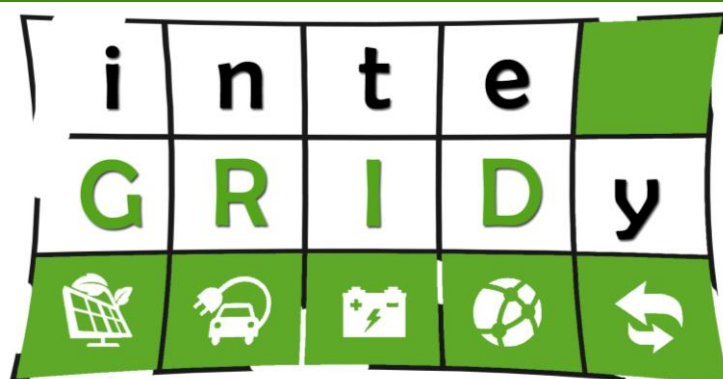


## Innovation Action



# inteGRIDy

integrated Smart GRID Cross-Functional Solutions for  
Optimized Synergetic Energy Distribution, Utilization  
& Storage Technologies

**H2020 Grant Agreement Number: 731268**

**WP4 – inteGRIDy Distribution Grid  
Optimization Framework**

**D4.2 - inteGRIDy Modelling Mechanisms  
for Topology Analysis, DR Flexibility and  
Storage**

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## Executive Summary

The inteGRIDy project includes ten pilot projects where innovative energy solutions are implemented. These energy solutions are based on a number of tools that perform modelling, simulation and optimization tasks. There are thirteen energy models in inteGRIDy covering a wide range of applications including energy system and grid characterization, load assessment, demand response and life cycle assessment and cost.

A comprehensive review of the inteGRIDy energy models is presented and classified into three macro-functionality categories: Network Modelling, Demand Response and Demand Side Management, and Storage Systems. The review has covered a number of technical aspects of the energy models including: mathematics & physics behind the model; calibration and validation results when available; dependencies of energy model with other tools and data; input/output data format and time period; programming language; supported operating system and architecture; hardware requirements; and availability of a demo. Furthermore, a detailed description of the implementation of the energy model in the inteGRIDy pilot project/s is provided.

The main areas covered by the energy models are energy system characterization, grid modelling, load assessment, demand response and demand side management. In addition, one of the energy models available in inteGRIDy can perform life cycle analysis and cost of energy systems.

The results of the review highlight the level of complexity behind the energy models. Furthermore, validation results show that the actual performance energy systems, grid network and demand assessment are well captured by a number of the energy models.

The feasibility analysis to containerize in Docker the energy models reveals that eight out of thirteen energy models could potentially be containerized. Moreover, outcomes of the analysis reveal that for some energy models only some functionalities may be containerized, while others may have restrictions due to the use of proprietary licenses.

Following the feedback provided by the EC in the second review, this document indicates how the inteGRIDy energy models address most of the expected impacts from the EU included in the work programme. Moreover, the improvements made in the energy tools due to the inteGRIDy project and innovations beyond the state of the art are highlighted. The results have revealed that some inteGRIDy energy models have no analogue commercial solution or, when this is available, the inteGRIDy solution seem to be, apart from fitting, more advantageous and innovative. The report has demonstrated the applicability to a wide range of scales of the inteGRIDy energy models.

This report includes an assessment of the potential synergies between existing inteGRIDy energy models. For each energy model, the energy models that could be integrated with are listed and the functionalities that they could provide to the analysed tool are highlighted. All identified synergies are summarized in a table, revealing that there are 69 potential synergies among inteGRIDy energy models.

The synergy assessment has revealed that no inteGRIDy energy model can provide any functionality to the tools SimaPro and Kisense Energy Management System. However, it is concluded that SimaPro could provide functionalities related to life cycle analysis and cost to at least more than half of the inteGRIDy energy models.

The synergy assessment has also identified several integration technical constraints. Integration of energy models with proprietary software has been detected as a significant limitation. In addition, while full integration of energy models will possibly require matching their programming language, if full integration is not required, these may only require adjustments in the data format and time step.



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## List of Acronyms and Abbreviations

Term	Description
AC	Alternating Current
AHU	Air Handling Unit
AI	Artificial Intelligence
API	Application Programming Interface
ASCII	American Standard Code for Information Interchange
BESS	Battery Energy Storage System
BMS	Building Management System
CAM	Computer-Aided Manufacturing
CDD	Cooling Degree Days
CHP	Combined Heat and Power
CMP	Cross-functional Modular Platform
COM	Component Object Model
CO <sub>2</sub>	Carbon Dioxide
CSV	Comma Separated Value
DC	Direct Current
DER	Distributed Energy Resource
DHW	Domestic Hot Water
DR	Demand Response
DSM	Demand Side Management
DSO	Distribution System Operator
ERP	Enterprise Resource Planning
EES	Energy Storage System
GUI	Graphical User Interface
GWP	Global Warming Potential
HDD	Heating Degree Days
HVAC	Heating, Ventilation and Air Conditioning
ICT	Information and Communication Technology
KPI	Key Performance Indicator
kW	Kilowatt
kWh	Kilowatt Hour
kWp	Kilowatt Peak
LCA	Life Cycle Analysis
LCC	Life Cycle Cost
LV	Low Voltage



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MAD	Mean Absolute Deviation
MAPE	Mean Absolute Percentage Error
MPC	Model Predictive Control
MPPT	Maximum Power Point Tracker
MV	Medium Voltage
MW	Megawatt
MWh	Megawatt Hour
MWp	Megawatt Peak
PV	Photovoltaic
RES	Renewable Energy System
SCL	Semantics Constraint Language
STC	Standard Test Conditions
SOC	State of Charge
SoTA	State of the Art
VBA	Visual Basic for Applications
VPP	Virtual Power Plant



## 1.Introduction

### 1.1 Scope and Objectives of the Deliverable

There are ten pilot projects in inteGRIDy where innovative energy solutions will be implemented and their performance evaluated. These solutions rely on thirteen energy models that will, among other functions, characterize energy systems, compute loads, or modify system's performance to comply with grid requirements. This report presents a comprehensive summary of the energy models available in inteGRIDy, splitting them among the three macro-functionality categories described in D1.5 – inteGRIDy Architecture & Functional/Technical Specifications: Network Modelling, Demand Response / Demand Side Management and Storage Systems [IND15].

The aims of the deliverable are as follows:

- Collect information of inteGRIDy energy models from technology providers and literature, addressing the mathematics behind the models as well as their operating requirements.
- Present a comprehensive technical review of the inteGRIDy energy models, including their application to specific pilot projects.
- Assess potential synergies between the inteGRIDy energy models.
- Provide information of inteGRIDy energy models to Tasks 4.3 and 4.4.
- Highlight the impact and advances beyond the state of the art of the inteGRIDy solutions.

This deliverable is an updated version of the earlier submitted D4.2 - inteGRIDy Modelling Mechanisms for Topology Analysis, DR Flexibility and Storage, that addresses the comments and feedback received in the second inteGRIDy review meeting. The changes and additions to the deliverable have been included in blue colour.

### 1.2 Structure of the Deliverable

The deliverable is structured as follows: Section 2 presents the methodology employed to perform the review and synergy assessment of the energy models; Section 3 describes the main functionalities of the inteGRIDy Modelling Mechanisms for Topology Analysis, DR Flexibility and Storage Layer and tools are mapped to these; Section 4 provides a high level review of inteGRIDy energy models; Section 5 is a new section and it is described in detail below; Section 6 assesses potential synergies between inteGRIDy energy models; finally, Section 7 draws the conclusions of the deliverable.

This deliverable includes Section 5, which provides an overview of the outcomes from the review of the models under the inteGRIDy Modelling Mechanisms for Topology Analysis, DR Flexibility and Storage Layer. Section 5 also addresses the impacts from the inteGRIDy solutions in the field of modelling mechanisms and their progress beyond the state of the art (SoTA). This additional section addresses part of the feedback received in the second review of the inteGRIDy project.

### 1.3 Relation to Other Tasks and Deliverables

Task 4.2 reviews and analyses the energy models available in inteGRIDy. Results from Task 4.2 are connected to the operation analysis framework and simulation from Task 4.3 (D4.3) and the decision making and optimization mechanisms/toolset from Task 4.4 (D4.4).

Furthermore, Task 4.2 presents links with Task 4.1 (D4.1) regarding measurements retrieval, either from field devices, or the Reference Knowledge Warehouse, Task 1.5 (D1.5 and its updated version D1.6) regarding the inteGRIDy architectural design and requirements that have defined Task 4.2 and all Tasks related to the CMP. In addition, there is a close relation



with WP5 activities and its related tasks. Moreover, because a number of energy models are employed in WP8, there is a relation with the activities of WP8 and, in particular, the activities of Task 8.4 and its respective deliverable D8.4.

Finally, as all part of WP4, Task 4.2 shares connections with WP6 and WP7 activities that involve the deployment of the tools.

## 2. Methodology

### 2.1 Steps of the Methodology

The analytical framework employed in the review of the inteGRIDy energy models is as follows:

- Analysis of information available from energy models in inteGRIDy D1.5 and D1.6 [IND15] [IND16].
- Collection and review of technical information from technology providers via questionnaires and available literature.
- Request for further information and clarification of technical aspects of energy models during inteGRIDy pilot project conference calls as well as offline.
- Clarification of technical specifications of models through one-to-one conference calls with technology providers.

The deliverable provides a comprehensive review of Task 4.2 inteGRIDy energy models, including the following information: general description of the inteGRIDy functionalities; details of the modelling process; technical specifications and advantages from the existing tools; expected advantages compared to commercial products; and implementation features and delivery.

The information collected from the review of Task 4.2 inteGRIDy energy models feeds the synergy assessment performed in this deliverable. The methodology employed is as follows:

- Collection of technical information from energy model owners via questionnaires and conference calls.
- Comprehensive review of the information provided by energy model owners, request of clarifications and further details when necessary.
- Assessment of synergies between the inteGRIDy energy models and preparation of preliminary identified list of synergies and possible technical constraints.
- Review by energy model owner of identified synergies and technical constraints.
- Deliver final list of identified synergies and technical constraints based on input from energy model owners.

### 2.2 Delivery of the Tools

The development of the functionalities of the energy models is a very important part of the work performed in the inteGRIDy project. Following the development and completion of the energy model, it is very important that the tool can be easily integrated with other tools and deployed under a pilot structure.

To ease the delivery and integration of the developed inteGRIDy energy models, the use of Docker [DOC19] containers has been adopted by the inteGRIDy WP4 members. Docker follows the principles of an Agile methodology. The Docker containers present the advantages that are stand-alone and lightweight, while they contain all the required elements to execute the tool. While Docker can run on Linux and Windows, it also presents the advantage that containerised tools can be executed in any environment. The inteGRIDy technology providers have received extensive information on the use and advantages from Docker, including guidelines and a specific one-to-one tutorial for those partners requesting it.

For every energy model, Section 4 details if it is been containerised or, alternatively, the approach selected by the technology provider to integrate and deploy their respective energy model.

Section 4 also includes the contact details from the technology provider for each specific energy model, in case the reader requires further detail or information.





## 2.3 Recommendation

Task 4.2 included the assistance and provision of advice to technology providers during the development of their respective energy models. This support was delivered in one-to-one or pilot meetings, as well as during inteGRIDy physical meetings.

The support focused on both technical and management areas. From the technical point of view, these were not addressing specific modelling issues but rather the approach taken and existing possible alternatives. The knowledge obtained from the review of the multiple energy models developed in inteGRIDy provided a very good insight of the different modelling strategies available. In addition, this was supported by in-house know-how in energy modelling. Suitable strategies available in the inteGRIDy project were shared with technology providers when required throughout the duration of Task 4.2. In addition, as described in Section 2.2 technical support also included the containerization of the tools for their integration and deployment.

From a management point of view, the development of the energy models was monitored to ensure the development progress stayed on track. Management support was delivered throughout the duration of Task 4.2.

Furthermore, the work performed in Section 6 concerning the assessment of synergies between energy models available in inteGRIDy has revealed to be of great interest to all technology providers. The possibility to expand the scope of their tools using functionalities from other tools has indicated that is an area of great potential during and beyond the inteGRIDy project. During the development of this task, this opportunity has been discussed with technology providers through online and physical meetings and recommendations were drawn.

### 3. Modelling Mechanisms for Topology Analysis, DR Flexibility and Storage Layer of the inteGRIDy Reference Architecture

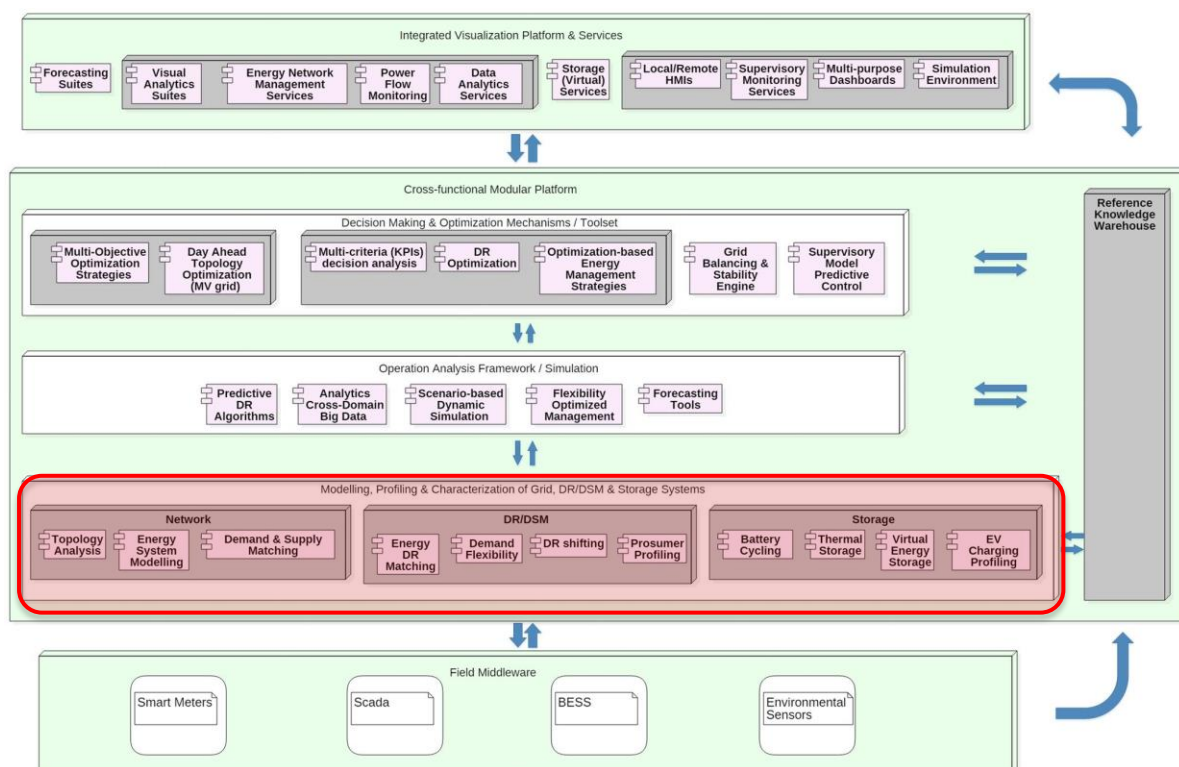
#### 3.1 Introduction

This section describes functionalities present in the Modelling Mechanisms for Topology Analysis, DR Flexibility and Storage layer, while detailing the relationship between this layer and the other layers in the inteGRIDy reference architecture. In addition, the energy models are mapped to functionalities available in the Modelling Mechanisms for Topology Analysis, DR Flexibility and Storage layer.

#### 3.2 Architectural Layer

The Modelling Mechanisms for Topology Analysis, DR Flexibility and Storage layer is in the core of the inteGRIDy Reference Architecture and delivers modelling capabilities in the inteGRIDy pilots.

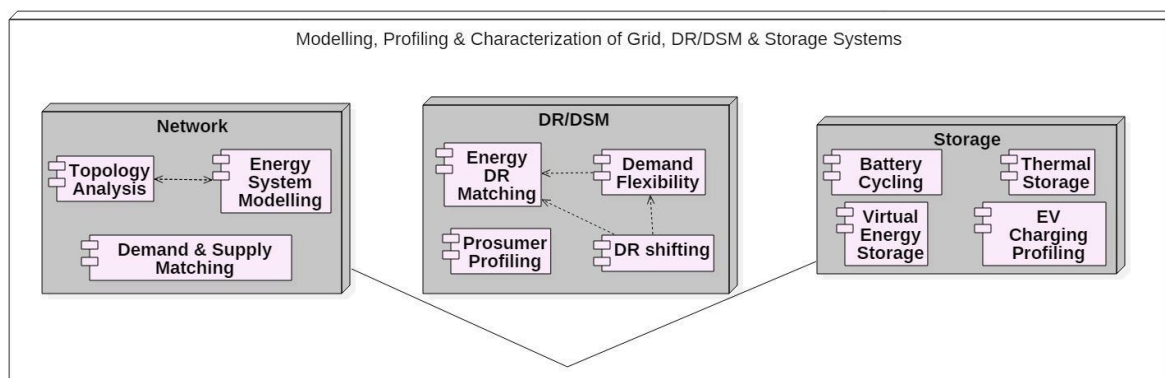
As depicted in Figure 1, the Modelling Mechanisms for Topology Analysis, DR Flexibility and Storage layer is one of the three layers included in the Cross-functional Modular Platform (CMP). The layer interacts directly with the other CMP layer Operation Analysis Framework/Simulation Layer and indirectly with the Decision Making & Optimisation Mechanisms/ Toolset Layer. The layer is built on the Reference Knowledge Warehouse, which is also used to store and transfer data to other layers. Furthermore, the layer interacts with the field devices to gather and send data through the Field Middleware Layer and provides visualisation capabilities to users through the Integrated Visualisation Platform.



**Figure 1. Modelling, Profiling & Characterization of Grid, DR/DSM and Storage System Layer and links with other layers available in inteGRIDy Reference Architecture.**

Following the classification described in “D1.5 – inteGRIDy Architecture & Functional/Technical Specifications” [IND15], energy models are arranged into three macro-functionality categories (Figure 2):

- Network Modelling to represent electrical grid including generation and consumption.
- Demand Response (DR) / Demand Side Management (DSM) to evaluate effectiveness and impact of DR and DSM to user consumption and demand flexibility.
- Storage Systems includes models of battery, thermal storage and virtual storage systems.



**Figure 2. Logical view of Modelling, Profiling & Characterization of Grid, DR/DSM and Storage System Layer (source: [IND15]).**

### 3.3 Mapping of the Tools over the Layer

Within the inteGRIDy project, there are four pillars: Demand Response, Smartening the Distribution Grid, Energy Storage and Smart Integration of Grid Users from Transport. Table 1 maps the tools falling under Modelling, Profiling & Characterization of Grid, DR/DSM and Storage System Layer to their corresponding inteGRIDy project pillar and macro-functionalities.



**Table 1. Mapping of the tools over the functionalities of Modelling, Profiling & Characterization of Grid, DR/DSM and Storage System Layer and corresponding pillars.**

inteGRIDy Tool	InteGRIDy T4.2 Layer											inteGRIDy project pillar			
	Topology analysis	Energy system modelling	Demand & Supply matching	Energy DR matching	Demand flexibility	Prosumer profiling	DR shifting	Battery cycling	Thermal storage	Virtual energy storage	EV charging profiling	Demand Response	Smartening the Distribution Grid	Energy Storage	Smart Integration of grid users from transport
Medium Voltage distribution Networks Management Tool (POLIMI)	X	X	X			X		X				X	X	X	
APROS Transient Process (CERTH)		X						X				X	X	X	
SIMAPRO (CERTH)		X						X					X	X	
Energy Integrated Information System (SIVECO)			X	X	X		X					X			
Nemo Tool (TEES)		X	X					X	X			X	X	X	
Building Occupancy & Energy Consumption Simulation (CERTH)			X	X	X		X					X	X		
Demand Side Energy Profiling (TREK)		X	X	X	X		X			X		X	X	X	
Multi-Carrier Hub Optimisation Engine (ENG)	X	X			X			X					X	X	
Kisense Energy Management System (VPS)			X								X	X			X
Integrated Test Environment (UNEW)	X		X	X	X		X	X				X	X	X	
Distributed Energy Management System (Siemens Spain)			X	X	X	X	X					X			
Swimming Pool Model (Aiguasol)		X							X	X		X		X	
Supervisory Model Predictive Control for Energy Systems (CERTH-CPERI)	X	X	X					X			X		X	X	X

## 4. Description and Features of the Modelling Mechanisms Toolset

### 4.1 Context

This chapter presents a comprehensive review of the thirteen inteGRIDy energy models.

Although for simplification the energy models are presented under exclusively one macro-functionality category, several energy models include functionalities that fall into more than one category.

Further to the information listed in Table 1, Table 2 lists the thirteen inteGRIDy energy models indicating the partner developing the energy model, macro-functionality category they fall under, as well as pilot project where these are implemented.

**Table 2. InteGRIDy energy models, developing partner, macro-functionality category and pilot project where energy model is implemented.**

Energy Model / Partner	Pilot Project		
	Network Modelling	DR DSM	Storage
Medium Voltage Distribution Networks Management Tool / POLIMI	San Severino Marche	San Severino Marche	-
APROS Transient Process / CERTH	Barcelona / Nicosia	Barcelona	Barcelona / Nicosia
SimaPro / CERTH	Barcelona / Nicosia	-	Barcelona / Nicosia
Energy Integrated Information System / SIVECO	Ploiesti	-	-
NEMO Tool / TEES	Barcelona	-	Barcelona
Building Occupancy & Energy Consumption Simulation Tool / CERTH	Thessaloniki	Thessaloniki	-
Demand Side Energy Profiling / TREK	St Jean	St Jean	-
Multi-Carrier Hub Optimization Engine / ENG	Terni	Terni	Terni
Kisense Energy Management System / VPS	-	Lisbon	-
Integrated Test Environment / UNEW	Isle of Wight	Isle of Wight	Isle of Wight
Distributed Energy Management System DEMS / Siemens	-	Barcelona	-
TRNSYS Swimming Pool Model / AIGUASOL	-	Barcelona	Barcelona
Supervisory Model Predictive Control for Energy Systems / CERTH-CPERI	Isle of Wight / Xanthi	-	Isle of Wight / Xanthi / Thessaloniki

The chapter is structured as follows: Sections 4.2, 4.3 and 4.4 present respectively the energy models for each of the three macro-functionality categories described above; finally, Section 4.5 draws the conclusions of the chapter.



