the interfaces of the UPS prototype (with PV, ESS, IT loads …) are reported in the UI of developed SEMS, but also the calculated optimal power flows for the internal converters.

Figure 20 shows the power in, power out and the losses for the rectifier component. The same kind of data is presented for the other UPS converters: inverter, battery charger and DC/DC PV (Figure 21, Figure 22 and Figure 23).

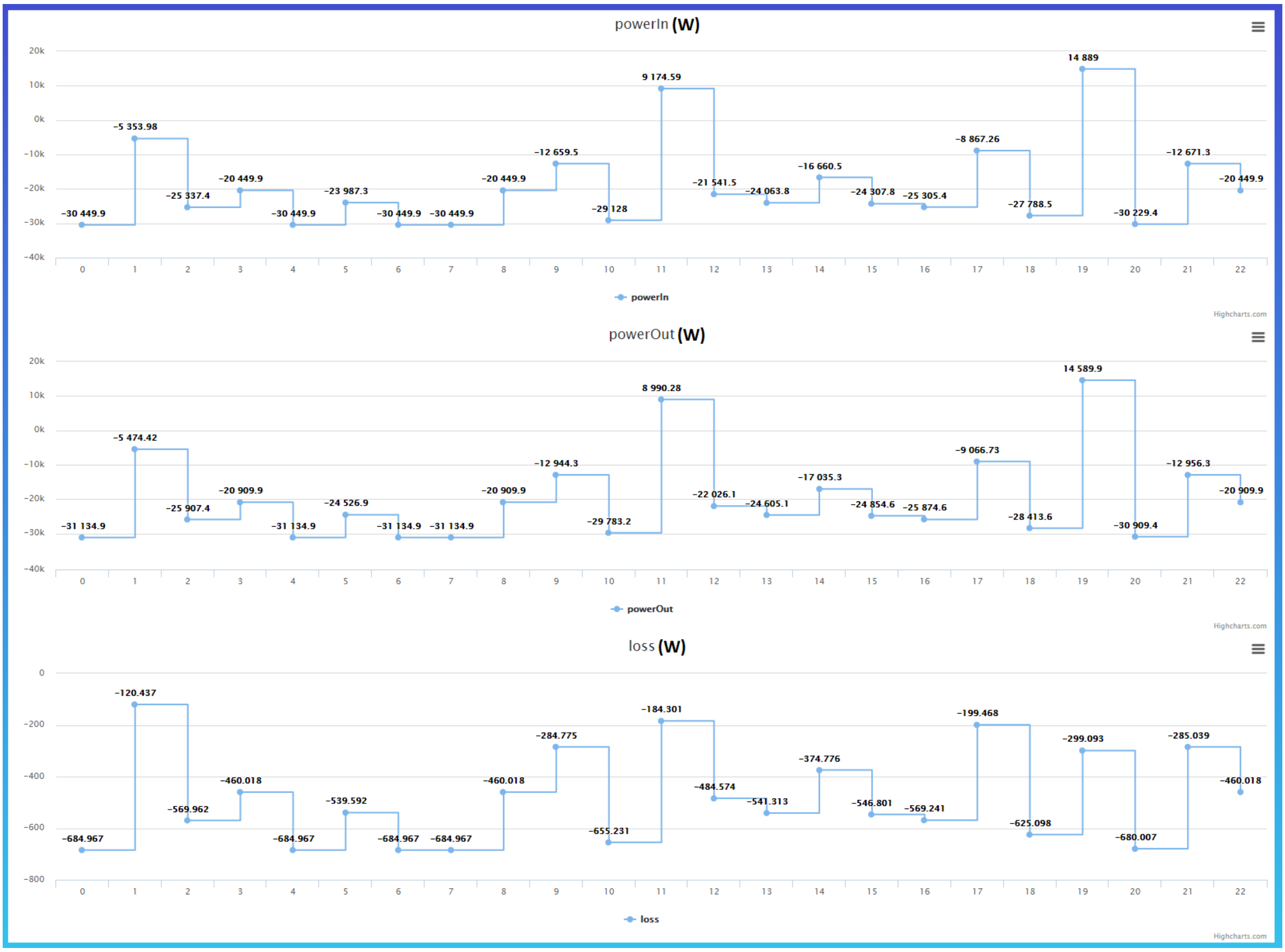

Figure 20- Calculated Power In, Power Out and Losses for the UPS rectifier

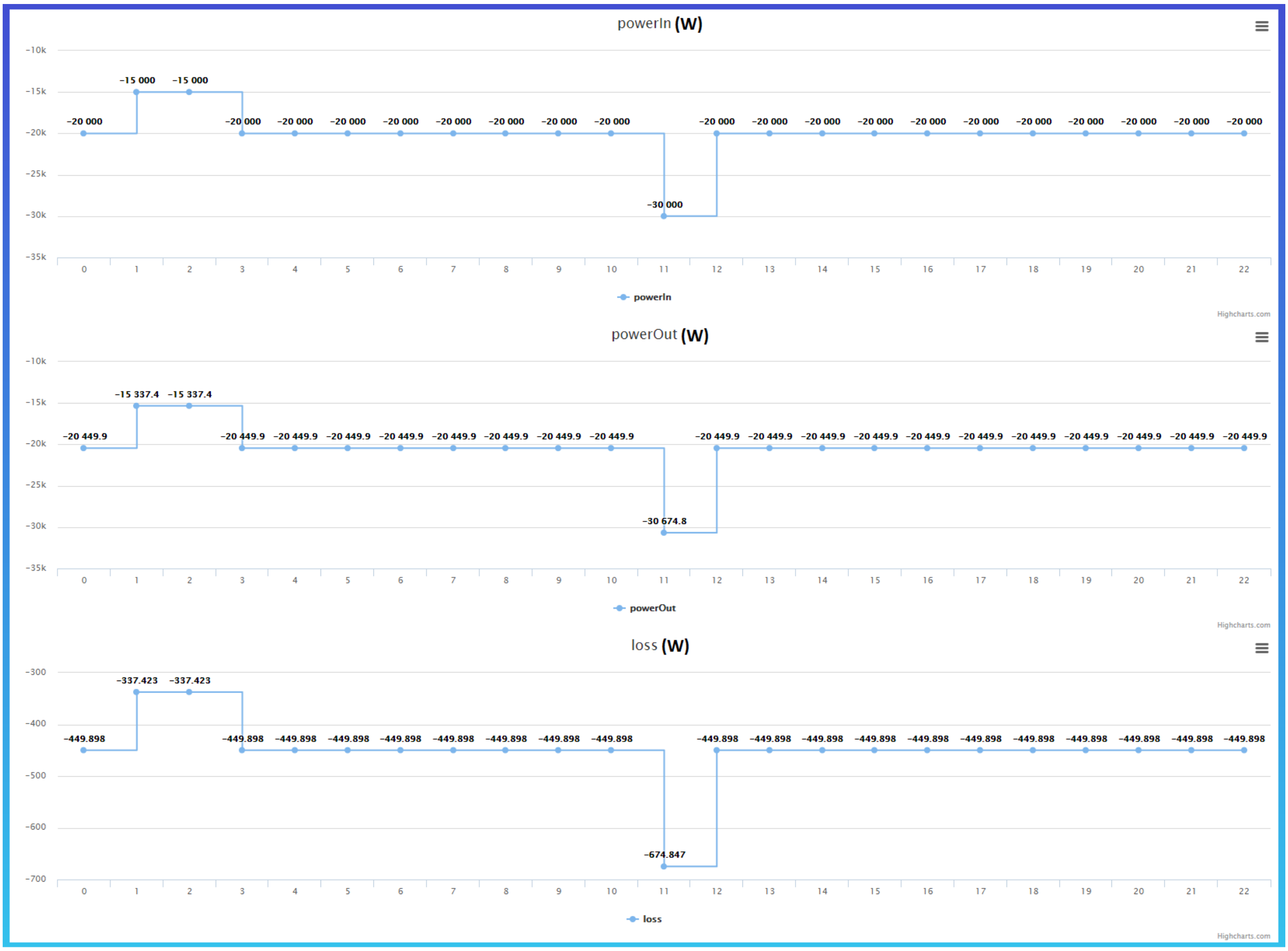

Figure 21- Calculated Power In, Power Out and Losses for the UPS inverter

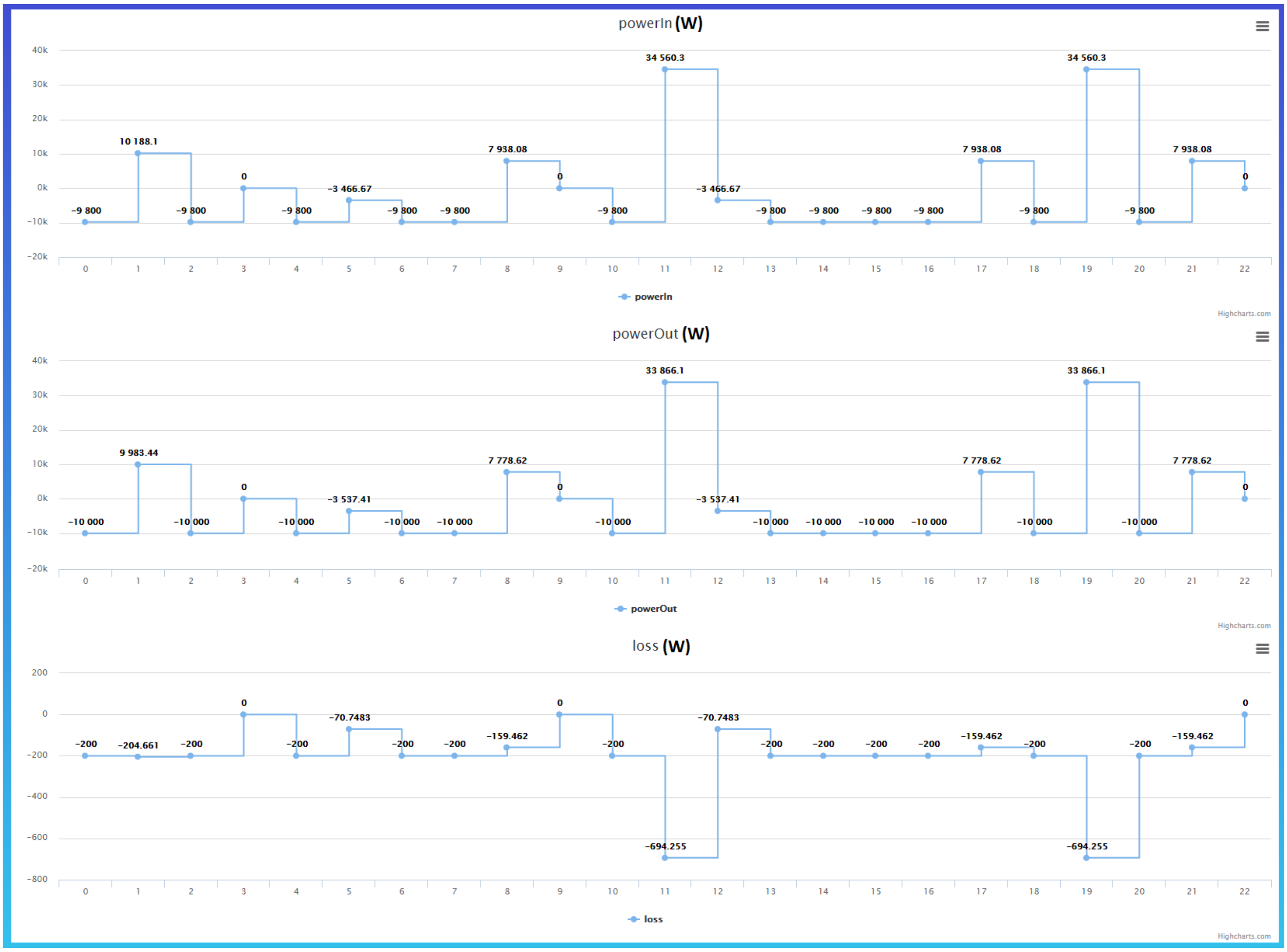

Figure 22- Calculated Power In, Power Out and Losses for the UPS Battery Charger

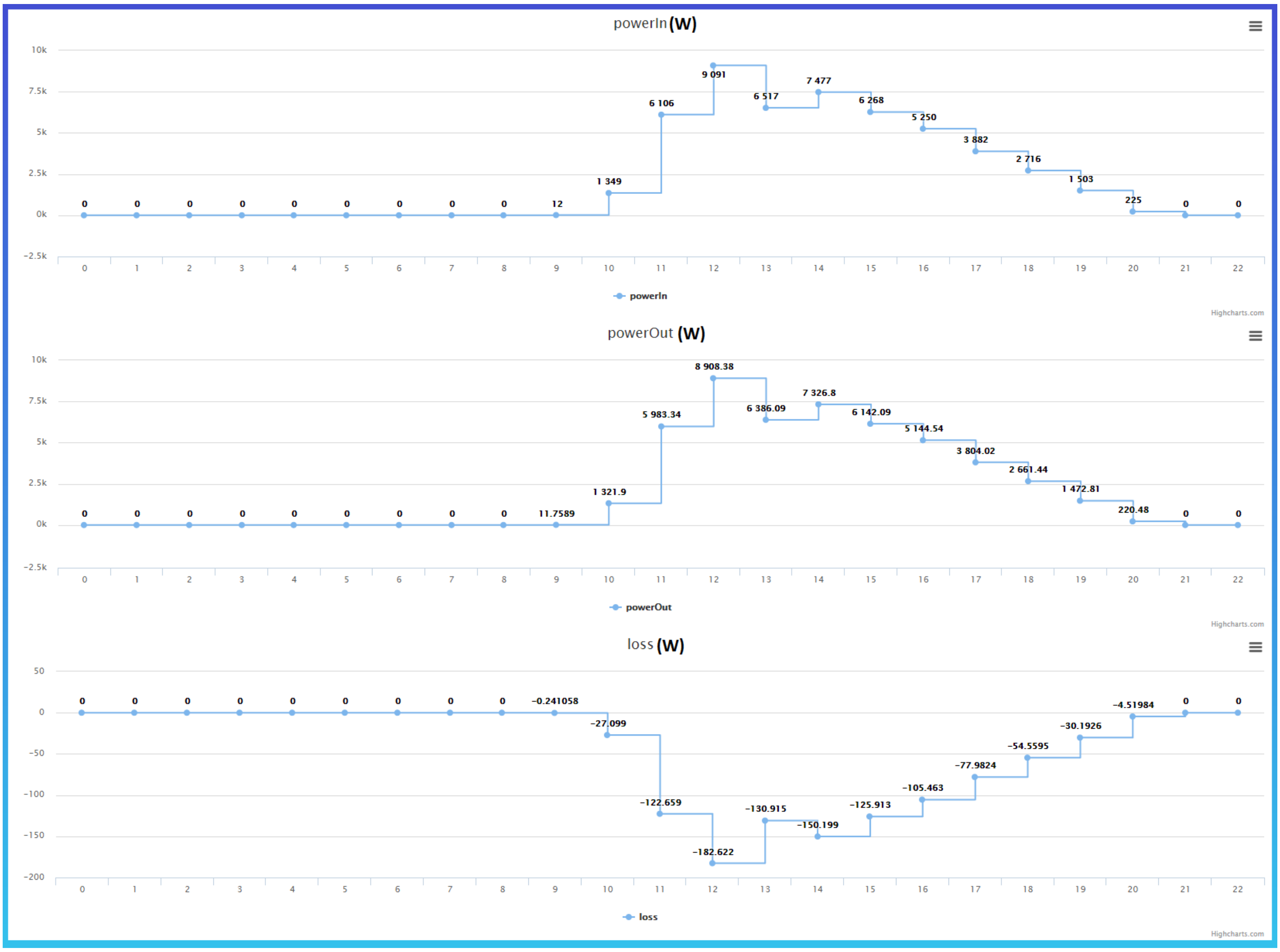

Figure 23- Calculated Power In, Power Out and Losses for the PV converter

8. CONCLUSION