## 4.2 Network Modelling

According to “D1.5 – inteGRIDy Architecture & Functional/Technical Specifications” and as [IND15] depicted, the macro-functionality Network Modelling includes the following layers:

- Energy System Modelling. This includes developed models of energy systems used to assess energy, environmental and financial aspects, and are particularly focused on electricity network models.
- Topology Analysis. This refers to models characterizing electrical properties of grid nodes and connections, including modelling of premises and other parts of the grid network.
- Demand and Supply Matching. Models of mechanisms to predict energy generation and demand, and ensure match between demand and supply at the grid nodes taking also into account economic factors and other constraints.

The following subsections characterize the inteGRIDy Network Modelling tools:

- Medium Voltage Distribution Networks Management Tool, developed by Politecnico di Milano (POLIMI).
- APROS Transient Process, implemented by CETH.
- SimaPro Life Cycle Assessment / Life Cycle Cost, implemented by CETH.
- Energy Integrated Information System, developed by SIVECO.
- NEMO Tool, developed by Teesside University (TEES).
- Building Occupancy & Energy Consumption Simulation Tool, developed by CETH.



#### 4.2.1 Medium Voltage Distribution Networks Management

##### General description of the inteGRIDy functionalities

This tool aims to support the Distribution System Operator (DSO) to manage the operation of grids with high penetration of distributed energy resources (DER). The tool includes a medium voltage (MV) network model that characterizes the electrical properties of distribution lines and transformers and accounts for real-time status of tie-switches and tie-lines provided by local DSO. The tool includes MV user profiling (both for passive and active one) to compute grid power exchange profiles.

The tool provides the following Task 4.2 related functionalities:

- Load and renewable energy system (RES) generation profiles from 24 to 72 hours in advance.
- Load and RES long term forecast, up to 1 year in advance.
- Calculate the optimal reconfigured topology of the MV distribution grid.
- Simulate an Ancillary Services Market and schedule consequently battery energy storage systems (BESS) deployed in the low voltage (LV) grid.

The tool is designed in order to manage three inteGRIDy pillars:

- **Smartening the Distribution grid:** a power profile forecast procedure is implemented in order to manage both generators and loads. Data relevant to the actual status of the grid, gathered thanks to the link with the DSO SCADA and data relevant to the forecasted trends are managed in order to define the optimal topology of the grid both in the short and in the middle term scenario.
- **Demand Response:** In case of a congestion, or a critical condition, in the local distribution grid, DSO will be in charge to ask for a service (increase or decrease the aggregated load) proposing also a price signal. The aggregator will be in charge to check the feasibility of the control action required and to evaluate its economic viability.
- **Energy Storage:** The proposed tool will be provided with a numerical emulator of the Italian Ancillary Services market. Price signals generated by such emulator will be managed in order to feed a routine in charge to schedule (singularly or in an aggregated way) energy storage unit deployed in the grid. The objective function will be to maximize revenues through the provision of ancillary services to the grid and/or to support final prosumers to maximize energy self-consumption.

##### Details of the modelling process

The tool is based on different procedures in charge to model the grid, solve the load flow model, predict the PV and load power profile and simulate the electric market in order to schedule energy storage units.

##### *Grid Modelling and Load Flow model*

The tool models the MV distribution grid and considers electrical parameters of lines and transformers including series resistance, reactance, transversal conductance and susceptance, etc. Load and generation profiles are considered for all grid nodes, based on measurements collected by real-time power meters installed in MV lines and selected secondary substations.

The data structure adopted for the network modelling is organized, according to the power flow theory, as:



- An admittance matrix representing the network topology and the electrical parameters of the connections (amplitude and phase,  $Y$  and  $\vartheta$ )
- A vector with the complex power injections in each node ( $P$ ,  $Q$ )
- A vector of electric potentials in each node (amplitude and phase,  $E$  and  $\delta$ )

$$P_p = \text{Re}(\overline{A_p}) = E_p \cdot \sum_q E_q \cdot Y_{pq} \cdot \cos(\delta_p - \delta_q - \vartheta_{pq}) \quad (1)$$

$$Q_p = \text{Im}(\overline{A_p}) = E_p \cdot \sum_q E_q \cdot Y_{pq} \cdot \sin(\delta_p - \delta_q - \vartheta_{pq}) \quad (2)$$

To this purpose, a customized version of MATPOWER [ZIM19] data format is adopted. More in detail, the MV network is represented by numerical data matrixes, modelling the characteristics of electrical nodes, branches (lines, transformers, switches), loads and generators. Matrixes in MATPOWER format are then converted in the data structure required by the power flow calculation.

The “BUS” matrix includes the information about the nodes of the network and the relevant power withdrawals by loads. It has as many rows as the number of nodes in the network. The content of the main fields of the table is the following (the readers should be aware that there are additional optional fields that have not been used):

- ID bus number
- Bus typology according to the power flow formulation (PQ, PE, slack, isolated)
- Active power absorbed
- Reactive power absorbed
- Voltage amplitude
- Voltage phase
- Rated voltage

Please notice that the table also includes the amplitude and phase of the nodal voltage, which are the variables evaluated in output to the power flow calculation procedure.

The “GEN” matrix is representative of generation nodes. It has as many lines as the number of generators in the network. The different data fields have the following contents:

- ID node number
- Injected active power
- Injected reactive power
- Maximum exchanged reactive power (for generators modelled as PE busses)
- Minimum exchanged reactive power (for generators modelled as PE busses)
- Setpoint voltage amplitude (for generators modelled as PE busses)
- Machine status (1 = in service, 0 = out of service)
- Maximum active power deliverable
- Minimum active power available

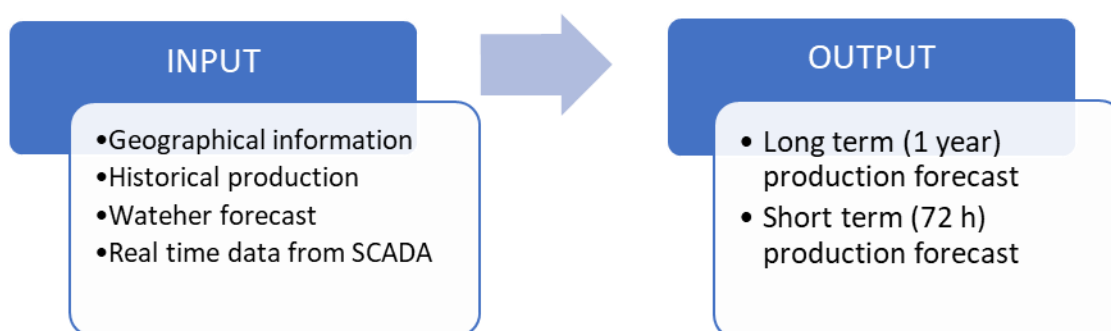
The “BRANCH” matrix reports data relevant to the electrical branches of the network, usually electrical lines but in some cases also electrical machines or equipment (e.g. HV/MV transformers, switch disconnectors, circuit breakers, etc.). The table has as many lines as the number of branches in the grid. In order to be able to reconstruct the network topology (connections between nodes) starting from the matrix organized data, for each branch the ID number of the “from” - “to” nodes is reported:

- ID number node “from”
- ID number node “to”

- Resistance
- Reactance
- Susceptance
- Ampacity
- Transformer ratio (if the branch is a transformer)
- Branch status (1 = in service, 0 = out of service)

#### *PV Generators and load power profile forecast*

Generation profiles of grid solar photovoltaic (PV) systems are created from weather forecasts and actual data from the solar PV plants. Figure 3 presents the structure of the solar PV generation forecast. The coefficients to characterize the solar PV systems are computed using a linear regression and random forest tree algorithms [IBR18] based on historical production and solar radiance data (global horizontal radiance and temperature) covering an area of 40 km<sup>2</sup> at the municipality of San Severino Marche with a 5 km resolution as shown in Figure 4. Selection of time span and period of historical production is that minimizing the error between modelled and actual data.



**Figure 3. I/O structure of the production forecast procedure.**



**Figure 4. Weather forecast spatial coverage and sampling data locations with at the municipality of San Severino Marche.**

The MV distribution grid model is fed with information from field sensors and external weather forecast data to estimate real-time and future status of the grid.

Weather forecast data is then fed to these derived solar PV system coefficients to compute the PV generation for the day/week ahead at the municipality of San Severino Marche. Characterization of additional DER technologies (e.g. hydro) is performed through the analysis of historical generation data. Since not all the power plants are monitored by the DSO and the historical data of the non-monitored plants is not available, to produce a forecast for their production, a transposing procedure is applied. For each non-monitored power plant  $i$ , the power produced at time  $t$  is evaluated as the mean normalized power of the  $j$  monitored plants of the same technology.

$$P_i(t) = \left( \sum_j \frac{P_j(t)}{P_{Nj}} \right) \cdot P_{Ni} \quad (3)$$

where  $P_{Ni}$  is the nominal power of the plant  $i$ ,  $P_j(t)$  is the forecasted power for the monitored plant  $j$  (directly obtained with the forecast technique), and  $P_i(t)$  is the forecasted power derived for non-monitored plant  $i$ .

Energy consumption profiles of MV/LV users are generated based on one-year recorded data at the grid substations. Summer and winter MV and LV user consumption profiles are generated through statistical analysis. Power exchange by LV users is modelled as injections/withdrawals at the point of grid connection and MV/LV substations. In addition, the model accounts for the current state of tie-switches and tie-lines over the network, obtained from DSO's SCADA.

#### *Electric market modelling and energy storage scheduling*

The model includes ancillary services market and expected trade trends in the implementation of demand response strategies.

The energy storage systems (ESS) deployed at residential level are aimed to provide both behind and front-of-the-meter services. The services provided are the following:

- Increase of self-consumption absorbing energy when PV production is in surplus with respect to load and vice versa
- Provision of primary frequency regulation, following Italian technical rules
- Provision of other frequency services traded on ancillary services market (i.e. Secondary and Tertiary Frequency Regulation), as a single aggregated virtual power plant selling on market
- Following local dispatching orders of the DSO
- A mix of the previous ones (simultaneous provision of multiple services)

PV and load data come from the real data measured at the domestic prosumer level. The network frequency is measured by the ESS. The market services are virtually sold on a market that emulates Italian ancillary services market. The local dispatching orders are sent by DSO on a database. The database is accessed by a communication procedure that links the DSO workstation and the ESS.

To do this, three procedures are developed.

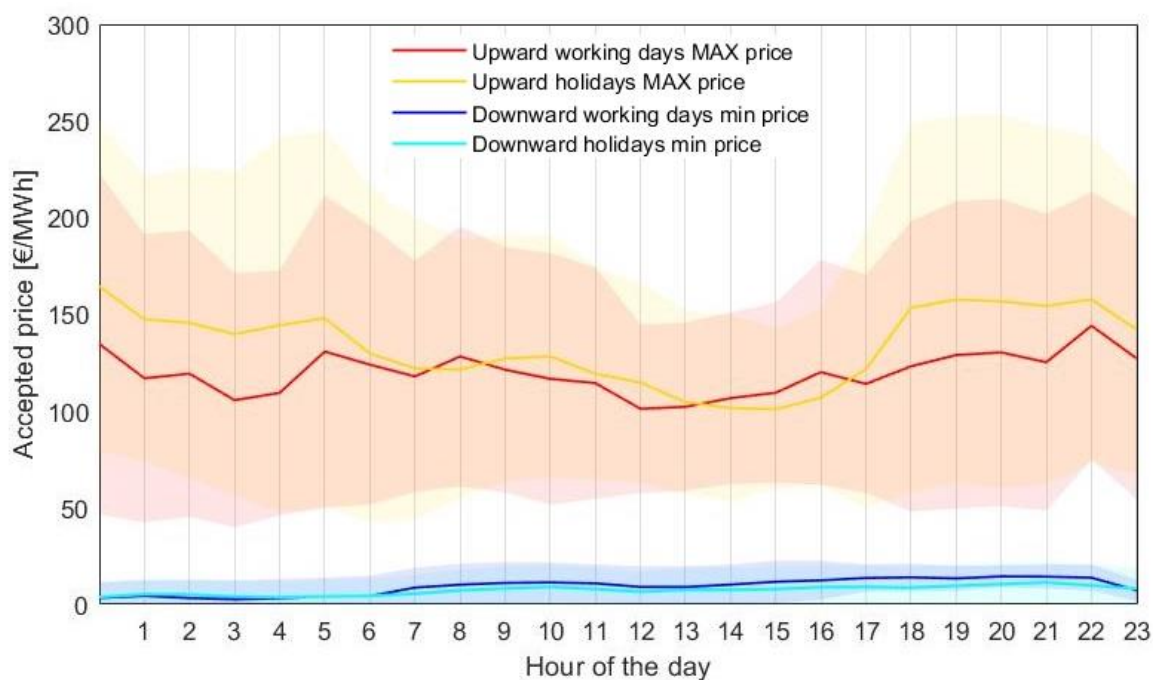
- The MarketModel is modelling the Italian ancillary services market in a verisimilar way. It receives as input statistical data on prices on the market and returns the accepted prices for each market session.
- The MarketStrategy develops the behaviour of the ESS individually and as an aggregated quantity on the market. It receives as input the data on the ESS operational parameters at the market gate closure and returns the power offered by each ESS, the

aggregated power and the outcome of the market session in terms of acceptance or rejection.

- The Real Time ESS Controller (RTESSC) computes the setpoint to be requested to each ESS in real time to perform the services requested. It receives as input the ESS mode, the operational parameters and the market outcomes and it returns the power setpoint requested to each battery. It also performs monitoring of ESS operation, measuring the gap between the requested and real operation.

The three modules represent three distinct functional units (as they do not communicate with each other but write and read from a shared relational database) but organic (as the failure of one module would affect the others). A better technical description of the modules is given in the following.

For what concerns the MarketModel tool, the code receives as input the results of a statistical analysis performed on Italian ancillary services price for Secondary and Tertiary Frequency Regulation based on the market operator data [GME19]. These services are traded on Italian market with hourly pay-as-bid offers. Therefore, statistical inputs include hourly average prices and standard price deviations, for both working days and holidays. Inputs are presented in Figure 5 for Secondary Regulation. A similar procedure is followed for Tertiary Regulation.

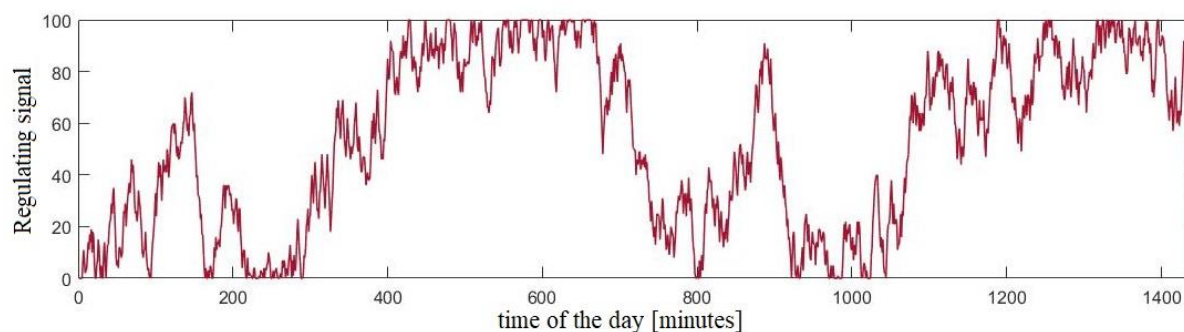


**Figure 5 Statistical analysis of accepted prices on balancing market**

Every day, for each hour of the day, for secondary and tertiary regulation bids of both reserves (upward and downward), the code extracts from the input data the average price and standard deviation from the statistical data. The algorithm elaborates on these data to return the market price for each hour. The market price is a value randomly extracted from the normal distribution with average equivalent to the average price of the hour of interest and the variance of the same hour. The prices are stored in a database. They represent the threshold to evaluate the acceptance/rejection of each bid submitted to the market. The MarketModel tool also provides the regulating signal for Secondary Frequency Control in Italy. It is a minute-based value communicated by the TSO some minutes in advance to real time [TER19]. It represents the percentage of the total regulating power awarded on the Secondary Regulation market to be provided each minute. The regulating signal is simulated as a random distribution of values from 0 to 100 following some rules that have been recognized as a result of a further statistical analysis (e.g. the maximum offset between a value and the previous one is 10 units; the



regulating signal is zero in the minutes before and after midnight). In Figure 6 it can be seen how the regulating signal, as simulated and stored in the database, looks like. A regulating signal equal to 100 means that in that minute the unit committed must increase the injection of the total amount of power awarded on the market (discharge). When regulating signal is 0, unit must decrease the power injection of the total amount offered (charge). 50 means no power output.



**Figure 6 Regulating signal for secondary frequency control**

Market prices and regulating signal are then accessed daily by the following tools, reproducing the interaction with the system in a realistic electricity market.

The MarketStrategy tool builds the bidding strategy of the ESS on market as an aggregated virtual power plant. The aggregated bid is represented by a quantity [MW] offered at a price [€/MWh], for each service (i.e. secondary and tertiary regulation) and each reserve (i.e. upward and downward). The code returns the outcome of the market session in terms of acceptance or rejection. The aggregated offer is then provided by each single ESS based on the single available capacity. The tool is launched every 4 hours, just before the gate closure of the Italian Balancing Market (BM) sessions (i.e. at 3AM, 7AM, 11AM, 3PM, 7PM, 11PM) [GME18]. The bidding strategy aims to perform simultaneously multiple services provision (Multiservice), exploiting the ESS as much as possible while limiting the possibility of the saturation of the ESS state of charge (SOC), to a lower (20%) or upper (100%) operation SOC thresholds.

The detail of the strategy is summarized below: the strategy must define the available power band for each service; it sets some priorities based on technical and economic criteria; these allow to establish a ranking while considering the energy budget [NAM19] necessary for each service. Energy budget of a service can be defined as the amount of energy content of the ESS to be accounted for provision of that service in a time window.

- Increasing the self-consumption is the priority, since it has the highest specific net revenue in Italian framework (around 0.21 € for each self-consumed kWh) [EUS18].
- Providing tertiary frequency control comes after. This is because it is an asymmetric service and allows SOC restoration strategies. Indeed, power band offered vary according to SOC and forecasted energy flows in the following hours. E.g. if SOC at the market gate closure is 80% and in next hours PV is foreseen to generate more than the load, a larger amount of upward reserve is offered to help discharging the battery and avoid upper saturation; if instead, SOC reaches 40% in the night time, a larger amount of downward reserve is offered to charge the battery.
- Then, secondary frequency control is provided with fixed bands. This is a symmetric service on Italian market (same upward and downward bid requested). Furthermore, the power requested is characterized by aleatory behaviour, as shown in Figure 6. Hardly or no robust SOC restoration strategies can be built on this type of services.

Anyway, since mean price awarded in secondary regulation market is the highest for Italian market, it is economically of interest to provide secondary regulation, too.

This strategy is tailor made on Italian market but can be then adapted to different frameworks by changing parameters. The targeted market has the following characteristics.

- Market sessions every 4 hours.
- An hour between market closure gate and delivery period (offers for hours from  $h$  to  $h+4$  must be submitted within  $h-1$ ).
- Offer consisting of hourly quantities in MW and price in €/MWh.

The MarketStrategy tool's operation is described in the following. It sends a query to the database and obtains the PV and load forecast data for the next 5 hours (distance to delivery + market session duration). It builds through those the estimated power profiles to maximize self-consumption. The average estimated setpoint per hour is obtained as follows.

$$P_{self} = P_{load} + P_{PV} \quad (4)$$

where the power setpoint ( $P_{self}$ ) is expressed in kW and is positive in case of injection (discharge), negative in case of absorption (charge). The load  $P_{load}$  is positive (discharge), while PV power ( $P_{PV}$ ) is negative (charge).  $P_{self}$  helps to estimate the 5-hour energy budget for providing the increase in self-consumption. The code then derives from the database the consumption of the battery auxiliaries, namely the power of self-discharge ( $P_{auto}$ ). The code derives the fixed bands reserved for secondary reserve from the database ( $P_{SR}$ ). The estimated total energy budget for the next five hours depends on:

- The contribution of self-consumption  $P_{self}$  from  $h-1$  to  $h+4$ .
- The contribution of the self-discharge  $P_{auto}$  from  $h-1$  to  $h+4$ .
- The contribution of tertiary regulation upward ( $P_{TRUp,h-1}$ ) or downward ( $P_{TRDn,h-1}$ ) provided by  $h-1$  to  $h$ .
- The contribution of secondary regulation  $P_{SR}$  provided by  $h-1$  to  $h$ .
- The expected contribution of secondary adjustment provided by  $h$  to  $h+4$ .

Following the above logic, if  $P_{self}$  is positive (expected discharge), the energy budget that should be allocated for the performance of the above services, net of the average charge and discharge efficiency ( $\eta_{ch}$  and  $\eta_{dis}$ ) is as follows.

$$E_{budgetUp} [kWh] = \left( \frac{P_{TRUp,h-1}}{\eta_{dis}} - P_{TRDn,h-1} * \eta_{ch} \right) * 1h + \left( \frac{P_{SR}}{\eta_{dis}} + \frac{P_{self}}{\eta_{dis}} + P_{auto} \right) * 5h \quad (5)$$

It results in an available band of SOC ( $\Delta SOC_{availableUp}$ ) before saturation to the minimum SOC.

$$\Delta SOC_{availableUp} = SOC_{init} - SOC_{min} - \frac{E_{budgetUp}}{E_{nom}} * P_{nom} * 100 \quad (6)$$

where  $SOC_{init}$  is SOC at the market closure,  $SOC_{min}$  is the minimum threshold set for standard ESS operation,  $E_{nom}$  and  $P_{nom}$  are nominal energy and power of the ESS

Similarly, regarding the available SOC variation ( $\Delta SOC_{availableDn}$ ) before upper threshold ( $SOC_{max}$ ) saturation.

$$E_{Dn} [kWh] = \left( P_{TRDn,h-1} * \eta_{ch} - \frac{P_{TRUp,h-1}}{\eta_{dis}} \right) * 1h + \left( P_{SR} * \eta_{ch} - \frac{P_{self}}{\eta_{dis}} - P_{auto} \right) * 5h \quad (7)$$

$$\Delta SOC_{availableDn} = SOC_{max} - SOC_{init} - \frac{E_{budgetDn}}{E_{nom}} * P_{nom} * 100 \quad (8)$$

The estimate in case of power for negative self-consumption (expected charge) is obtained in the same way, with minimal variations of sign. From the available SOC band it is possible to switch to the power that can be offered on the market for tertiary regulation.

$$P_{TRUp} = \min \left( P_{nom}, \max \left( 0, \frac{\Delta SOC_{availableUp}}{100 * 4h} * E_{nom} * \eta_{dis} \right) \right) \quad (9)$$

$$P_{TRDn} = \min \left( P_{nom}, \max \left( 0, \frac{\Delta SOC_{availableDn}}{100 * 4h} * \frac{E_{nom}}{\eta_{ch}} \right) \right) \quad (10)$$

Once the offered quantity (in kW) is defined, it is bid at a price. The price offered for secondary regulation is fixed and aims at providing the service only if revenues are high. Price offered for tertiary regulation depends mainly on  $SOC_{init}$ , based on a strategy called merchant/reliability. If SOC is far from saturation, then the aim is maximizing the market gain (merchant). If ESS is close to saturation (at  $SOC_{max}$  or  $SOC_{min}$ ), the aim switches to guaranteeing the continuity of service (reliability). The bid price will be more likely to be accepted (lower prices) if the acceptance helps SOC restoration. The drawback is the limited revenue. Oppositely, the prices will be higher in merchant strategy, to guarantee larger revenues. The drawback is the increase in the risk of being rejected. Prices and quantity offered are stored in a database.

When the available power has been computed for each single ESS and the price and quantity are stored in the database, aggregation occurs. The aggregated quantity offered ( $P_{aggrSR}$ ) is the summation of the single quantity available.

$$P_{aggrSR} = \sum_{i=1}^{nEss} P_{SR,i} \quad (11)$$

$$P_{aggrTRUp} = \sum_{i=1}^{nEss} P_{TRUp,i} \quad (12)$$

$$P_{aggrTRDn} = \sum_{i=1}^{nEss} P_{TRDn,i} \quad (13)$$

Instead, the aggregated offered prices ( $p_{aggrXR}$ ) are the weighted average of the single prices ( $p_{XR,i}$ ).

$$p_{aggrSR} \left[ \frac{\text{€}}{kWh} \right] = \frac{\sum_{i=1}^{nEss} P_{SR,i} * p_{SR,i}}{P_{aggrSR}} \quad (14)$$

$$p_{aggrTRUp} \left[ \frac{\text{€}}{kWh} \right] = \frac{\sum_{i=1}^{nEss} P_{TRUp,i} * p_{TRUp,i}}{P_{aggrTRUp}} \quad (15)$$



$$p_{aggrTRDn} \left[ \frac{\text{€}}{\text{kWh}} \right] = \frac{\sum_{i=1}^{n_{ESS}} P_{TRDn,i} * p_{TRDn,i}}{P_{aggrTRDn}} \quad (16)$$

The aggregated prices offered are then compared with the marginal prices accepted on the market for that hour as modelled and stored in the database by the MarketModel. As mentioned, the secondary reserve is symmetric, therefore no one or both (upward and downward) aggregated offers are awarded. In this case, acceptance depends on the price differential between upward and downward reserve. If the bid differential is lower than the marginal one, the bid is awarded. Tertiary reserve, instead, is awarded either upward or downward based on the prices. If both offers, based on the price criterion, are more convenient than marginal prices, then the larger difference between bid and marginal price (upward or downward) is selected. The aggregated acceptance reflects on the single effort requested. In the database table dedicated shown in Figure 7, the quantity offered is stored in kW (MARKETTRQBIDUP and MARKETTRQBIDW), while a Boolean variable for each reserve (MARKETTRAVUP and MARKETTRAVDW) indicates whether the offer is awarded (1) or not (0).

	MARKETTRQBIDUP	MARKETTRQBIDW	MARKETTRAVUP	MARKETTRAVDW	MARKETTRAVUP	MARKETTRAVDW
237 30-SEP-19 12.45.00.0000000000	1.072	1.076	1	1	0	1
238 30-SEP-19 12.30.00.0000000000	1.072	1.076	1	1	0	1
239 30-SEP-19 12.15.00.0000000000	1.072	1.076	1	1	0	1
240 30-SEP-19 12.00.00.0000000000	1.072	1.076	1	1	0	1
241 30-SEP-19 11.45.00.0000000000	1.072	1.076	1	1	0	1
242 30-SEP-19 11.30.00.0000000000	1.072	1.076	1	1	0	1
243 30-SEP-19 11.15.00.0000000000	1.072	1.076	1	1	0	1
244 30-SEP-19 11.00.00.0000000000	1.072	1.076	1	1	0	1

**Figure 7 Database view of quantity offered and outcome of the market session**

The real-time power setpoint to each single ESS is returned by the RTESSC. Every few seconds it receives as input data from the database the mode in which the ESS is working, the real time data on load and PV generation, the outcomes of the market and the related power setpoints. Its operation is better detailed in the following. The code is firstly querying the database for the mode in which each ESS is working. Different modes are available, corresponding to a specific service provided.

- Mode 0 is for ESS controlled locally by the end user.
- Mode 1 is for primary frequency regulation.
- Mode 2 is for the Multiservice already described (i.e. self-consumption + market services).
- Mode 3 is for self-consumption only.
- Mode 4 is for DSO local dispatching.

If mode 0 is active, no power setpoint is delivered remotely to the ESS, that is therefore in the complete availability of the residential customer. To do this, a Boolean parameter is sent every loop to the database, disabling the remote control.

Mode 1 sends to the database a signal for the activation of primary frequency regulation on ESS. This built-in service imposes a power setpoint to the ESS correlated to frequency deviation by a droop curve.

Mode 2 sends to the ESS the overall setpoint resulting by superposition of self-consumption, self-discharge, secondary frequency regulation and tertiary frequency regulation. The detailed description is proposed here below. The code reads from database the latest measured values

of user production and consumption (quasi real-time). In case of real-time data unavailable, it uses the forecasts. The sum of load (positive) and PV power (negative) is the setpoint for self-consumption ( $P_{setpointSelf}$ ). It reads  $P_{auto}$ . It reads from database the regulating signal ( $RegS$ ) for secondary frequency regulation and transforms it into the secondary regulation setpoint ( $P_{setpointSR}$ ) based on the power awarded.

$$P_{setpointSR} = P_{SR} * \frac{RegS - 50}{50} \quad (17)$$

The code reads from the database the awarded quantity for each single ESS for tertiary regulation: this is exactly the setpoint to be provided for tertiary regulation, negative if downward and positive if upward ( $P_{setpointTR}$ ). The code then calculates the net energy to be moved as the algebraic sum of the setpoints. Multiplies or divides the average battery performance to require the correct continuous side setpoint ( $P_{reqMulti}$ ).

$$P_{reqMulti}[kW] = P_{setpointSelf} + P_{auto} + P_{setpointSR} + P_{setpointTR} \quad (18)$$

The RTESSC writes on the database, for each ESS, a bit to enable the remote control and the setpoint requested in real-time for the provision of Multiservice.

Mode 3 just maximizes the self-consumption of the household using the already presented ESS setpoint.

$$P_{self} = P_{load} + P_{PV} \quad (19)$$

This mode can be used on field to propose to end-user the cost-benefit analysis of introducing also market services provision.

Mode 4 allows to respond to DSO to local dispatching orders. The pilot project in San Severino is foreseeing the possibility of local market operated by DSOs, or anyway the possibility of having dispatch orders sent to units for provision of local ancillary services. If the DSO needs provision of local services, can store a quantity and a price on the database. If in real-time there is technical possibility and economic convenience, the ESS performs the regulation requested by the DSO. Therefore, mode 4 checks if there is available energy content (if  $\Delta SOC_{availableUp}$  or  $\Delta SOC_{availableDn}$  are larger than zero, considering the ongoing market session), converts it in available power and verifies if available power is larger than requested power by DSO. If yes, it responds the local dispatching order. If not, it computes if there is economic convenience in not providing the market services, paying the fees and following the local dispatching order and decides consequently. Mode 4 implements therefore demand response based on local services, that are foreseen to enter more and more the field of electricity markets.

Downstream the setpoint definition, the code performs monitoring of the ESS performance. Based on SOC variation with respect to previous iteration, the power flows in the ESS are computed. These (net of the efficiencies) are compared with the requested power for services provision. The power provided ( $P_{ok}$ ) is evaluated at the market price stored in the database (if applicable) or at conventional prices coming from historical data ( $P_{ok} * p_{mkt}$ ). The fraction non provided ( $P_{ko}$ ) is monetized at a penalty price ( $p_{fee}$ ) different for each service. If not all the services are provided completely (Multiservice), a system of priorities is adopted for estimating the quality of service.

- If  $P_{setpointTR}$  is greater than  $P_{ko}$ , all the penalties are referred to tertiary reserve.

$$P_{koTR} = P_{ko}$$

- If  $|P_{setpointTR}| < |P_{ko}| \leq |P_{setpointTR}| + |P_{setpointSR}|$ , penalties are referred to tertiary reserve and the remaining part to secondary reserve.

$$P_{koTR} = P_{setpointTR}$$

$$P_{koSR} = P_{ko} - P_{koTR}$$

- If  $|P_{setpointTR}| + |P_{setpointSR}| < |P_{ko}| \leq |P_{setpointTR}| + |P_{setpointSR}| + |P_{self}|$ , penalties are referred to tertiary reserve, to secondary reserve and the remaining part to self-consumption.

$$P_{koTR} = P_{setpointTR}$$

$$P_{koSR} = P_{setpointSR}$$

$$P_{koSelf} = P_{ko} - P_{koTR} - P_{koSR}$$

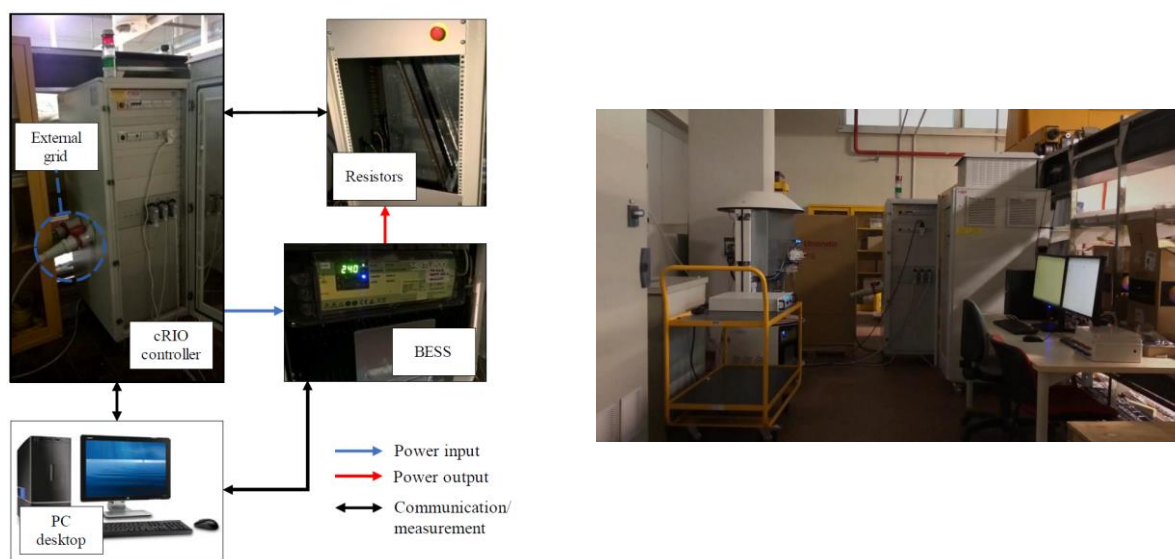
Regarding model calibration and validation, these are performed with the State Estimation algorithm [SCH70], which minimizes the difference between actual (i.e. electric readings) and modelled data.

Characterization of electrical grid network is based on standard load flow techniques [STO74]. Samples of these load flow techniques are available both in MATLAB [ZIM19] and DigSilent [DIG19] formats.

DER power plant generation models will be validated through an ex-post comparison between modelled and actual measured generation profiles.

In particular, to validate the tools, preliminary tests have been performed on the San Severino Market Pilot, evaluating the error between the forecasted power profiles and the sampled one. Similarly, real-life tests have been performed for the electric market emulator procedure.

Finally, in order to validate the energy storage scheduler (in charge to control the battery providing ancillary services), a lab test campaign has been activated (since November 2018) in Politecnico di Milano. In the lab, a PV emulator and a load emulator allow to create a very wide set of possible working condition of a single energy storage equipment (Figure 8). Tests have been performed in close cooperation with UNE, the partner in charge of the energy storage unit manufacturing. Lab Tests resulted to be a very useful resource in order to fix bugs, optimize the control laws and properly set the control parameters. Several improvements have been coded in the Medium Voltage Distribution Networks Management tools provided by POLIMI and in the firmware of ZHERO Technology (the energy storage unit), provided by UNE.



**Figure 8. Lab arrangements in Politecnico di Milano. ZHERO energy storage system coupled with the control workstation managing the Medium Voltage Distribution Networks Management tools**

### Technical specifications and advances from the existing tools

The MV network can be modelled for time horizons of 1 day, 1 week, up to 1 year. Lower time horizons are not considered as they do not provide enough value to the grid optimization process. Output data have a time resolution up to 15 minutes.

In terms of model input and output data, input data includes the following:

- MV network structure, in terms of grid topology, electrical parameters of lines and transformers.
- Characteristics and positioning on the grid of the protection and tie-switches and tie-lines.
- Measurements (active/reactive power, voltage, etc.) collected in real-time in the Primary Substation and along MV feeders imported through ORACLE DB.
- Measurements, preferences and logic states of the users enabled to the provision of ancillary services to the power system.
- Historical data about the grid's and users' behaviour.
- Real time and weather forecast data in comma separated value (CSV) format, as depicted in Figure 9.

```
lat;lon;date;temperature;wind_speed;wind_direction;relative_humidity;precipitation;solar_radiation_ghi
43.055;12.947;2018-05-25T07:00:00+00:00;17.3;1.64;52;78;0;428.6
43.055;12.947;2018-05-25T08:00:00+00:00;18.3;1.64;52;72;0;604.2
43.055;12.947;2018-05-25T09:00:00+00:00;19.2;1.56;50;68;0;753.3
43.055;12.947;2018-05-25T10:00:00+00:00;20.2;1.78;52;62;0;869.2
43.055;12.947;2018-05-25T11:00:00+00:00;21;1.91;43;60;0;913.5
43.055;12.947;2018-05-25T12:00:00+00:00;21.3;1.9;18;58;0;837
43.055;12.947;2018-05-25T13:00:00+00:00;21.3;1.97;336;54;0;678.5
43.055;12.947;2018-05-25T14:00:00+00:00;21.3;1.52;337;64;0.1;688.8
43.055;12.947;2018-05-25T15:00:00+00:00;19.6;2.04;11;78;0.9;530
43.055;12.947;2018-05-25T16:00:00+00:00;18.4;1.84;22;85;0.8;328.1
43.055;12.947;2018-05-25T17:00:00+00:00;17.9;1.46;74;86;0.3;198.6
43.055;12.947;2018-05-25T18:00:00+00:00;17.1;0.91;84;90;0;100.8
43.055;12.947;2018-05-25T19:00:00+00:00;15.9;0.89;63;94;0;0
43.055;12.947;2018-05-25T20:00:00+00:00;15.4;0.71;82;95;0;0
43.055;12.947;2018-05-25T21:00:00+00:00;15;0.51;79;94;0;0
43.055;12.947;2018-05-25T22:00:00+00:00;14.7;0.45;117;93;0;0
43.055;12.947;2018-05-25T23:00:00+00:00;14.4;0.32;108;93;0;0
```

**Figure 9. Example of weather forecast data format in CSV format provided by Datameteo (Source: [DAT19]).**

The output data from the model include internal variables and these are provided in ASCII format (American Standard Code for Information Interchange) files.

In addition, the tool presents several dependencies. as already described the tool requires both real-time and forecasted weather data. These data will be retrieved from the external commercial data provider Datameteo [DAT19]. Access to weather forecast data is available since March 2018. Moreover, the tool depends on the software module devoted to the DER, load and ancillary service market forecasting. The tool relies on field collected grid network data provided by the DSO, and interacts with the UNE's ZHERO technology to monitor a cluster of Energy Storage Systems.

The tool is developed in MATLAB framework and DigSilent Power Factory Code. The package is developed for Windows (7 or higher).

Furthermore, the tool collects real-time and historical grid network operation data from the SCADA/DMS. Metering devices and monitored sectionalizing switches are required to collect field data. In addition, LV users equipped with RES are monitored.

Finally, it is worthwhile to report the improvements in the Medium Voltage Distribution Networks Management tools obtained thanks to the inteGRIDy project. Actually, inteGRIDy is the first project where those tools are adopted, i.e. in the past they have been developed internally in the university and tested in internal research project. Functionalities related to the forecast of power profile and related to distribution grid topology optimization were available in a preliminary release but just as a stand-alone MATLAB code.

Within inteGRIDy project, these functionalities have been improved (both in terms of robustness of the algorithm and in terms of computational efficiency), and a shared data structure has been developed and an interface with a commercial SCADA has been activated. Finally, the code has been validated adopting real life data gathered thanks to the interface with the DSO SCADA.

Functionalities related to the market simulator and to the energy storage scheduler have been developed from scratch.





## Expected advantages compared to commercial products

The tool providing multiple simultaneous services is an organic and all-inclusive tool for DERs integration in markets. It supports the network through the provision of :

- Fundamental services for network reliability such as primary frequency regulation
- Market services for the TSO, therefore supporting the grid at country-scale
- Local services for the DSO, therefore supporting the local network
- Self-consumption, therefore decreasing the burden for the network caused by non-programmable RES and increasing consequently RES hosting capacity

This solution presents an advantage with respect to state of art market solutions, since it enables DERs to support simultaneously local and countries' market. Local services are foreseen to be more and more involved in electricity markets [IRE19]. The tool proposed enables effective exploitation of DERs in schemes already presented by literature [MIN18] and by operators [BNE16]. The solution is scalable: it is foreseen for some tens of kW of flexibility provision (coherent with local markets), anyway a larger effort by aggregators for pooling can provide a bid size of the order of 1 MW.

## Implementation features and delivery

The tool is applied in the San Severino Marche inteGRIDy pilot project where it models the MV distribution grid, based on recorded load and generation profiles, as well as models the output of solar PV plants, while it also includes ancillary services market and trade trends related to the application of DR strategies.

The tool is a standalone application running on a workstation and developed in MathWorks MATLAB software environments. In particular, PowerFactory is a power systems analysis software, with advanced capabilities designed to manage both static and dynamic networks' analyses. The mathematical model of the network is implemented in the MATLAB, exploiting software interfaces with the DSO's SCADA and/or other external devices/systems.

The flexibility of MATLAB programming language is used to develop the state estimation algorithms, control strategies and forecasting tools required for optimizing the network operation.

Containerization in Docker may be restricted as the platform is designed as a monolithic tool which prevents containerization of individual modelling functionalities. In addition, since it is required to maintain the link to the DigSilent package as this is used by the DSO, not all developed routines under inteGRIDy project could be containerized. [For more information on the code, please contact:](#)

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No demo is available for this energy model. Actually, in order to provide a demo a huge set of data has to be settled up. In order to test and validate the procedure, on field tests have been performed in San Severino Marche, i.e. MV Distribution Networks Management Tools have been linked to the DSO SCADA and fake controls have been simulated.

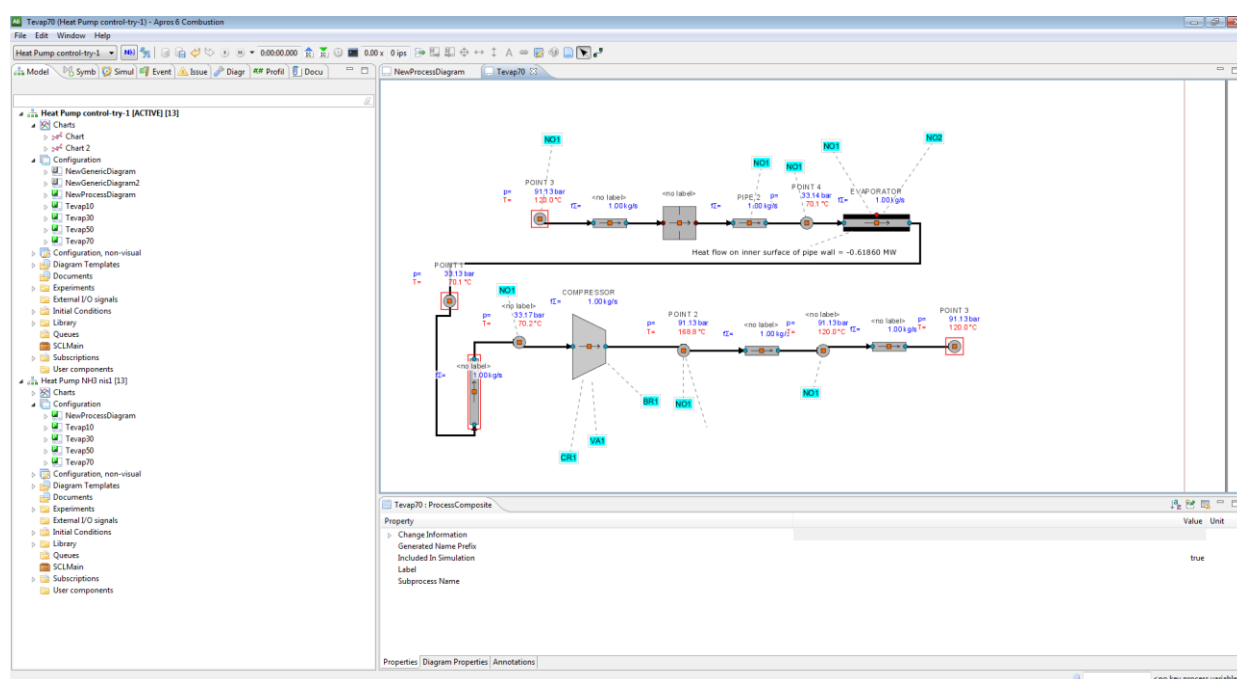
## 4.2.2 APROS Dynamic Process Simulation

### General description of the inteGRIDy functionalities

APROS Dynamic Process Simulation (APROS) is a commercial software developed by FORTUM and VTT, capable of modelling thermal and electric energy systems under steady state and dynamic conditions [VTT14], that combines high-fidelity solvers together with fully graphical user interfaces (Figure 10).