This deliverable presents the structure of the GreenDataNet Smart Energy Management System (SEMS). The SEMS is designed in order to optimally manage the energy usage of an Urban Data Centre equipped with local renewable energy production (here PV, as PV panels may be easily located close to Urban Data Centres) and storage. The aim of this software is to optimize the use of the renewable energy in order to minimize the consumption of the costly energy from the grid. The SEMS is structured in two main parts:

- the Smart Data Centre Energy Controller (SDCEC) aims to optimize IT loads consumption through changes in the Virtual Machine allocation. This part permits to forecast optimal IT loads consumption. It has been developed by EPFL and University of Trento; a first version of this controller is presented in Deliverables 3.2 and 3.3, as this controller interacts with the Electricity Consumption Forecasting Tool.
- the SEMS core and the Model Predictive Control (MPC) block aim to manage optimally the energy for the next 24h (with time steps of 1h or less) at the DC level, taking into account the IT power consumption forecast, cooling consumption forecast, PV production forecast and electricity price

forecast. This part permits to increase the self-production ratio of the Data Centre and to allow the DC working in peak shaving mode.

The first part of this report focuses on the description of the design and development of the SEMS core and MPC, while the second part provides a first set of results.

It has been demonstrated that the SEMS software is functional to optimize the energy at Data Centre level. It has been developed in C++ to insure the robustness and rapidity of the optimization. This tool is designed launch an optimization at least once every hour or more frequently if the GreenDataNet demonstrator would require it.

It interacts with the other components through XML files, which permits to have a weak but very robust interaction. Hence, the interaction with the analytical model for the thermal behaviour of DC developed by Eaton is made through this XML file. The outputs of the IT load forecast and PV production forecast are also expected to be XML files. Then, the SEMS sends SOE and IT load power targets to the SDCEC for the next time step through the XML file, and is able to communicate to the Eaton UPS control a charge/discharge power to be applied to the ESS for next time step.

A User Interface has been designed to display the optimization results.

The current version of the SEMS software will be improved after the first testing results with the GreenDataNet prototype are available. Hence, it has been designed in a way that it is easy to modify: for example it is possible to modify the parameters of the analytical model included in the MPC. The introduction of new plug-ins is easy as it is performed through a new XML file and the definition of a new system architecture in XML.