APROS provides libraries and in-house code ports to model individual or multi-component energy systems such as:

- Thermal power plant
- Solar PV farm
- Wind farm
- Electrical systems [KOM12]
- Heat pumps
- Battery energy storage systems (BESS)



**Figure 10. APROS graphical user interface (Source: [VTT14]).**

For the scope of inteGRIDy, new house-built components (e.g. heat pump, microgrid-main grid interface, EMS) have been developed by CETH/CPERI to accommodate for the needs of the pilots, where this will be used, i.e. the Barcelona and Cyprus pilot sites. Extensive description of these components is given further below.

The aim of APROS utilization in the cases of Barcelona and Cyprus pilots was the provision of Scenario-based Dynamic Simulations functionalities, therefore having strong relations with the CMP layer Operation Analysis Framework and Simulation, that is further presented in Deliverable D4.3. Main contribution of this development is to indicate the best strategy for power and heat production and storage management at different periods during the year investigating scenarios with higher power production and larger storage capacity. The tool analyses are involved in three out of four pillars of the project: Demand Response (peak shaving strategies for load smoothening); Energy Storage (BESS development); and Smartening the Grid (potential integration of forecasting algorithms for load and RES



production with the APROS tool). The time framework of the investigated scenarios was one-year period, in order to have an overall view of the energy systems performance during a year, taking into account aspects such as weather variation, time of use, etc.

### Details of the modelling process

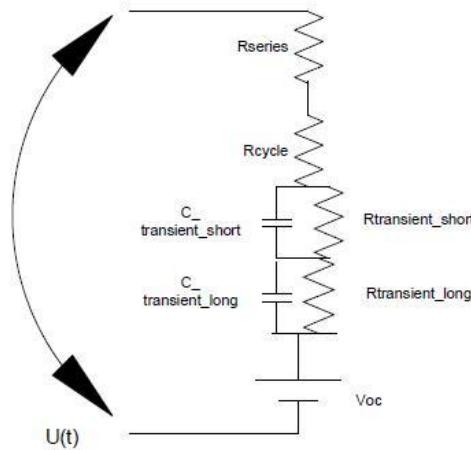
This section includes a description of selected models employed to characterize the behaviour of electrical batteries, solar PV panel and heat pumps.

#### *Electric lithium battery*

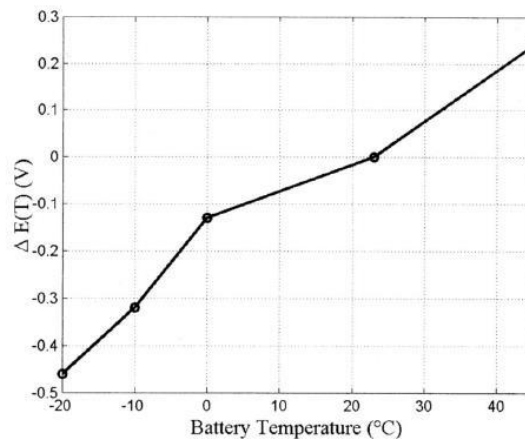
The voltage of the lithium battery  $U(t)$  (Figure 11) is described in APROS as:

$$U(t) = V_{OC} \cdot n - \frac{n}{m} (R_{series} + R_{cycle} + R_{tr_{sh}} + R_{tr_{ln}}) \cdot I + n \cdot \Delta E(T) \quad (20)$$

where  $V_{OC}$  represents the open circuit voltage of each cell, which is a function of remaining capacity;  $n$ ,  $m$  are the number of cells in series and the number of strings in parallel respectively;  $I$  is the current; the  $R_i$  parameters represent internal resistances of the battery; and the term  $\Delta E(T)$  is related to the battery temperature and its effect on voltage (Figure 12).



**Figure 11. One-cell equivalent circuit model for lithium cells.**



**Figure 12. Term  $\Delta E(T)$  as function of the battery temperature.**

The current battery capacity  $C(t)$ , updated at each time step, is computed as follows:

$$C(t) = C(t - \Delta t) - I \cdot \frac{\Delta t}{3600} \quad (21)$$

where  $\Delta t$  is the time step which in this case is set to 0.2s in order to capture small-scale voltage and current dynamic transients.

The number of cycles equivalent is calculated as:

$$N_{eq} = \int \frac{\frac{1}{2} |I|}{3600 \cdot C_{max}} \quad (22)$$

The maximum remaining capacity of the battery and dependence on battery aging and degradation effects is resolved as:

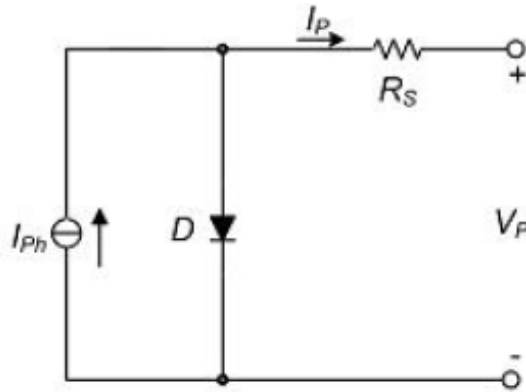
$$C_{max} = C_{nom} \cdot [1 - (f_{sl} + f_{cl})] \quad (23)$$

where  $C_{nom}$  is the nominal capacity of the BESS and the coefficients  $f_{sl}$  and  $f_{cl}$  account for lifetime storage and cycle losses respectively.

The remaining battery capacity is used with the current maximum capacity at every simulation step to calculate the state of charge (SOC).

#### Solar PV module

Solar PV modules are modelled as a direct current (DC) source with an internal resistance that changes non-linearly with solar radiation. Module's current  $I$  and voltage  $V$  are adjusted based on the load of electrical system, module I-V curve and maximum power point tracker (MPPT) algorithm used. PV cells are modelled based on the single-diode equivalent circuit as described in [BEL09] and illustrated in Figure 13.



**Figure 13. Single-one diode equivalent circuit of a PV cell.**

Solar PV module parameter setting are based on standard test conditions (STC) and are used to compute PV cell's current and voltage:

$$I_{sc} = \frac{G}{G_0} [I_{sc0} + k_T (T - T_0)] \quad (24)$$

where  $I_{sc}$  is the short circuit cell current,  $G$  and  $G_0$  are the actual and STC ( $1,000 \text{ W/m}^2$ ) solar radiances,  $I_{sc0}$  is the short circuit cell current at STC,  $k_T$  is a temperature coefficient for  $I_{sc}$  (in  $A/^\circ C$ ),  $T$  is the cell temperature and  $T_0$  is the cell temperature at STC ( $25^\circ C$ ). The panel manufacturers include in their product datasheets the temperature coefficients for both  $I_{sc}$  and the open circuit voltage  $V_{oc}$ . The PV current  $I_p$  can be determined as a function of the voltage  $V_p$  as:

$$I_p = I_{sc} [1 - C_1 (e^{\frac{V_p}{C_2 V_{oc}}} - 1)] \quad (25)$$

where the coefficients  $C_1$  and  $C_2$  are function of the PV module parameters  $I_{SC0}$ , open circuit voltage at STC  $V_{OC0}$ , current at maximum power point at STC  $I_{MPP0}$  and voltage at maximum power point at STC  $V_{MPP0}$ . These technical parameters are provided by manufacturers in the PV module datasheets. Open circuit voltage  $V_{OC}$  is computed from  $V_{OC0}$  as:

$$V_{OC} = V_{OC0} + m_T(T - T_0) - \Delta V(G) \quad (26)$$

where  $m_T$  is the temperature coefficient for  $V_{OC}$  (in V/°C) and  $\Delta V(G)$  is a correction term for the voltage.

There are two MPPT methods available in APROS to determine operation voltage  $V_{MPP}$  and current  $I_{MPP}$  of an array of PV modules to yield the maximum power output  $P_{MPP}$  under given temperature and irradiance conditions:

1. Fractional Open Circuit Voltage Method is derived from the linear relationship between  $V_{OC}$  and  $V_{MPP}$ .
2. Incremental Conductance Method based on the zero slope of the PV array power curve at the MPP and characterized by the following equations:

$$\frac{\partial P}{\partial V} = \frac{\partial (IV)}{\partial V} = I + V \frac{\partial I}{\partial V} \quad (27)$$

$$\frac{\Delta I}{\Delta V} + \frac{I}{V} = 0 \quad \text{at MPP} \quad (28)$$

$$\frac{\Delta I}{\Delta V} + \frac{I}{V} > 0 \quad \text{left of MPP} \quad (29)$$

$$\frac{\Delta I}{\Delta V} + \frac{I}{V} < 0 \quad \text{right of MPP} \quad (30)$$

Further details and validation of the solar PV module model in APROS software can be found in [RUU07].

#### Heat Pump model

APROS can perform detailed thermal-hydraulic dynamic simulations through the solution of dynamic conservation equations for mass, momentum, and energy:

$$\frac{\partial A\rho}{\partial t} + \frac{\partial A\rho v}{\partial z} = 0 \quad (\text{mass balance}) \quad (31)$$

$$\frac{\partial A\rho v}{\partial t} + \frac{\partial A\rho v^2}{\partial z} = \frac{\partial A p}{\partial z} + S_m \quad (\text{momentum balance}) \quad (32)$$

$$\frac{\partial A\rho h}{\partial t} + \frac{\partial A\rho v h}{\partial z} = S_h \quad (\text{energy balance}) \quad (33)$$

Built-in modules, such as the heat pump, are integrated into a model network and solve simultaneously, thus enabling the analysis of a multi-component system. Modules required to characterize numerically the heat pump include compressor and throttle valve, heat transfer and piping connections.

The compressor module calculates the different states of the gas compression process with the corresponding dimensionless user defined compressor map and based on the following equations:

$$\Pi = \frac{p_2}{p_1} \quad (34)$$

$$\Pi^{k+1} = \Pi^k + \frac{\partial \Pi^k}{\partial q_m^k} (q_m^{k+1} - q_m^k) \quad (35)$$

$$\Delta p^{k+1} = p_1 (\Pi^{k+1} - 1.0) \quad (36)$$

$$P_A = \frac{1}{\eta_{isA}} q_m C_p T_1 (\Pi^{\frac{R}{C_p}} - 1.0) \quad (37)$$

where  $q_m$  is the dimensionless mass flow rate,  $p$  the pressure,  $T$  the temperature,  $\Pi$  the pressure ratio,  $P_A$  the compressor power,  $R$  the gas constant,  $C_p$  the specific heat capacity and  $\eta_{isA}$  the isentropic efficiency.

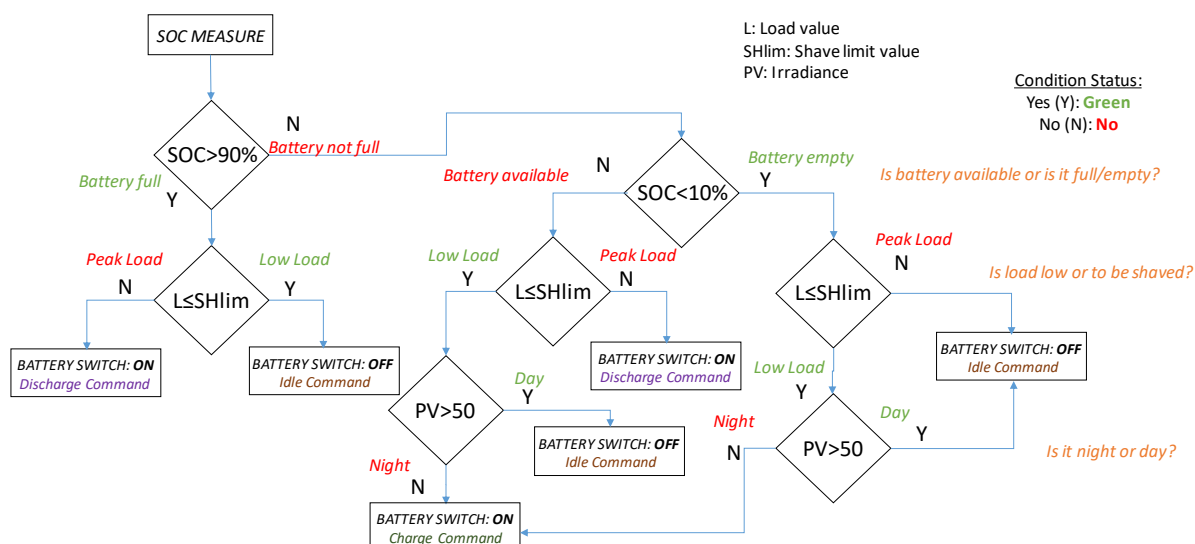
Further details of the thermal-hydraulic process modelling in APROS and validation results may be found in [JUS95] and [ALO17].

### *EMS algorithms description*

Having the dynamic simulation model developed, it was possible to implement the different EMS algorithms with basic analogue and binary modules and simulate each operation strategy separately. In the Barcelona pilot, two different operation strategies are investigated, one peak shaving-based scenario and another pricing based.

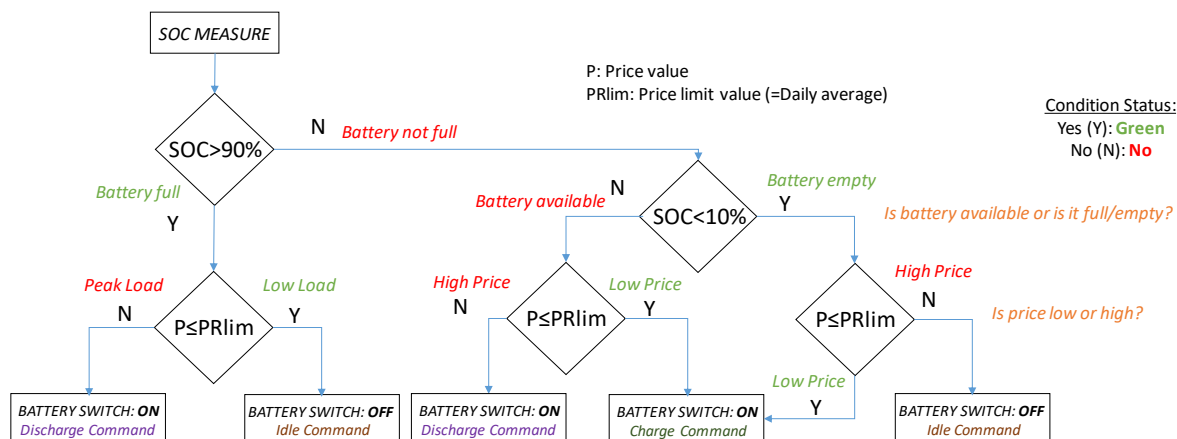
For the peak shaving scenario, the aim is to reduce the maximum daily energy demand of the microgrid and replace it with stored energy from the BESS (Figure 14). This common demand response technique is mostly suitable for power systems that present a non-uniform load curve which is particularly peaked at specified time periods. This may affect the cost of electricity if a demand charge scheme is in use, which is also a common case for highly demanding industrial consumers. The algorithm firstly takes measurement of the current state of charge of the battery and checks if it is within the accepted operational range which was set between 10% and 90%. Then, when the battery SOC is within this range, the battery is considered as a possible source or load depending on the irradiance level and the peak shave limit. The peak shave limit is set as the 90% of each day's maximum load and this value is also set as a limiter value for the power imported from the grid. Therefore, if the load at the sport centre microgrid is less than the specified shave limit value, any combination of grid import, battery power and PV power is possible but if the load is greater it should be covered from the BESS and the PV installation exclusively. Considering that the peak pattern does not always coincide with the maximum PV power production, the BESS should be able to discharge enough power to have a maximum penetration during the peak load time period. Thus, the BESS should charge only when the load is below the peak shave limit and the SOC below 90%. In this way, right before the peak load period the BESS was at maximum possible SOC and ready to provide energy

during the peak time period. In case the battery is full and the load is relatively low, or the battery is empty and the load is relatively high, the battery would be disconnected and set on idling mode, until the reverse conditions appeared. The charging procedure of the BESS was decided to be during the night hours (namely when the irradiation is below 50 W/m<sup>2</sup>) in order to avoid sudden impulse of grid power import that may exceed the shave limit value. This function is based on the fact that by visual pre-processing of the load and daylight curves, the load values at the night hours were found to be relatively low compared to daylight time period. Consequently, for the peak shaving management system developed, the BESS is charged from grid power.



**Figure 14. Peak shaving strategy flowchart.**

The second energy management algorithm developed and implemented in the APROS dynamic simulation is based on the provided electricity pricing signal (Figure 15). This pricing-based scenario is also in accordance with Aguasol's indications based on the Spanish market and is focused on the economic dispatching of the storage system. The purpose of this strategy is to control the charging and discharging of the BESS according to the mean value of the daily cost of electricity. Thus, the battery charges when the electricity price value is below the daily mean value in order to take advantage of the low cost and discharges when the price is above the daily mean value and a possible grid power usage is rather expensive. The algorithm is once more initiated with the state of charge measurement. In case that this is within the acceptable range (10-90%) then the pricing signal is checked and if this is lower than the calculated mean value then the battery charges. In the other case the battery discharges power.



**Figure 15. Pricing based strategy flowchart**

For the Nicosia pilot a third EMS algorithm was developed. Its main operational principle is based on the DC link voltage level which varies according to the dynamic energy equilibrium between the campus microgrid and the main grid. Therefore, when the total energy produced in the microgrid is greater than the current consumption, the voltage level increases and this would mean that the surplus energy should be either stored in the BESS if it is possible, or be exported to the main grid. Otherwise, the current consumption should be balanced from the main grid, meaning that the system could not be relied on its own production.

For model validation, APROS models are multicomponent systems and, as such, this involves individual validation of each of the system components. Validation of the system components is performed based on the technical specifications as detailed in the respective datasheets. For instance, at the inteGRIDy Barcelona pilot project, the thermal ratings (condensing/evaporating power and compressing power) were used as the main validation criteria of the heat pump as depicted in Table 3.

**Table 3. Validation of APROS heat pump model against manufacturer (mf) data for four different ambient temperatures.**

	$Q_{\text{cond}}$ [kW]	$Q_{\text{evap}}$ [kW]	$W_{\text{comp}}$ [kW]
$T_{\text{amb}}$	mf	APROS	Dev. [%]
5	232.6	229.47	1.346
7	244.7	244.49	0.086
10	262.9	262.05	0.323
15	299.2	299.3	-0.033

Regarding the solar PV model employed in APROS software, validation results can be found in [RUU07], and detailed description and further information for various APROS modules can be found in [ALO17].

### Technical specifications and advances from the existing tools

APROS can be executed in multiple time-step sizes, adjustable to the user requirements, including hourly-based time steps. Time framework of the scenarios can extend to time periods of representative weeks within the year, which enables the model to fully characterize the



performance of the energy systems and their dependency upon multiple variables such as weather changes, load fluctuations and time of use.

In terms of I/O data, input data include time-series representing the boundary conditions (e.g. weather time-series), thermal load and user profiles that are imported as \*.txt/CSV files. In addition, the technical specification of the system equipment is an input of the APROS model. The output time series of the simulations can be exported in various formats such as CSV or \*.xls and be used directly by other tools.

Regarding APROS' dependencies, in order to perform the multi-system energy modelling, the developed APROS model requires 24 hours weather data that can be retrieved from an external source, e.g. [SAH14]. In addition, thermal load profile of the facility and technical specifications of the system components need to be sourced to APROS model. Data exchange is done through the APROS communication library interface accepting standard files types such as \*.txt and \*.xls.

APROS is coded in the Haskell dialect Simantics Constraint Language, and can be coupled with other simulation tools such as ANSYS, Abaqus, MATLAB/MATLAB Simulink through available an OPC UA interface. APROS is executed in Windows operation system (*Windows 7, Windows 8, Windows 10*), and does only need a computer with internet connection to be run.

Regarding the progress made in the tool development within inteGRIDy, in addition to the usage of default components of APROS libraries, new house-built modules have been developed and integrated into the pilot models by CERTH/CPERI. These modules concern the heat-pump, the microgrid – main grid interface and three versions of EMS algorithms and their implementation was based on the appropriate modification - and combination of default APROS components. A detailed analysis of these APROS house-built components is performed in the revised D4.3 Deliverable.

### **Expected advantages compared to commercial products**

The advantages of APROS compared to available tools are depicted in revised D4.3.

### **Implementation features and delivery**

APROS is employed in both Barcelona and Nicosia inteGRIDy pilot projects.

In the Barcelona pilot project, APROS is used to model dynamically a heat pump used to heat up the common spaces and swimming pool of a sport centre. This heat pump is modelled within a grid-connected microgrid that also includes a BESS system and a solar PV plant. APROS analyses a number of scenarios based on peak shaving or pricing strategies.

In the Nicosia pilot project, APROS is used to model the microgrid of the University of Cyprus' campus based on a large-scale BESS-PV installation system, in order to assess the degree of self-sufficiency for a renewable based operation. The results from the associated dynamic simulations in APROS are also used as input in the assessment of the economic impact of the BESS-PV system on the cost of electricity, based on the existing pricing scheme.

In terms of architecture, APROS is a closed code software with dedicated modules architecture for external code implementation in DLL format. The source code of APROS is stored in the file system of the computer in which the software is installed. However, as APROS is a proprietary software no source code retrieval is possible. The development and utilization of external models does not require the delivery of any source code add-ons by the APROS developers.

APROS provides libraries with components to model actual devices and mechanisms:





- The power plant library includes modules such as heat exchanger, turbine, compressor, shaft etc.
- The electrical library includes modules such as PV panel, irradiation module, Proportional–Integral–Derivative controller, DC/AC (Alternating Current) & AC/DC inverters, bus, line, switch, connector etc.

The hierarchy followed by the software is divided in three levels for the model development: diagrams, process component and calculation nodes. Diagrams are subsystems of the model, each diagram includes a number of process modules and their connections and each module consists of a number of nodes in which all the necessary equations are solved in calculation level.

Containerization of the tool in Docker is restricted as APROS requires a graphical interface, and thus the installation of the APROS software is needed. Execution of the software in virtual machines is limited by the license type of each end-user. A demo of APROS can be downloaded from VTT [VTT18].

The source code is available only upon request. Please contact:

Nikos Nikolopoulos: [n.nikolopoulos@certh.gr](mailto:n.nikolopoulos@certh.gr)

Konstantinos Atsonios: [atsonios@certh.gr](mailto:atsonios@certh.gr)

### 4.2.3 SimaPro

#### General description of the inteGRIDy functionalities

SimaPro is a tool to collect, analyse and monitor the sustainability performance data of products and services based on ISO 14044. The software can be used for a variety of applications, such as sustainability reporting, carbon and water foot printing, product design, generating environmental product declarations and determining key performance indicators. In SimaPro the user can easily model and analyse complex life cycles in a systematic and transparent way, measure the environmental impact of your products and services across all life cycle stages, identify the hotspots in every link of your supply chain, from extraction of raw materials to manufacturing, distribution, use, and disposal [PRE18].

SimaPro presents a functionality where the user can modify and adjust in-house code models. These capabilities allow SimaPro to estimate the overall environmental footprint of virtually any system component and/or processes across all life cycle stages, and identify the hotspots in every link of the supply chain, from extraction of raw materials to manufacturing, distribution, use, and disposal. The external costs would be estimated based on the environmental indicators exported by Life Cycle Analysis (LCA). Hence all the costs involved in a product or service will be performed through Life Cycle Cost (LCC) modelling.

Two pillars of the project are addressed indirectly, through the use of SimaPro:

- **Energy Storage:** This pillar is addressed through SimaPro, since the environmental impact of the battery is estimated and linked to the cost estimation (through the use of LCC).
- **Smartening the Grid.** Batteries and their associated environmental benefits contribute significantly in RES penetration and smartening of the electricity grids.

#### Details of the modelling process

This section provides a description of the procedure used by SimaPro to perform an LCA of a solar PV and battery integrated system installed in a building. SimaPro requires the following technical data of the energy system:

- DC solar PV capacity.
- Degradation rate of solar PV modules.
- Electricity generation by solar PV system in life time.
- Storage and Inverter capacity.
- Round trip efficiency and Degradation of BESS.
- Building electricity consumption.
- Infrastructure and system assembly long-term emissions are not considered.

SimaPro calculates the global warming potential (GWP) of associated emissions to the solar PV and battery integrated system using as a reference the global warming impact of carbon dioxide (CO<sub>2</sub>) (units of kg CO<sub>2eq</sub>). SimaPro computes the GWP as follows:

$$GWP(x) = \frac{\int_0^{TH} ax \times [x(t)]dt}{\int_0^{TH} ar \times [r(t)]dt} \quad (38)$$

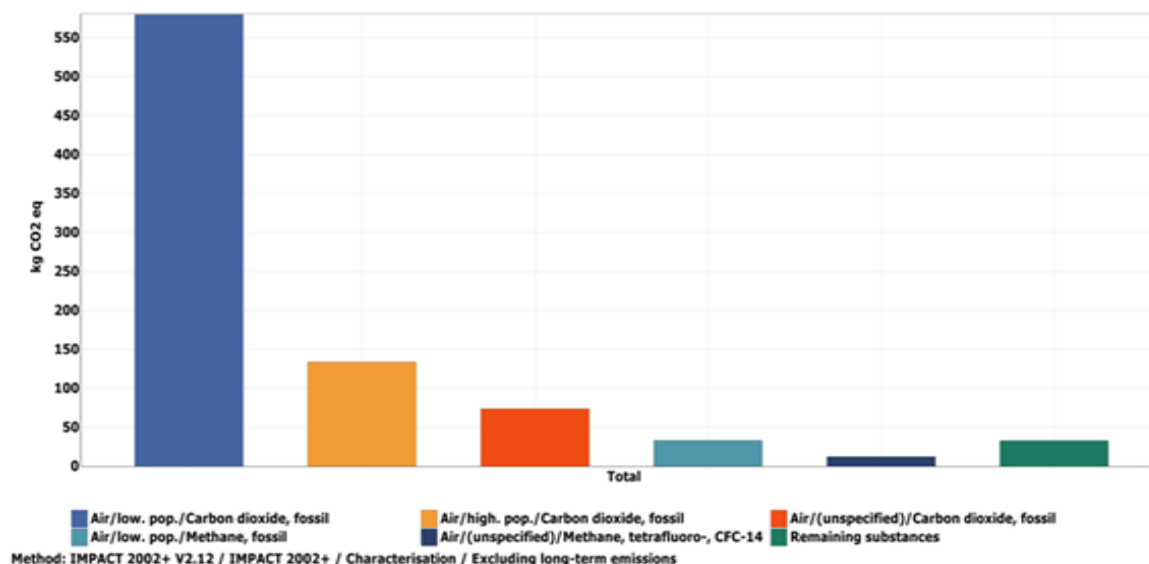
where  $TH$  is the time period considered in the computation of the GWP, e.g. 20, 100 or 500 years;  $ax$  is the radiative efficiency due to the increase of a unit in the atmospheric abundance of the substance ( $Wm^{-2}kg^{-1}$ );  $x(t)$  is the time dependent decay in abundance of the substance, assuming an instantaneous release at time  $t = 0$ ;  $ar$  is the CO<sub>2</sub> radiative efficiency; and  $r(t)$  is the time dependent function of pulses of the injected CO<sub>2</sub>.

The equivalent life cycle CO<sub>2</sub> emissions of the PV + battery system is computed by SimaPro as follows:

$$LCCE = \sum_{i=1}^{T_0} \text{Direct emissions } (i) + \sum_{i=1}^{T_1} \text{Indirect emissions } (i) \quad (39)$$

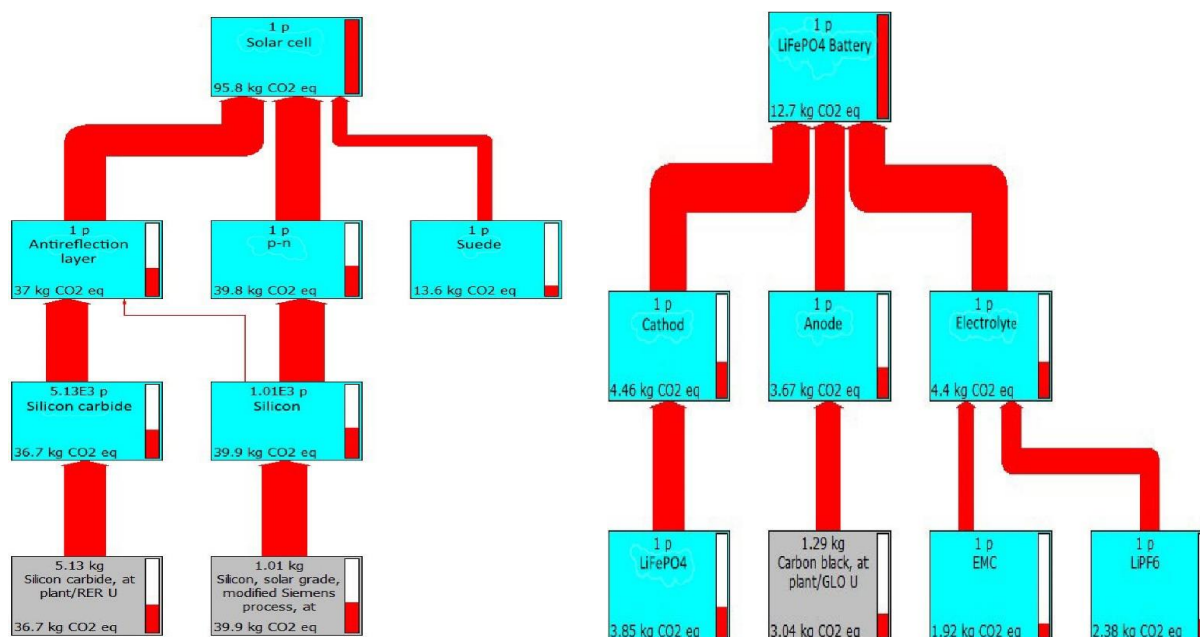
where direct CO<sub>2</sub> emissions (kg CO<sub>2eq</sub>) correspond to those emitted during the operational phase;  $T_0$  is the timespan of the operational phase; indirect emissions (kg CO<sub>2eq</sub>) include pre and post-operation emissions such as those associated to the production and transportation of raw material, component assembly energy consumption, etc.; and  $T_1$  is the timespan of the pre and post-operational phases.

For the calculation of the LCA, the system boundaries determine the processes to be included in the LCA study. SimaPro can plot the computed life cycle emissions for the analysed solar and battery system (Figure 16). CO<sub>2</sub> was chosen by the Intergovernmental Panel on Climate Change (IPCC), as the reference unit for greenhouse emissions, because it is the most emitted substance from human activities. Hence, the reference unit upon which all emissions corresponding to the global warming potential impact are performed, is the CO<sub>2eq</sub>. CO<sub>2eq</sub> signifies the amount of CO<sub>2</sub> emitted, which would result in an equivalent global warming impact, as of the origin



**Figure 16. Total life cycle emissions associated to the analysed solar PV and battery integrated system.**

Figure 17 depicts the carbon footprint analysis of the solar PV and lithium iron phosphate battery integrated system as provided by SimaPro. The analysis of a solar PV module breaks down the carbon emissions into those associated to cell's raw materials, antireflection layer, p- n and suede of solar cell, silicon carbide and silicon. For the electric battery, associated carbon emissions to raw materials, cathode, anode and electrolyte are listed.



**Figure 17. SimaPro's breakdown of equivalent CO<sub>2</sub> emissions for the different components of solar PV module (left) and lithium iron phosphate battery (right) integrated system.**

Regarding model calibration and validation, due to the methodology employed in SimaPro to calculate the LCA based on already existing well established databases, the concept of calibration and validation is not applicable in this case.

### Technical specifications and advances from the existing tools

The time horizon of the inventory is selected according to the purpose of the case study. The lifetime period of the product/process is considered the critical point for this selection.

The tool can compute the environmental impact and carbon footprint for a system or process on daily, monthly or annually timescale.

The selection of the appropriate LCA impact methodology depends on the following criteria: a) the type of emissions that need to be estimated (for example Green House Gas emissions, Particulate emissions) b) the performance of the system after being normalized on the basis of different profiles (for example characterisation, weighting, damage assessment), c) the time horizon for which the impact is estimated (e.g. 20, 100 years), and d) the calculation method (e.g. single or multitasking impact method). For the latter, there is a plethora of calculation methodologies per impact category. The methodologies are distinguished as either a) single issue ones that focus on the estimation of one impact category (e.g. the global warming potential impact) or b) the typical European methods that evaluate more than one impact categories by taking into consideration the most appropriate weighting factors.

SimaPro uses two types of data, namely:

1. Primary data are specific data needed to model a system (e.g. capacities, efficiencies) that can be derived from technical specifications given by the demo site operators or the foreseen measurements (e.g. energy consumptions) during demo activities
2. Secondary data, these refers to the production of generic materials, energy, transport and waste management. No actual measurements exist in the field. Such data can be tracked

from both SimaPro Ecoinvent database [WER16], covering over 10,000 processes, as well as from literature, e.g. [PET17] and [GER14].

Furthermore, SimaPro allows the user to code their own models.

SimaPro is a stand-alone program and does not require from the input of other software to calculate LCA. SimaPro can be linked to other software via a two-way component object model interface. This enables the use of LCA results in other tools or to receive additional data to perform the LCA. Compatible software with SimaPro include CAD, Computer-Aided Manufacturing, Enterprise Resource Planning and Product Lifecycle Management systems.

SimaPro is executed in a Windows operation system. All software that can use COM interface are supported, this includes for example: Excel, Word (Visual Basic for Applications (VBA)), Delphi, C++, Visual Basic, PHP, Visual studio (C#, VB.NET).

SimaPro is supported only by operating system Windows 7 or later versions, and does not require any hardware device.

In inteGRIDy project, new in house-built modules are developed for each component. According to the selected scenarios of each pilot, the integrated modules are investigated in life cycle analysis terms (work to be performed in Task 8.4). Specifically, the beyond of state-of-the-art work corresponds to the monitoring of the environmental impact under different configuration conditions. Assembly scenarios for each case will be investigated by taking into consideration the energy demands of the investigated pilots (Barcelona and Cyprus) resulting to dynamic impact assessment instead of the static studies found in the literature. Hence the saving emissions from the operation of the proposed systems will be estimated (not only the impact by the manufacturing stage that is usually found in other published works). For this reason, the functionalities, presented above, will be adapted in the examined scenarios using the technical specifications of the components, as well as the profile of the pilot in terms of energy characteristics (energy mix, consumptions). Similar estimations will be carried out by using LCC methodology focusing in the three aforementioned main stages: manufacturing (investment costs), operational (production cost of energy and maintenance) and end-of-life (disposal costs). In addition, the externalities will be estimated corresponding mainly to the environmental costs. The estimation will be based on LCA considerations.

### **Expected advantages compared to commercial products**

A detailed literature review about existing works in LCA of energy systems has been conducted in the D3.1 [NIK17].

For each component, three different phases are taken into consideration: manufacturing, operational and end-of-life

**Battery:** The main objective of the existing work is the investigation of different types of batteries (Li-ion, Vanadium, Lead Acid, Sodium-nickel, Nickel-cadmium, Sodium-sulphur) using an LCA methodology approach to estimate the GHG emissions. The manufacturing stage correspond to the main components of the battery, such as the battery case, cells, etc. The operational stage is directly linked with the battery key parameters, such as total cycle during the useful life, daily charge/discharge cycles, capacity, useful life, charge time, stand by periods, working periods, depth of discharge, round trip efficiency etc, while the end-of-life stage is linked with the use of recyclable materials.

**PV:** Regarding the construction of the component, the data could be taken either from literature or technical specifications. The main components of a PV system are the a) PV modules, b) aluminium (used for casing), c) the concrete, d) the inverters, and e) the interconnected control panels. The energy consumption for manufacturing of solar PV modules varies between 11 - 45 MWh th/kWp. The variations can be attributed to technological assumptions and system



boundaries [BEC14]. It should be mentioned that data regarding the construction of PV (aluminium production, concrete production, energy consumptions etc) are given in the study [GAR09]. During the operational phase, there is no external source of energy supply. During the de-commissioning phase, it is assumed that the solar PV module would be landfilled after removing the aluminium frames. The recovered aluminium corresponds to its use as a construction material. In general, the end-of life phase includes the treatment of waste from the plant components

Heat pump: The majority of the work refer to the conduction of a life cycle analysis study for the comparison of heat pumps with the industrial boilers. The functional unit used correspond mainly to 1 kWh of thermal energy

In Table 4, a review of commercial LCA tools is provided. For each commercial tool, the key benefits and the weaknesses are presented. SimaPro is the world's leading life cycle assessment (LCA) software. SimaPro contains the latest in science-based methods and databases. A wide variety of add-ons and reporting features make it easy to be fully conscious of the LCA studies. Through SimaPro, it is possible to model the modules of PV, heat pump, batteries and grid required for the two pilots to be investigated in life cycle analysis terms. Specifically, the technical specifications of the investigated components will be incorporated in house-built modules, while secondary data provided by the databases of SimaPro will cover the gaps performed in the LCA estimations (mainly those corresponding to the manufacturing stage, which is generally not provided by the demo operators).

**Table 4. Advantages and disadvantages of LCA commercial tools.**

Software name	Main features (Advantages (Adv) and Disadvantages (Dis))
SimaPro	Adv: Modelling of a product or system from a life cycle perspective, Variety of LCI databases, such as Ecoinvent 3.0, ISO compliant, impact assessment methodologies to be applied according to the needs of the investigated scenario, compatibility with CAD, Computer-Aided Manufacturing, Enterprise Resource Planning and Product Lifecycle Management systems, modify and adjust in-house code models user-built components and scripts can be used, drag and drop flow sheet building, robust and powerful solver, easy and user-friendly debugging. Dis: no optimization tool, difficulties in modifying all the data in the tree process according to the needs of the scenario
Gabi	Modelling every element of a product or system from a life cycle perspective, easily accessible and constantly refreshed content database that details the costs, energy and environmental impact of sourcing and refining every raw material or processed component of a manufactured item. presentation alternative options for manufacturing, distribution, recyclability, pollution and sustainability, user-friendly debugging, robust solver, Dis: Limited databases, difficulties in modifying all the data in the tree process according to the needs of the scenario
OpenLCA	Adv:OpenLCA runs properly on Linux and macOS, an experimental flow mapping tool is included. With its help, it is possible to create flow mappings for imports and replacements of flows in a database, Data quality systems, Automatic and graphical modelling, contribution tree, parameters, developer tools (eg python) to write an open code for the LCA estimation, three allocation methods: physical, economic and causal. Dis: Limited number of databases and implementation methods.
One Click LCA	Compliant with more than 20 other Green Building certifications, including LEED, DGNB, and Energie Carbone. Friendly user interface, BIM automation, speed calculations. Dis: Limited capabilities, limited secondary data, focusing mainly on buildings
Air.e HdC	Calculation and assessing GHG emissions of organizations, products, services, events, and projects using a life cycle approach. Air.e HdC has been developed to follow international standards such as ISO 14040, PAS 2050, GHG Protocol, ISO 14064, ISO 14064 and ISO 14069. Dis: Limited data, limited capabilities for in house-built components, limited impact assessment methodologies



## Implementation features and delivery

In the inteGRIDy project, SimaPro is used in the pilot projects of Barcelona and Nicosia.

In the Barcelona pilot project, SimaPro is employed to perform LCA of the swimming pool heating system and the microgrid containing a BESS and a solar PV plant. More specific two scenarios were defined for the case of Barcelona demo.

The first scenario refers to the integration of the 25 kilowatt peak (kWp) PV power with the grid supply in order to charge the battery when the price of the energy is lower than the daily average electricity price. This scenario will be implemented in SimaPro simulation platform in order to assess the system operation under different pricing profiles. For such a study to be accomplished in SimaPro, the expected outputs are

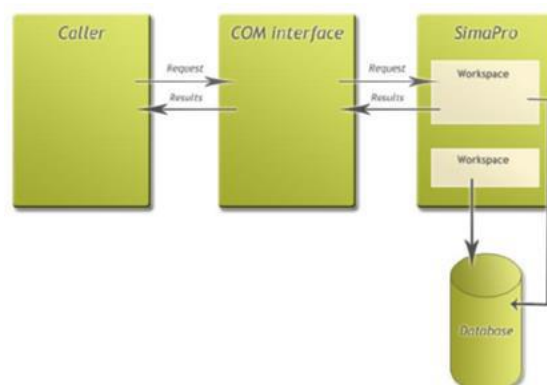
- CO<sub>2</sub> equivalent payback time for the components of PV and battery
- CO<sub>2eq</sub> saving emissions: (Direct emissions corresponding to the operational phase and Life Cycle emissions corresponding to manufacture, operational and disposal phase)

The replacement of oil boilers with heats pumps will be also taken into consideration in LCA modelling. Hence, the overall environmental footprint will be estimated, including the operation of PV and battery, as well as the operation of heat pumps.

The second scenario concerns the use of the battery system for peak shaving the maximum demand values of each day. Towards to this direction, the battery should charge during the off-peak hours in order to cover the peak demand appeared later during the day. This can also have a beneficial effect on the cost of electricity, as long as the demand charge of the system is lower, considering that the maximum demand of the system will be covered by the battery and not by the grid. From the simulation in SimaPro, the environmental profit from the achieved target of peak shaving through integration of PV and battery system will be reported

In Nicosia demo site, SimaPro is used to perform LCA of an integrated system of PV and BESS in large scale. The scale up will be based on data provided by the nanogrid and microgrid systems. The specifications of the scale up system are the following: PV: 10 MW peak and battery: 7.5 MWh. The main indicator to be investigated is the CO<sub>2</sub> equivalent payback time for the components of PV and BESS.

The workspace contains the used database, project and results from the last calculation as depicted in Figure 18. The source code of SimaPro is stored in the file system of the computer in which the software is installed. However, since SimaPro is a commercial software no source code retrieval is possible. The development and utilization of external models does not require the delivery of any source code add-ons by the SimaPro developers.



**Figure 18. Operating architecture of SimaPro and links with database and component object model interface.**



Containerization in Docker of the tool may not be possible as SimaPro requires a license and a graphical interface running in the background.

For the scope of inteGRIDy, new house-built modules have been developed and integrated into the investigated models by CERTH/CPERI. The modules mainly concern PV, heat pump, battery and the connection to the grid.

The tool presents a step-by-step guide that includes multiple screenshots to help users understanding the tool. In addition, users can download a 30-days free access to the web tool [SIM19].

For more information about the SimaPro code, please contact:

Dimitrios Kourkoumpas: [kourkoumpas@certh.gr](mailto:kourkoumpas@certh.gr)

#### 4.2.4 Energy Integrated Information System

##### General description of the inteGRIDy functionalities

The Energy Integrated Information System (EIIIS) tool is presented from the perspective of inteGRIDy Modelling Mechanisms. The EIIIS tool is a new software system, built from scratch for the purpose of inteGRIDy project, addressing the inteGRIDy project pillar Demand Response.

The general objectives considered when developing the tool were:

- Integrate innovative smart grid technologies, enabling optimal and dynamic operation of the distribution system's assets within high grid reliability and stability standards
- Validate innovative Demand Response technologies and relevant business models
- Provide modelling & profiling extraction for network topology representation, innovative DR mechanisms facilitating decision making in DG's operations
- Provide predictive, forecasting tools & scenario-based simulation, facilitating an innovative Operation Analysis Framework

The EIIIS tool will impact on:

- Operations by reconfigurable topology control & supervision
- Market by providing new services
- Customer by enhanced engagement through DR mechanisms
- Transmission by novel forecasting scenarios for the MV/LV areas

The Energy Integrated Information System tool includes the following features:

- Uses smart meters with DR functionality to collect electricity consumption data in residential buildings
- Assesses the power demand and monitors the consumption
- Determines the tendencies and prognosis of the consumption
- Automatic control of power demand based on the implementation of smart DR algorithms
- Optimizes the consumer bill based on the prognosis of consumption and the applied rates
- Optimizes the performance of electrical infrastructure
- Displays and provides access to consumption data and monetary savings
- Reduces the consumption and peak load through implementation of DR algorithms
- Provides system alerts, notifications for the optimization of energy consumption and costs

The sequence diagrams for the aforementioned functionalities are described below:

##### Details of the modelling process

Concerning inteGRIDy Task 4.2, the EIIIS features the determination of the tendencies and prognosis of the consumption profile and related statistics required for an effective energy management and control system.

##### *Basic approach*

The whole system and its modelling mechanism is Machine Learning System. This system can be categorized as:

- Supervised Learning system
- Model-based learning, using a Linear Regression Algorithm based on spline curves

- Able to learn batch volumes of data and also online data incrementally

The system is used to:

- detect peak values
- propose optimized behaviour and forecasting
- run what-if scenarios.

Accordingly, a Supervised Learning system is selected, using a Linear Regression Algorithm, able to learn batch volumes of data and also incrementally. Considering that the system should detect patterns, and based on the data available it was decided to use a model-based learning. The model chosen is a polynomial model for short time intervals, and splines based on cube polynomials (natural cubic splines) for longer time intervals.

The polynomials used are cubic of the form:

$$P(x) = \sum_{i=0}^3 a_i * x^i \quad (40)$$

The polynomial for a specific time interval, considered between two peaks is:

$$P_i(x) = \sum_{k=0}^3 a_k * (x - x_i)^k \quad (41)$$

where  $i$  is the number of peak ( $>1$ )

The border of splines is defined by the peak detected values. In those peak detected values, conditions for function equality are used together with first and second derivate equality. The  $x$  coordinate is the time stamp of the peak, and the  $y$  ( $P(x)$ ) coordinate is the peak value of registered data.

The Machine Learning System, using regression is used to reach the following objectives:

- Detect the peak time intervals and the peak values
- Optimize the power consumption and give advises for DSO and consumers
- Prepare optimizations for DR system
- Make forecasts with or without disturbances
- Run what-if scenario

Considering the results of data analysis, the system is targeted for the following data domains:

- Data registered in a day cumulated at hour level
- Data registered in a week cumulated at day level
- Data registered in a month cumulated at day level
- Data registered in a year cumulated at month level

The data considered is divided in:

- Data for consumers
- Data for DSO

All the algorithms discussed in this document are applied to the four domains presented, separately for DSO and consumers.

#### *Optimization method*

An optimization algorithm based on peak values is proposed. The goal is to maintain the consumption level without affecting the comfort level of the consumer while decreasing the consumption during peak times and increasing it in periods with low consumption. To

implement this, a Gradient Descent optimization algorithm with a cost function based on mean square error (MSE) is used.

The correlation between elements of multidimensional values is very low, and computations are made based on “Distance correlation”.

As an example, the correlation between active power and down time is low (near 0). For this reason, instead on working with one time series and multidimensional ( $n$  dimensional) values, we are treating separately  $n$  time series with one dimensional data.

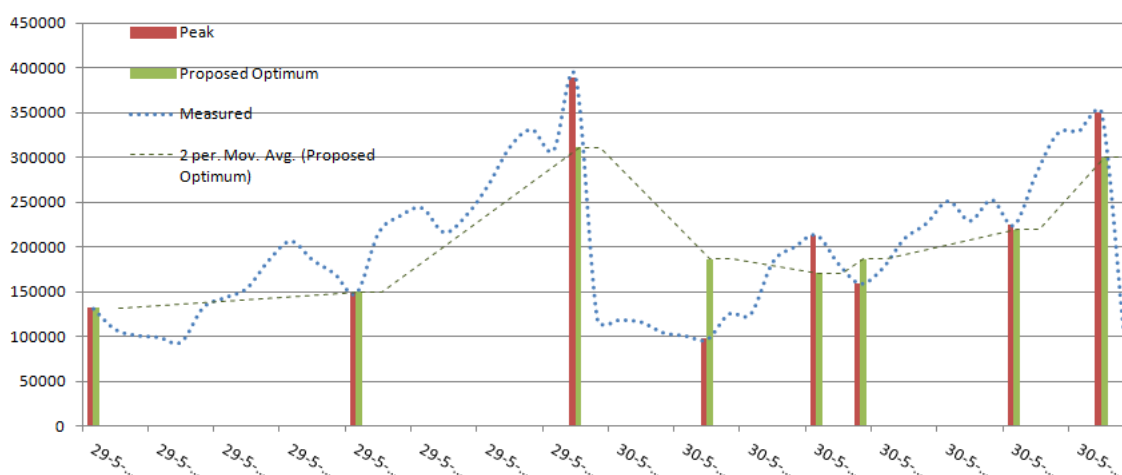
The model used and presented earlier considers no disturbances in the system. Disturbances will be included in the forecasting and what-if scenarios, and will be in the form date-time, duration, Sign (+ or -), percent. Disturbances will cover: Weather conditions, National Holidays, Special holidays and Special conditions.

Two types of peak values are considered:

- Positive peak – a value where there is a change in the time series gradient from positive to negative. The peak is considered only if before the change of gradient from positive to negative there were at least  $n$  positive gradients and  $n$  negative gradients ( $n > 1$ , usually  $n=4$ )
- Negative peak – a value where there is a change in the time series gradient from negative to positive. The peak is considered only if before the change of gradient from negative to positive there were at least  $n$  negative gradients and  $n$  positive gradients ( $n > 1$ , usually  $n=4$ )

Figure 19 presents an example of peak values ( $n=2$ ). The principles of optimizations used in by the system are:

- The positive peaks are decreased with a value dependant on the gradient before and after the peak
- The negative peaks are increased with a value dependant on the gradient before and after the peak
- The sum of the values for the data domain selected remain the same



**Figure 19. Optimized raw time series.**

Peak detection is performed on all data stored from smart meters. That means that peaks are detected inside dedicated time intervals (e.g. Inside a day it is identified at what hours there are peaks).

Detection of peak is based on two elements: a) Maximum or minimum values registered; and b) gradient of consumption changes in a period of time. It is possible, from setup, to tune the number of peaks considered.

### Technical specifications and advances from the existing tools

The time horizon used in the EIIS can be any time window within a day, i.e. between the 00.00 and the 23.59 of every day of operation. The operator can set the analysis time horizon and time stamps. The user can select time steps between 10 min, 15 min, 30 min and 1 h.

In terms of I/O data, EIIS uses sets of data of power consumption and corresponding time stamp, which are structured in vectors, arrays, and lists. The most common format employed for data exchange is the Json one, and data are stored in a central RDBMS (MySQL). The system is using JPA and access to data is only via application user interface or RS services. The output data, which are stored in RDBMS tables, are used in the Energy Integrated Information System forecasting and optimization tools.

Furthermore, the tool does not present any dependency on other tools. However, as the tool relies on the volume of data collected, Energy Integrated Information System needs to interact through open communication protocols with Meter Data Management systems for data transfer.

EIIS includes several development languages:

- JRE 8 as run time
- Java 8 as programming language
- JEE 7 as main system architecture
- RS web services
- JSON and XML for data plotting
- Glassfish 4.1.2 web server
- Primefaces JSF
- MySQL database
- OpenADR 2.0 protocol

The tool is supported in Windows 7, Windows 10, Linux Ubuntu and Linux RedHat.

The Intelligent Energy Demand and Supply Matching tool connects directly with Smart Meters.

Regarding the development of the tool through the inteGRIDy project, EIIS is a solution developed from scratch for the Ploiesti Pilot, offering a good opportunity not only for implementing an innovative DR technical solution in the energy domain, but also the opportunity to implement and validate domain specific smart algorithms and intelligent domain specific business models.

EIIS provides specific features to determine the tendencies and prognosis of the consumption profile and related statistics required for an effective energy management and control system. Furthermore, EIIS is the only tool able to actively learn from experience and apply latest AI (Artificial Intelligence) principles for data processing. It also offers rich sets of API, which expose data to other application, in an integrated environment. The innovative tool was tested in the environment of Ploiesti Pilot, but has no restrictions on any other DSO which can use it. For instance, a DSO can use EIIS by defining the following parameters:

- DSO general parameters (name, Location, IP address, etc)
- Locations (name, address, id)
- Smart Meters (id, type, values measured, etc).



In addition, EIS is horizontally scalable, as new locations and new Smart Meters can be added at any moment.

Considering that the actual status of the pilot implementation is providing the size, complexity and TRL described in the proposal, the major goal for the next period is to improve the performance of the EIS system and enlarge its usage (size) to more Smart Meters and use more historical data for the machine learning system, and consequently improve the forecasting and What-If scenarios modules.

### **Expected advantages compared to commercial products**

EIS is a solution developed from scratch, offering a good opportunity not only to implement an innovative DR technical solution in the energy domain, but also the opportunity to implement and validate domain specific smart algorithms and intelligent domain specific business models.

The solution enables the following functionalities: smart metering (smart grid infrastructure), modelling (based on smart DR algorithms, simulation models, forecasting), optimization of energy consumption, monitoring and control, alerts and notifications.

The solution provides dedicated graphical interfaces, accessible and intuitive, for both end-users – DSOs and consumers.

EIS provides the majority of functionalities specific to the energy management software solutions (EMS), namely:

- Collecting energy measurement data from the field and making it available to users through graphics, diagrams and dashboards
- Providing online monitoring tools
- Enabling the management of energy consumption and resources.

From the comparative analysis of EIS with similar EMS solutions presented in the literature and with similar commercial solutions existing on the market, resulted that the EIS does not only cover the specific functionalities to ensure energy quality analysers.

EIS covers all other functionalities proper to EMS as shown below:

- Data collection and storage from a large number of devices able to implement MQTT communication protocol
- Data modelling (automated DR profiles)
- Peak identification
- Optimization considering peak values and costs
- Forecasting
- What-if scenarios.

The analysis of available tools in the market providing similar solutions has revealed the following results:

*Energy Manager Software by Dude Solutions (<https://www.dudesolutions.com/>)*

Energy Manager Software is a cloud-based solution that supports conservation and cost savings by utilizing data on current utility spend to relieve savings opportunities by identifying possible billing errors, low performing buildings and raising stakeholder awareness.

The solution allows the creation of a large number of reports for compliance & show the progress of the energy consumption efforts. Specific savings tools are provided to create increased community participation and reduce usage.

*JadeTrack Software by JadeTrack (<https://www.jadetrack.com>)*

JadeTrack is a cloud-based energy management software that delivers real-time insights, data automation and savings opportunities. The platform provides specific functionalities as follows: automated utility bill management, ENERGY STAR benchmarking for facilities, up to 1-minute real-time monitoring and sustainability reporting.

Whether is about one building or across an entire enterprise, the JadeTrack solution streamlines the utility (energy, water, waste, emissions, ...) data collection process.

*Wattics Software by Wattics (<https://www.wattics.com/>)*

Wattics is a cloud-based facilities management solution appropriate for small to midsize businesses in a variety of industries. Wattics provides specific features including trend analytics, energy monitoring, measurement and verification (M&V), cost allocation analysis, wastage analysis and projected savings.

Wattics offers the possibility to users to manage activities such as saving projects, user behaviors, performance contracts and energy conservation. The solution offers integration with various meters, sensors and data systems. Wattics entitles users to analyze and compare energy consumption and associated costs to identify areas where conservation can be improved. The solution can automatically send notifications when cost or consumption deviates from expected patterns.

*MACH Energy Software by Mach Energy (<https://www.machenergy.com/>)*

MACH Energy Software is a modern energy management software for commercial buildings of all sizes.

The solution is cloud-based (subscription) and accessible online and via mobile devices, including native iOS/Android apps.

MACH Energy Software offers facilities to save money or reduce risk including demand response (DR), energy procurement and air quality monitoring. The software also includes an Initiative feature, which automatically identifies and quantifies savings opportunities. The solution provides specific functionalities to save time include tenant billing software, energy budget forecasting, variance reporting, building and portfolio reporting, including greenhouse gases/carbon footprint, automated energy accruals etc.

The four similar solutions presented above have been analysed and compared against EIIS, concluding that these do not have the innovative modelling capabilities offered by EIIS to ensure optimization, forecasting and what-if scenarios.

EIIS provides specific features to determine the tendencies and prognosis of the consumption profile and related statistics required for an effective energy management and control system.

Moreover, as competitive advantages, distinctive features of consumption prognosis were implemented:

- What-If scenarios using perturbations like: weather forecast, banking holidays, extreme weather, unplanned un-working days
- What-If scenario based on different cost prices.

The EIIS solution was extended with an innovative data collector component (EIIS Data Exchange Tool as presented in deliverable D4.1, Section 4.9 Ploiesti) able to connect to a big number of devices and sensors, and fully covering the functionality of DC (Data Concentrator).

The solution EIIS implemented in Ploiesti Pilot ensures all levels of “smartening the grid”:

- Smart measuring
- DR Modelling (smart algorithms, simulations, forecasting)
- Optimization

- Monitoring / Tracking and control
- Alerts and notifications.

In the following are presented the currently achieved and expected progress beyond state of the art for Ploiesti Pilot, according to the DoA:

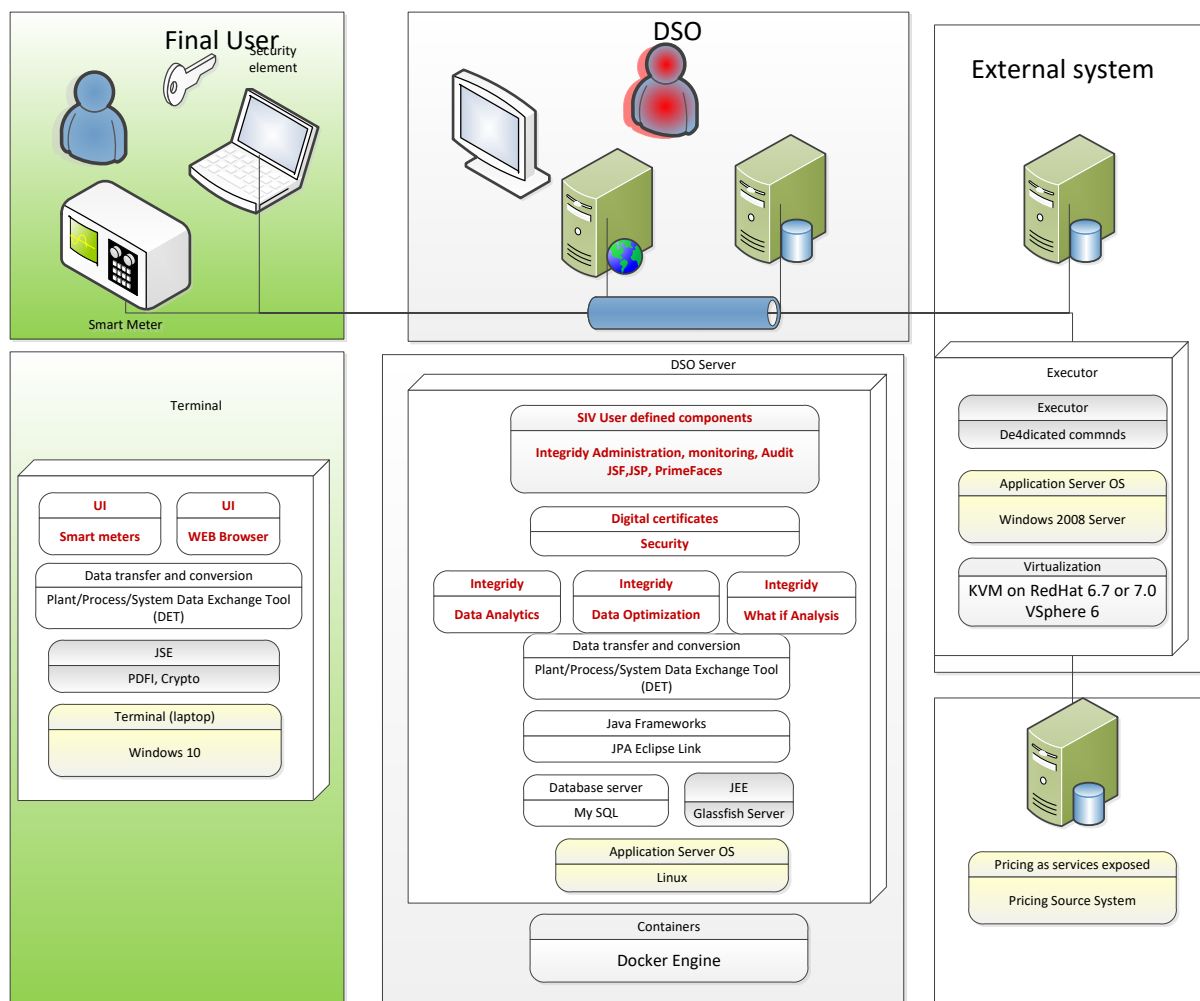
- Cross Domain Big Data Analytics for improving decision making of system operators.
  - Big data implemented with RDBMS (Relational Data Base Management Systems)
  - DR activities for reducing consumers' energy bills, implemented within EIS
  - Power Flow Monitoring & Forecasting Suites through Visual and Data Analytics Services.
- Adaptive Energy Management Strategies relying on Optimal Forecasting.
  - Providing statistical forecasting algorithms with additional physical asset modelling approaches (What-If scenarios using perturbations).
- Intelligent Predictive Supervisory Control & Automation.
  - Up-to-date forecasts for optimum scheduling (day/ week/ monthly basis)
  - Powerful communication for real-time optimization
- DR Optimization & Flexibility Determination for Maximum Engagement and Increased Energy Awareness.
  - Implement dynamic pricing
  - Consumer engagement via real time notifications
- Responsive Grid Balancing & Stability for Coordinated Active and Passive Network Configurations.
  - Forecasting tools

### Implementation features and delivery

EIS is employed in the Ploiesti inteGRIDy pilot project, where it provides the tendencies and prognosis of consumption profiles of residential and commercial buildings.

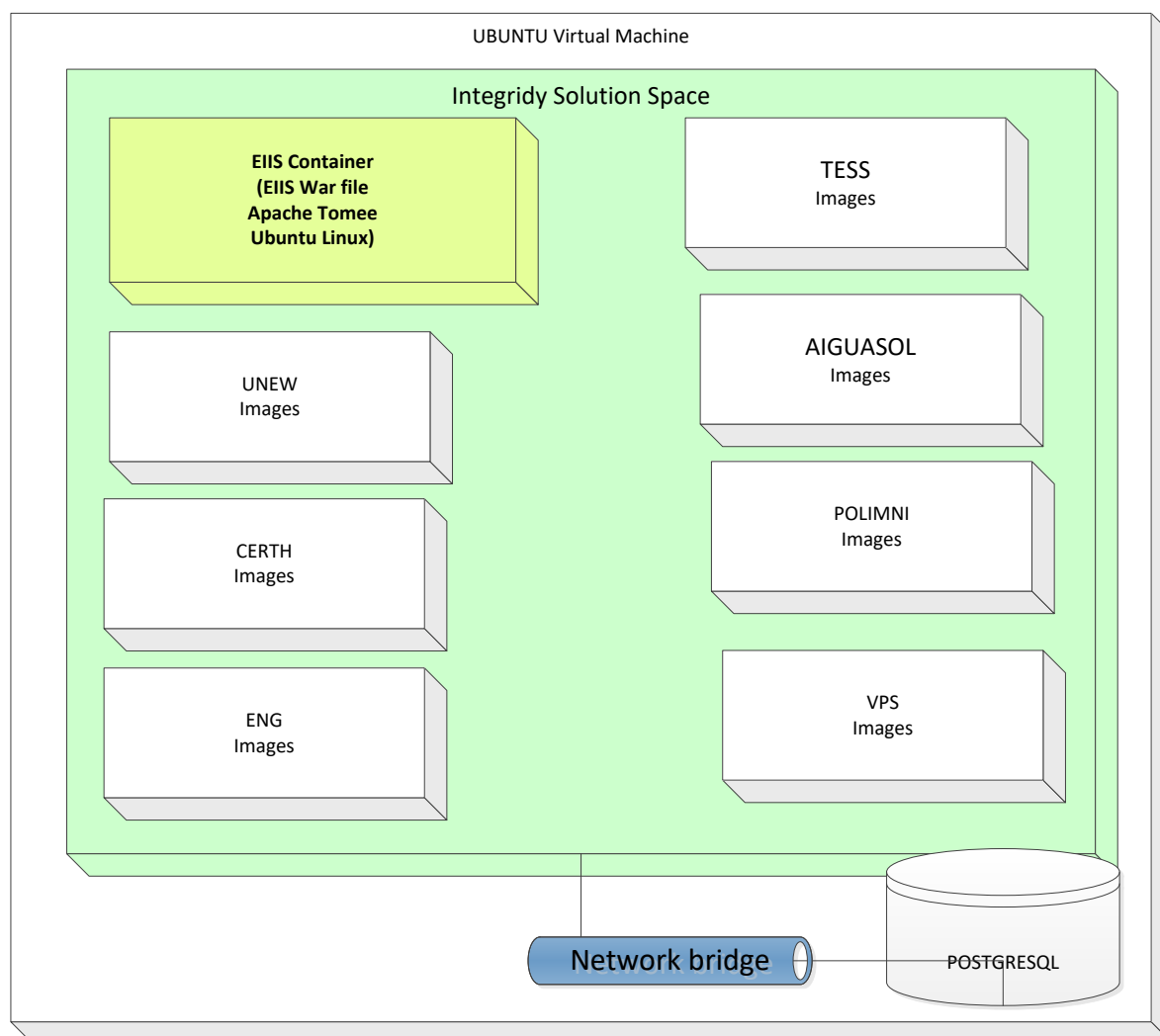
EIS is a standalone web application running on a server and accessible from web browsers. The architecture of the tool (Figure 20) includes the following components:

- Smart Metering
- Energy Management and Control System
- Energy Command and Decision system
- Automated DR component
- Public web portal, mobile application



**Figure 20. Energy Integrated Information System architecture.**

The tool can be alternatively deployed using Docker, producing a Docker image of the whole tool as shown in Figure 21.



**Figure 21. EII Docker image in Solution Space**

Once the application is fully ready, a demo will be available on the web.

For more information about the EII code, please contact:

Iacob Crucianu: [Iacob.Crucianu@siveco.ro](mailto:Iacob.Crucianu@siveco.ro) [mailto:](mailto:Iacob.Crucianu@siveco.ro)

#### 4.2.5 NEMO

##### General description of the inteGRIDy functionalities

NEMO provides energy and heat demand prediction, allocates generation resources between multiple energy assets, optimizes generation dispatch, creates energy management events and responds to external Demand Response requests. In addition, NEMO functionalities include:

- Pre-processing of raw meter data to refine meter consumption files in a correct format ready for prediction. Pre-processing includes removing outliers, cleaning zero values by interpolating the values if they are missing, and normalizing the data and timestamps by aligning meter data to the nearest 15-minute resolution.
- Prediction of energy demand based on time series of energy requirements and temperatures. NEMO prediction algorithm takes the pre-processed data to predict the electricity and heat demand using the Exponentially Weighted Recursive Least square (EW-RLS) algorithm. The EW-RLS has autoregressive terms that picks up the statistical correlations between the current demand and historic measured demand plus moving average terms that picks up the correlations with temperature signals.
- Optimization of energy generation of multiple assets based on cost and/or CO<sub>2</sub> reduction. NEMO optimizer takes the forecasts, events and other parameters to optimize vectors such as HVAC pre-cooling setpoints based on Dynamic Programming (DP) approach, self-consumption of PV generation etc.
- Communication: NEMO has connectivity options to Building management system (BMS) and metering systems; interoperability with other tools via OpenVPN (ingests DR requests from DEMS in OpenADR format) and communication protocols such as SCADA Modbus, BACnet, etc.

NEMO addresses the inteGRIDy pillars of Demand Response, Smartening the distribution grid and Energy Storage technologies.

##### Details of the modelling process

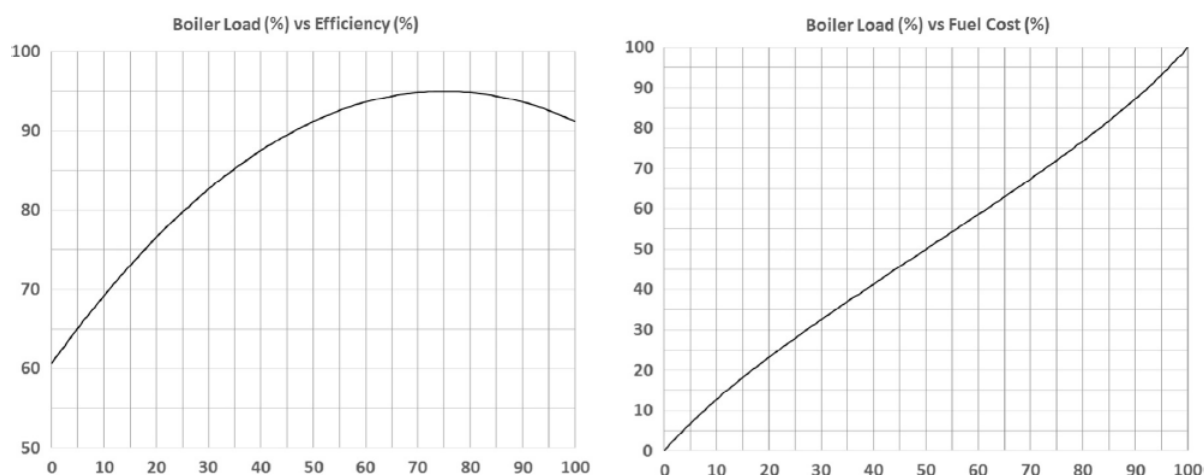
This section presents the energy modelling options that NEMO has available which are relevant to the inteGRIDy project.

###### *Energy management*

Energy management is approached in NEMO as an optimization of cost and supply balance based on the demand forecast for a decentralised small/medium-scale (10-50 megawatt MW) combined heat and power (CHP) plant [SHO17]. It is assumed that the CHP plant presents thermal and electrical storage capacity, and a gas boiler to address peaks in heat demand. Several electrical storage technologies are considered including direct systems such as BESS or indirect systems like compressed air energy storage and flywheels where electrical energy is converted into mechanical energy to be later converted back into electrical energy.

The tool can either adopt a Linear Programming or Mixed Integer Linear Programming model incorporating a non-linear boiler efficiency curve for the main plant as shown in Figure 22.





**Figure 22. Boiler efficiency as a function of load (left), and required fuelling as a function of boiler load in black (right).**

#### *Solar PV generation*

The mathematical solar PV model assumes that maximum power is generated by the PV module at noon, and that the power generated depends on the solar irradiance falling on the solar module, as well as the atmospheric and weather conditions. The methodology to compute the solar irradiance received by the solar PV module is detailed below:

#### *Modelling the clear sky outdoor irradiance*

This irradiance model follows the approach described by [DUS19] and [MAS04], where the clear sky solar irradiance at the surface is equal to the sum of direct, diffuse and reflected irradiance components (Table 5).

**Table 5. Solar irradiance model inputs indicating their units and sources.**

Inputs		
Value	Unit	Source
Latitude	Degrees	User defined
Longitude	Degrees	User defined
Day of the year n	Integer (1-365)	User defined
Local time hours	0-23	User defined
Local time minutes	0-59	User defined
Day of the year summer starts	Integer (1-365)	User defined
Day of the year summer ends	Integer (1-365)	User defined
Local standard time (LSTh)	0-23 hours	Calculation (summer time offset)
Local standard time (LSTm)	0-59 minutes	Calculation (summer time offset)
Local standard time meridian (LSTM)	Degrees	User defined
Slope of panel	Degrees	User defined
Azimuth of panel	Degrees	User defined

Ground reflectance $\rho$	Input	User defined
Solar Panel Area $A$	Input $\text{m}^2$	User defined
System efficiency $\eta$	Input (0.0-1.0)	User defined
Sky clearness Index $SCI$	0.0(full cloud) -1.0 (clear sky)	Weather station

### Modelling attenuation in solar irradiation due to clouds

A model of solar irradiation attenuation due to clouds was developed by [SKA92].

In this model, the direct beam radiation  $I_{BC}$  ( $\text{W}/\text{m}^2$ ) is calculated as:

$$I_{BC} = I_B \cos \theta \quad (43)$$

where  $I_B$  is the direct beam radiation at the earth's surface and  $\theta$  is the angle of incidence between the normal to the module's plane and incoming direct beam.

The diffuse radiation on panel  $I_{DC}$  ( $\text{W}/\text{m}^2$ ) is given by:

$$I_{DC} = CI_B \left( \frac{1 + \cos \Sigma}{2} \right) \quad (44)$$

where  $C$  is the sky diffuse factor and  $\Sigma$  is the module slope.

The reflected radiation on the solar panel  $I_{RC}$  ( $\text{W}/\text{m}^2$ ) is given by:

$$I_{RC} = \rho I_B (\sin \beta + C) \left( \frac{1 - \cos \Sigma}{2} \right) \quad (45)$$

where  $\rho$  is the ground reflectance, also referred as albedo, and  $\beta$  is the altitude or zenith angle.

The total radiation on the solar PV module based on clear sky conditions  $I_{TOTAL}$  ( $\text{W}/\text{m}^2$ ) is computed as:

$$I_{TOTAL} = I_{BC} + I_{DC} + I_{RC} \quad (46)$$

The net radiation received by a PV module  $I_{NET}$  ( $\text{W}/\text{m}^2$ ) accounts for the cloud cover index  $SCI$  and is calculated as:

$$I_{NET} = SCI \times I_{TOTAL} \quad (47)$$

The power generated  $P_{PV}$  ( $\text{W}$ ) by the solar PV module is finally calculated as [PAA07]:

$$P_{PV} = SCI \times I_{NET} \times A \times \eta \quad (48)$$

where  $A$  is the area of solar PV module ( $\text{m}^2$ ) and  $\eta$  is the efficiency of the solar panel.

### Electric battery

Minute-resolution lead acid battery models are preferred in real-time demand/supply applications, such as the one proposed by [PAA07].

The model considers both AC and DC power generation sources, power losses in inverters (for AC sources), power electronic equipment and losses during battery charge and discharge cycles. An AC domestic load is assumed. The model assumes DC output from solar PV modules is converted to AC via an inverter. Lead acid battery model is described in [PAA07], and Table 6 shows the main solar PV and battery storage model parameters.

**Table 6. Solar PV and battery storage model parameters.**

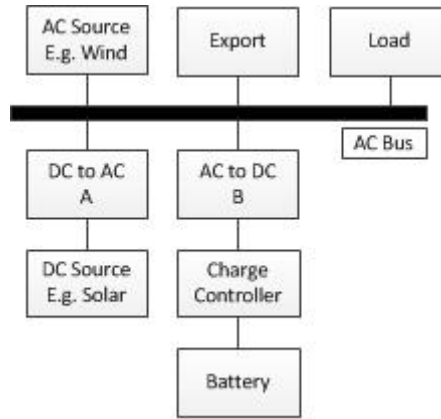
Required input	Suggested default
Electrical demand (kW)	Minutely profile
DC onsite generation (kW)	Minutely profile
AC onsite generation (kW)	Minutely profile
Voltage across cell (V)	2.1
Maximum discharge rate	C/5
Maximum charge rate	C/10
No. of cells in series $n$ for each battery	User defined
No. of batteries in parallel	User defined
Maximum cell capacity $C_{cell}$	50 A h
Lower capacity limit of battery SOC	20%
Maximum capacity limit of battery SOC	100%
Number of batteries in parallel $N$	User defined
Storage capacity of battery pack containing $N$ batteries in parallel $C_0$ (Ah)	Sum of capacities of $N$ batteries in parallel
Battery-to-load inverter power rating (kW)	Based on max. discharge power
DC-to-load inverter power rating (kW)	Based on max. DC generation
Efficiency of charge controller	98%

#### Power at AC bus

An AC, DC generation, battery, load and grid configuration is given in Figure 23. The tool is capable of integrating wind power from turbines as well as PV sources. The total power at the AC bus  $P_{BUS}$  is calculated as:

$$P_{BUS} = P_{AC} + \epsilon_A P_{DC} \quad (49)$$

where  $P_{AC}$  and  $P_{DC}$  are respectively the AC and DC power sources, and  $\epsilon_A$  is the DC-AC conversion efficiency of inverter A. The inverter efficiency is a function of both the inverter power output and power rating.



**Figure 23. Power at AC bus adapted from [PAA07].**

When the power demand of the building  $P_D$  is lower than the power available at the bus  $P_{BUS}$ , this leads to a surplus power  $P_+$  given by:

$$P_+ = P_{BUS} - P_D, P_{BUS} > P_D \quad (50)$$

When the power available at the bus is lower than the power demand, the power deficit  $P_-$  is given by:

$$P_- = P_D - P_{BUS}, P_D > P_{BUS} \quad (51)$$

The power demand can only be satisfied when there is power surplus available at the bus. The power needed  $P_{RES}$  to satisfy the power demand is given by:

$$P_{RES} = P_{BUS} - P_+, P_+ > 0 \quad (52)$$

If there is no power demand at the bus, then  $P_{RES} = 0$  and  $P_+ = P_{BUS}$ .

#### *Discharge and charge currents*

The charge controller will limit the charging current to maximum allowed charging current  $I_{Cmax}$ . According to this model, the value of the available charge current  $I_{C0}$  (i.e. ignoring the state of the battery) at any time is given by:

$$I_{C0} = \frac{P_+ \times \epsilon_C \times \epsilon_{B1}}{V_B} \quad (53)$$

where  $\epsilon_C$  is the efficiency of the charge controller (approx. 98%),  $\epsilon_{B1}$  is the efficiency of the AC to DC converter and  $V_B$  is the voltage across the battery.

Likewise, the discharge current  $I_{D0}$  is calculated as:

$$I_{D0} = \frac{P_-}{V_B \times \epsilon_C \times \epsilon_{B2}} \quad (54)$$

where  $\epsilon_{B2}$  is the efficiency of the DC to AC inverter. The maximum value of discharge current is limited to  $I_{Dmax}$ . The SOC is limited to minimum state of charge of  $SOC_{min}$  (typically 20%).

### Battery state of charge

The battery SOC is determined from the values of charging  $I_{C0}$  and discharging  $I_{D0}$  currents at any given time. At 100% SOC, the total capacity  $C_0$  (Ah) of the battery pack (number of batteries connected in parallel) is given as:

$$C_0 = N \times C_i \quad (55)$$

where  $N$  is the number of batteries in parallel and  $C_i$  is the capacity of the individual battery. When the battery is discharging, then the discharged capacity  $C_D$  (Ah) during interval  $\Delta t$  is given by:

$$C_D = \frac{I_D \times \Delta t}{\alpha}, \quad 0 \leq \alpha \leq 1 \quad (56)$$

where  $\alpha$  is the discharge efficiency and it is calculated as:

$$\alpha = \frac{13.3 \times \ln(C_0 \div I_D) + 59.8}{100} \quad (57)$$

$\alpha$  is limited to 1 and this ensures that the maximum charge removed during time period  $\Delta t$  will be limited to  $I_D \times \Delta t$ . During charging, the change in battery capacity  $\Delta C$  during time  $\Delta t$  is given by:

$$\Delta C = I_C \times \Delta t - C_D \quad (58)$$

$\Delta C$  is negative during discharging and positive during charging. The battery capacity at any time  $C_t$  according to this model is given by:

$$C_t = C_{t-1} + \Delta C \quad (59)$$

where  $C_{t-1}$  is the charge of the battery during the previous time period. This will be limited by the expression:

$$SOC_{min} \leq C_t \leq SOC_{max} \quad (60)$$

### Power satisfying electrical demand

The local power generation will cover the building power demand, the battery charge demand, and power export (if there is surplus power available). It is assumed that the power demand is covered at all times, and any shortfall of power will be covered by the grid as:

$$P_{grid} = P_D - P_{BUS} - P_{batt} \quad \text{for } P_D > P_{BUS} \quad (61)$$

Thus:

$$P_{grid} = P_- - P_{batt} \quad (62)$$

Alternatively:

$$P_{grid} = P_- - I_D \times V_B \times \varepsilon_{B2} \times \varepsilon_C \quad (63)$$

where  $P_{batt}$  is the power output of the battery at any time

When no power is supplied by the battery, the power shortfall between the local power generation and the building power demand is met by the grid. Conversely, if the power shortfall is equal to the power supplied from the battery, there is no power supplied by the grid.

#### Exported power

It is possible to export power in the circumstances where  $P_+$  is positive and battery is either fully charged or the charge current  $I_{C0}$  is greater than  $I_{Cmax}$ . The power exported  $P_{exp}$ , is given by:

$$P_{exp} = \left( \frac{I_{C0}}{\varepsilon_{B1} \times \varepsilon_C} - I_C \right) \times V_B \quad , \quad \text{for } I_{C0} > I_C \quad (64)$$

The exported power is due to the difference in the available and allowed charge currents and the power electronics efficiencies.

#### General configuration

The general configuration of the electric load/generation setup is as follows:

1. The load / generation scheduling horizon is divided into  $H > 0$  uniform time slots ; each time slot is of length  $T > 0$  h
2. Typically, each slot will be of length  $T = 1$  h, for a given period of 24 hours.
3. Model includes PV panels and wind turbines, with BESS and switchgear.
4. Virtual energy storage facility, stores energy at each hourly time-step.

#### Phases of operation

##### Start-of-cycle

The counter variable  $h$  is updated as  $h = h + 1$  and this can be hourly, daily or weekly increments.

##### Data Acquisition Phase

This phase includes the following steps:

- Consumption data for the last hour is forwarded from the measurement system and processed to obtain the latest measured energy demand for each in the last hour
- Renewable availability data is calculated using the simulation models to obtain the latest measured energy supply in the last hour
- Current weather conditions at the site are obtained, and any updates of the future building occupancy data is forwarded by the measurement system.
- Weather forecast information is retrieved from an online database for every hour over the prediction horizon, and combined to form the fundamental variable matrices  $F_D[(h+k)]$  and  $F_S[(h+k)]$ ,  $k = 0, 1, 2, \dots, H-1$ .
- CO<sub>2</sub> emissions information is retrieved from an online database.
- Stored energy availability is calculated using the simulation to obtain the latest measured availability of the neighbourhood storage resources  $C(h)$ .



### Pre-processing / Prediction Phase

- Current consumption data is added for each building to obtain the site energy demand for the last hour.
- Current renewable energy supplies are added for each building to obtain site energy supply for the last hour
- The site demand is predicted over the time horizon considered.
- The site supply is predicted over the time horizon considered.
- Grid CO2 emissions are predicted for each step over the prediction horizon.
- Grid price vectors are set from the knowledge of the pricing and tariff structure, as well as the current hour, day and month, and the peak#1 and peak #2 start/stop times.

### Energy demand prediction

NEMO prediction algorithm for short-term electricity loads was described in details in [SHO17], and briefly described below:

Considering an Auto-Regressive Integrated Moving-average (ARIMA) white noise with DR signal and other exogenous inputs such as temperature, the model is structured as:

$$A_E(z)D_E(t)=B_E(z)T(t) + C_E(z)\frac{e_E(t)}{\Delta} \quad (65)$$

where  $A_E(z)$ ,  $B_E(z)$  and  $C_E(z)$  are polynomials in back shift operator denoted by  $z^{-1}$ ,  $e_E(t)$  is a zero-mean white noise sequence,  $T(t)$  is the average ambient temperature for any start time  $t$  and  $\Delta = 1 - z^{-1}$  is the differencing operator

To capture the effects of short-term load history, temperature effects and moving average error, M parameter is added to the model, considering M =3

$$\begin{aligned} \Delta D_E(t) = & ah_1 \Delta D_E(t-1) + ah_2 \Delta D_E(t-2) + ah_3 \Delta D_E(t-3) \\ & + ah_{24} \Delta D_E(t-24) + ah_{168} \Delta D_E(t-168) \\ & + bh_0 \Delta T(t) + bh_1 \Delta T(t-1) + bh_2 \Delta T(t-2) \\ & + e_E(t) + ch_1 e_E(t-1) + ch_2 e_E(t-1) + ch_2 e_E(t-3) \end{aligned} \quad (66)$$

where  $ah_i$ ,  $bh_i$  and  $ch_i$  are the  $i^{th}$  coefficients of the  $A_E$ ,  $B_E$  and  $C_E$  polynomials for M=3 parameters respectively.

The above information is used to describe the one-step ahead prediction of electricity demand as follows:

$$\begin{aligned} \dot{D}_E(t+1|t) = & D_E(t)ah_1 \Delta D_E(t) + ah_2 \Delta D_E(t-1) + ah_3 \Delta D_E(t-2) \\ & + ah_{24} \Delta D_E(t-23) + ah_{168} \Delta D_E(t-167) \\ & + bh_0 \Delta \dot{T}(t+1|t) + bh_1 \Delta T(t) + bh_2 \Delta T(t-1) \\ & + ch_1 \dot{e}_E(t) + ch_2 \dot{e}_E(t-1) + ch_3 \dot{e}_E(t-2) \end{aligned} \quad (67)$$

where a dot upon a variable indicates that predicted value is to be used in the next prediction. As such, the two-step prediction is recursively modelled from equation 3 as shown below:

$$\dot{D}_E(t+2|t) = \dot{D}_E(t+1)ah_1 \Delta \dot{D}_E(t+1) + ah_2 \Delta D_E(t) + ah_3 \Delta D_E(t-1) \quad (68)$$

This approach is used to obtain the  $k$ -step ahead prediction across the whole horizon.

For the described model, the error  $e_E(t)$  at any time step  $t$  can be estimated by calculating the difference between the actual measured load and predicted forecast as given below:

$$\dot{e}_E(t) = (\Delta D_E(t) - \Delta \hat{D}_E(t | t)) \quad (69)$$

The final weighted quadratic error relating to electricity demand is modelled as a weighted least square problem:

$$J(t) = \sum_{i=0}^{t-1} \lambda^{(t-i)} \left( \Delta D(i) - \Delta \hat{D}(i) \right)^2 \quad (70)$$

where  $0 < \lambda \leq 1$  represents the forgetting factor and  $J$  is the objective function. The parameter estimation to optimally solve and minimize  $J(t)$  at each time step can be efficiently carried out using the method of EW-RLS. Following the regression updates to estimate the unknown model coefficients at time  $t$  using the available measured data, the predictions for electricity demand are then carried out recursively

#### Optimization

Assume that initial state of the storage facility  $C(h)$  satisfies  $C^{Min} \leq C(h) \leq C^{Max}$ . Let the expected financial profit for hour  $k$  ( $k \geq h$ ) be defined as the difference between the energy sold to the grid and the energy bought from the grid:

$$Profit(k) = Z_{GS}(k) \cdot P_S(k) - Z_{GD}(k) \cdot P_D(k) \quad (71)$$

where  $Z_{GS}()$ , represents the time-series of the optimal decisions on how much energy is to be purchased from the grid;  $P_S()$ , represents the time-series of the grid energy purchase price;  $Z_{GD}()$  denotes the time-series of the optimal decisions on how much energy is to be sold to the grid and  $P_D()$  is the time-series of grid energy sale price.

As such, the total expected profit made at any given hour  $h$  across the horizon  $H$  can be derived from the available specification for neighbourhood energy management tool [IDE13] as:

$$Profit_H(h) = \sum_{i=0}^{H-1} Profit(h+i) \quad (72)$$

Similarly, the total expected CO<sub>2</sub> emission costs is given by:

$$CO_{2H}(h) = \sum_{i=0}^{H-1} CO_2(h+i) \quad (73)$$

Hence, the weighted objective function can be expressed as:

$$OBJ_H(h) = (1 - \gamma) Profit_H(h) + \gamma CO_{2H}(h) \quad (74)$$

where  $\gamma \in [0, 1]$  represents the relative importance between financial and CO<sub>2</sub> emissions costs.

Therefore, the objective problem is to Maximize  $\{OBJ_H(h)\}$  with respect to:

$$Z_{GD}(h+k), k = 0, 1, 2, 3, \dots, H-1;$$

$$Z_{GS}(h+k), k = 0, 1, 2, 3, \dots, H-1;$$

$$X_C(h+k), k = 0, 1, 2, 3, \dots, H-1;$$

where  $X_C()$ , represents the time-series of the optimal decisions relating to the storage and retrieval of energy into/from the storage facility

Subject to constraints:

Energy balance constraints:

$$\forall i, 0 \leq i \leq H - 1 :$$

$$S(h+i) + Z_{GS}(h+i) + X_C(h+i) = D(h+i) + Z_{GD}(h+i)$$

Non-negative supply/demands:

$$\forall i, 0 \leq i \leq H - 1 :$$

$$Z_{GS}(h+i) \geq 0$$

$$Z_{GD}(h+i) \geq 0$$

Energy storage constraints:

$$\forall i, 1 \leq i \leq H - 1 :$$

$$C(h+i) = C(h+i-1) - \max \{C_{\alpha}, X_C(h+i-1), X_C(h+i-1)\}$$

Energy storage/retrieval rate and capacity constraints:

$$\forall i, 1 \leq i \leq H - 1 :$$

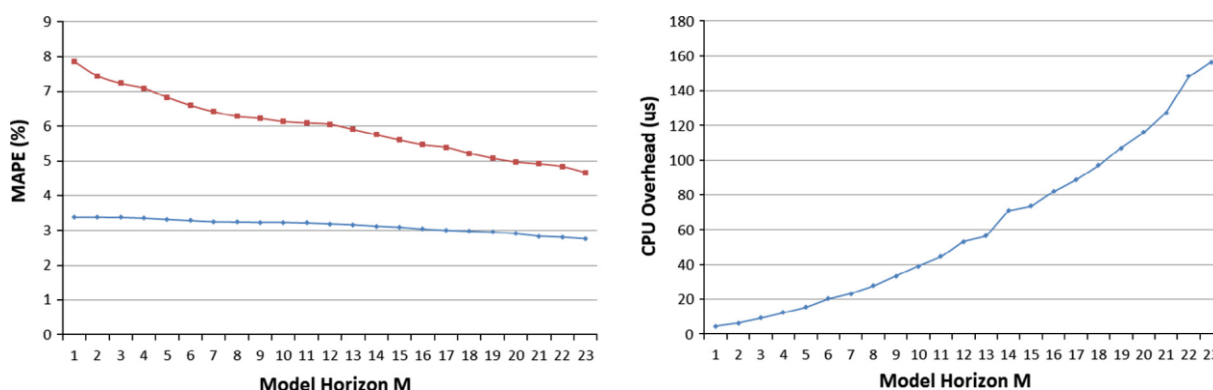
$$C^{min} \leq C(h+i) \leq C^{max}$$

$$\forall i, 0 \leq i \leq H - 1 :$$

$$\Delta C^{min} \leq X_C(h+i) \leq \Delta C^{max}$$

The formulated optimization problem based on linear programming is to be solved twice to explore various trade-offs between costs and emissions by varying  $\gamma$ . This is such that for  $\gamma = 0$  (Solution Sol 1) emissions are not taken into account, and for  $\gamma = 1$  (Solution Sol 2) financial costs are not taken into account.

Regarding the calibration and validation of NEMO, the accuracy of NEMO's prediction algorithm is measured using mean absolute percentage error (MAPE) for a prediction model horizon M (time steps) as shown in Figure 24. In addition, Figure 24 plots the CPU execution time resulting from the model horizon M considered.



**Figure 24. Resulting MAPE (left) and CPU execution time (right) for model horizon M considered.**

### Technical specifications and advances from the existing tools

NEMO calculations can be performed using time steps of 5, 10, 15, 30 or 60 minutes through a time horizon of 1-2 days or more. Time horizon depends strongly on the selected time step.

In terms of I/O data, format can be in CSV, Json, timeseries or XML. NEMO requires the following input data for the modelled horizon:

- Consumption data for the last hour. These are provided by the building management system (BMS) at the site, or the metering/monitoring system.
- The simulated models provide renewable availability data.
- Current weather conditions and the weather forecast are provided by a web-based source.
- CO<sub>2</sub> emissions data are obtained from country's government sites or from published articles.
- Stored energy availability and energy generation are provided by the simulation models.
- Pricing and tariff structures.

NEMO yields as output data an energy demand profile over a time horizon in the form of a column-based timeseries text file. This time horizon and time step can be adjusted according to the user's preferences.

NEMO does not present any dependency from external software or equipment, and only requires input data as detailed earlier.

NEMO requires C++ runtime libraries. NEMO can operate under Windows 7 or later as well as in Linux, and does not have any hardware dependencies.

### Expected advantages compared to commercial products

NEMO tool is unique and there are no known existing commercial products with diverse functionalities as NEMO. The NEMO software components can be used in conjunction with other open-source software (e.g. SCADA database management) and web services (e.g. weather forecast APIs) to enable a fully integrated environment for decentralised CHP plant management and optimisation at very little cost, which translates into significant financial savings over the course of a year. In terms of energy prediction, most energy companies do not publish the details of their prediction algorithm for energy baseline calculations; rather they

explain the selection process as in the case of Kiwi Power and S3C KIBER-net project [S3C19]. However, as part of DR-BOB project [DRB16], Siemens energy Bureau undertook an independent validation and assessment audit of the NEMO prediction algorithm (known as Local energy manager in DR-BOB project). Siemens reviewed the accuracy of the projections in all operational modes and the overall uncertainty against the magnitude of DR events. The findings for different validated meter readings and baselines confirm the accuracy of NEMO prediction tool [NEW 18].

### Implementation features and delivery

NEMO tool is applied exclusively to Barcelona pilot project. The tool will model the operation of a solar PV and battery system (charge & discharge) based on current and load forecast and weather conditions. In addition, the tool considers costs in the system modelling.

NEMO is a standalone software component for load prediction (both heat and electricity), CHP / HVAC optimization and communication / interoperability functionalities. NEMO is written in C++, developed in Visual Studio 2015 environment and executable under windows and Linux operating system..

Communication relay: NEMO is a versatile tool capable of communicating in various formats. NEMO is central to communicating, retrieving and relaying data, including but not limited to:

- Retrieves Set points and asset status via SCADA Modbus
- Retrieving meter reading, weather and pricing data from the Knowledge Reference Warehouse via Rest API
- Relays Swimming pool initial conditions and proposed set points to swimming pool thermal flexibility tool via REST API
- Relays indoor conditions and retrieves proposed setpoints from the swimming pool optimal configuration tool via Rest API
- Receives DR Events signals from the DEMS tool via OPEN ADR
- Receives assets generation set points and sends assets status to DEMS via IEC104
- Send optimum generation schedules to DEMS via Rest API
- Sends Asset load shed forecast and assets consumption forecasts to DEMS via a.csv text file
- Notifies building managers in the event of grid outages and DR events via GSM

Prediction tool: Using the installed PV data, and the weather conditions, NEMO calculates the amount of energy availability, which is termed as PV flexibility.

Similarly, by polling asset (battery) status with regard to state of charge and voltage levels, NEMO calculates the amount of energy available for use, which is termed as the battery flexibility.

Optimisation: Given a specific battery and PV flexibility, the tool may choose the optimum strategy to charge or discharge the battery.

Decision-making: When the optimal strategy is set, charging and discharging of battery is decided and the decision is executed via a control signal to the inverter via MODBUS.

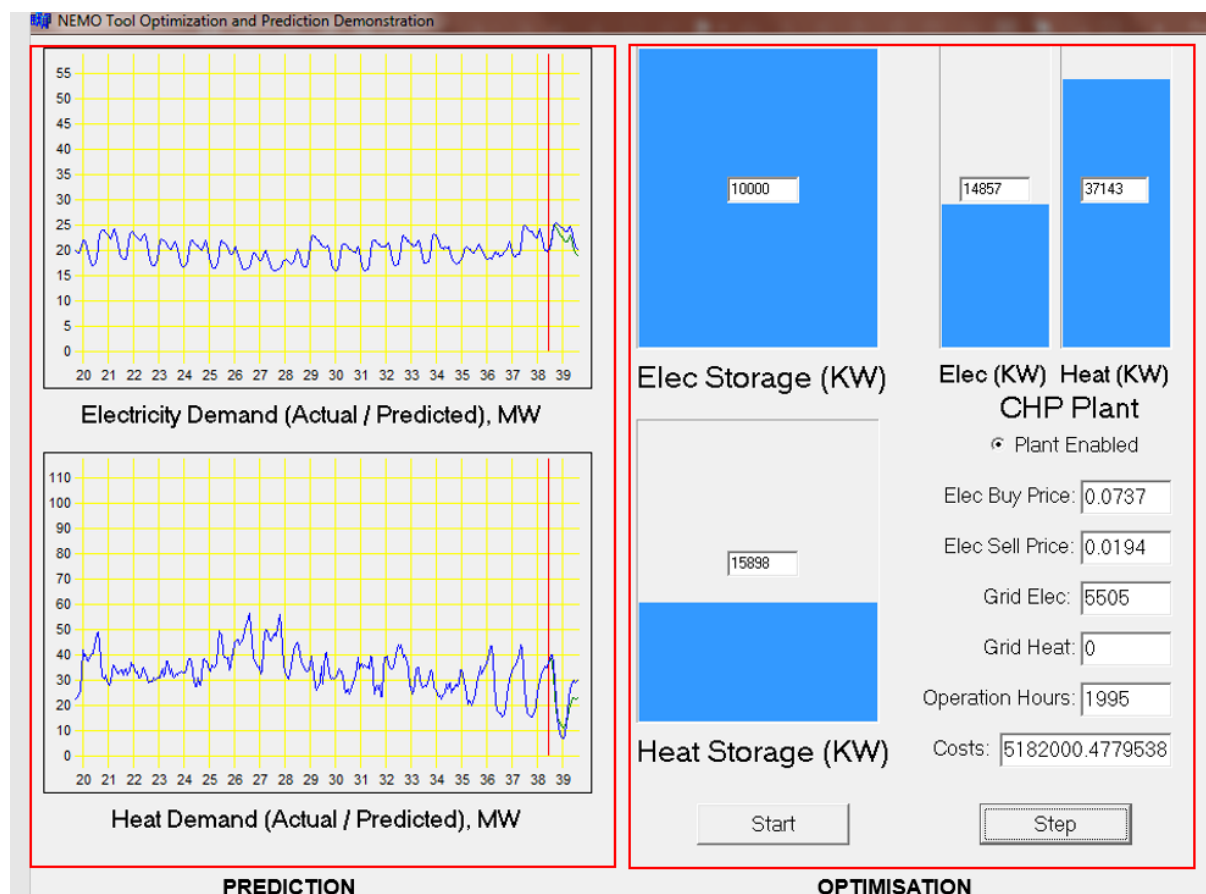
Demand Response: Upon receiving a Demand Response signal, and optimising the outcomes, if the DEMS tool decides to act upon on the DR event, assets are controlled via Modbus and notifications are sent to assets to carry out the event and to the actors (building manager).

Grid Outage: Considering the battery and PV flexibility, the tool makes a decision to provide energy to the building in case of a grid outage and acts on assets via MODBUS.

Deployment: There are no foreseen restrictions to deploy NEMO in Docker. Presently, NEMO is located on a password protected PC in Teesside University Research office at the Phoenix

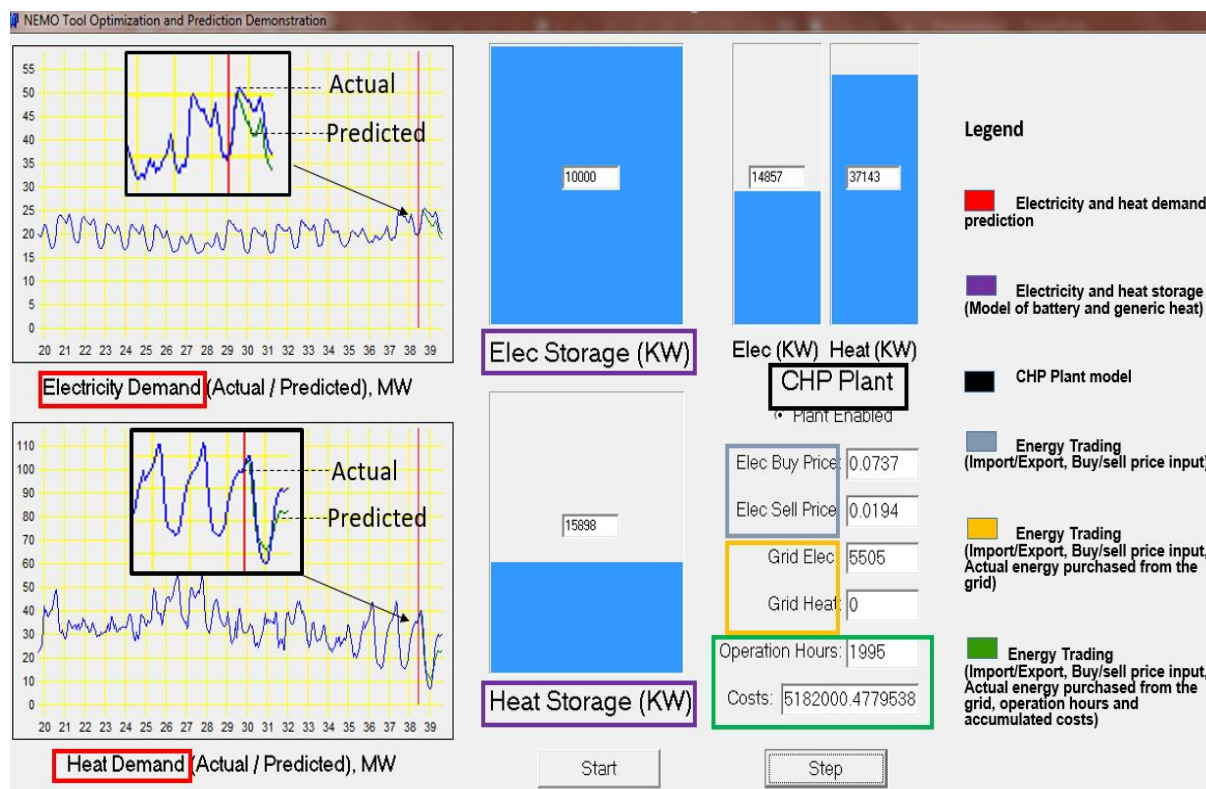
Building, UK. Consequently, NEMO can be deployed in a password protected PC at the Barcelona pilot site and can be remotely controlled from Teesside University, if required.

A demo of the NEMO tool is available. Figure 25 and Figure 26 depicts screenshots of NEMO showing CHP plant dispatch and electricity and heat storage status.



**Figure 25. CHP plant dispatch and status of electricity and heat store as calculated by NEMO.**





**Figure 26. Overview of NEMO tool showing CHP plant Actual/Predicted Electricity and heat demand, optimization of electricity and heat storage and the energy trading**

For more information about NEMO, please contact:

Hatice Tuncer: [H.Tuncer@tees.ac.uk](mailto:H.Tuncer@tees.ac.uk)

## 4.2.6 Building Occupancy & Energy Consumption Simulation

### General description of the inteGRIDy functionalities

This tool has been developed to provide additional support to the load forecasting mechanisms employed by the Intelligent Building Flexibility Prediction and Forecasting tool, in order to generate a more accurate load forecast, [when addressing the Demand Response and Smartening the Distribution Grid project pillars](#). To that end, it takes into account the Consumers, or Facility's previous energy consumptions and after a statistical analysis and clustering methods (k-means), and produces an initial pattern of the Consumers, or Facility according to the respective season and type of day. Through that pattern, it also aids to defining the consumers' or facility's load flexibility.

The tool provides the following Task 4.2 related functionalities:

- Consumer/Facility Profiling,
- Load Flexibility

### Details of the modelling process

The mathematical model for the User Profile is based on a statistical analysis of the available historical data of energy consumption. Daily profiles of time periods of one or more years are employed. These profiles are classified according to seasons, i.e. Spring, Summer, Autumn, Winter, and in additional three categories:

1. Working days, or week days
2. Saturdays
3. Sundays or Bank Holidays

Thus, the tool considers 12 sets of daily profiles, e.g. winter working days, summer working days, spring Saturdays, autumn Sundays/holidays, etc.

For each of these categories the mean value and the 10%, 90% percentiles are extracted, along with the Mean Absolute Deviation (MAD) as an index. These are used as an indication of the user's flexibility during a day, and there will feed the load/DR forecasting to increase the accuracy of the predictions.

As a comparison, a clustering method of k-means will be used to benchmark the results [LAV15].

In addition, through the use of weather data of the same time period, a correlation between power consumption and external temperature might be established and feed the Load/DR forecasting processes [HVU14] [AVD13] [GIA06].

A classification or clustering of the users would take place according to their particular characteristics as collected in surveys [VIE16].

Regarding the calibration and validation of the tool, the consumption profiles of two consumers are employed in the calibration and validation process of the tool. The mean, 10% and 90% percentiles, and MAD of the consumption values of two consumers are plot in Figure 27, Figure 28, Figure 29 and Figure 30. These data are discretised according to the day of the week (working day, Saturday and Sunday), the season and the year (2014-2016).

It is observed that, as expected, both users present almost null consumption during night hours, and medium to high activity during the rest of the day. Furthermore, during the periods of greater activity, might be argued that the consumer presents greater flexibility as well, since MAD is higher during those time-periods, thus it implies a possible timeframe for the DR Forecasting.

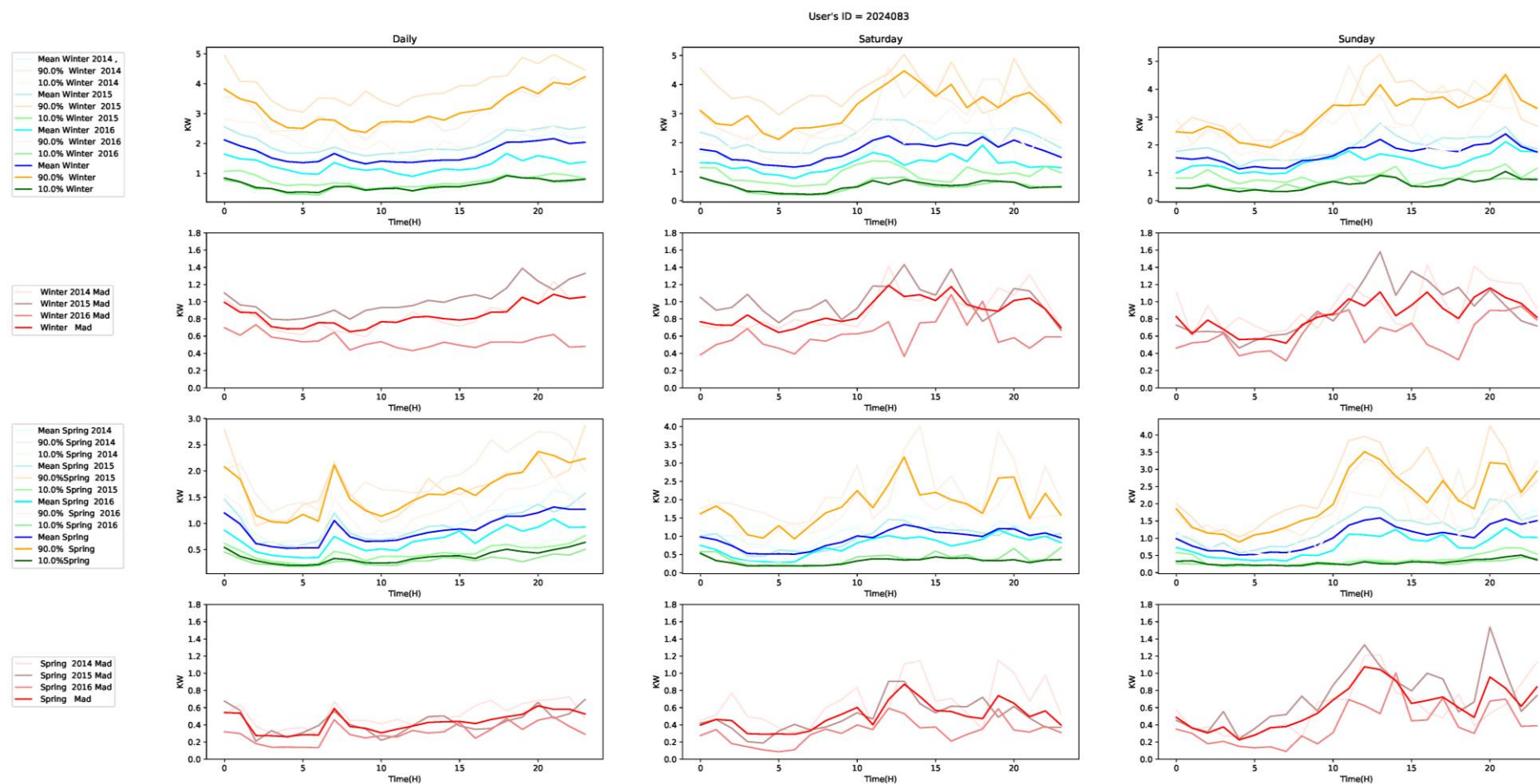
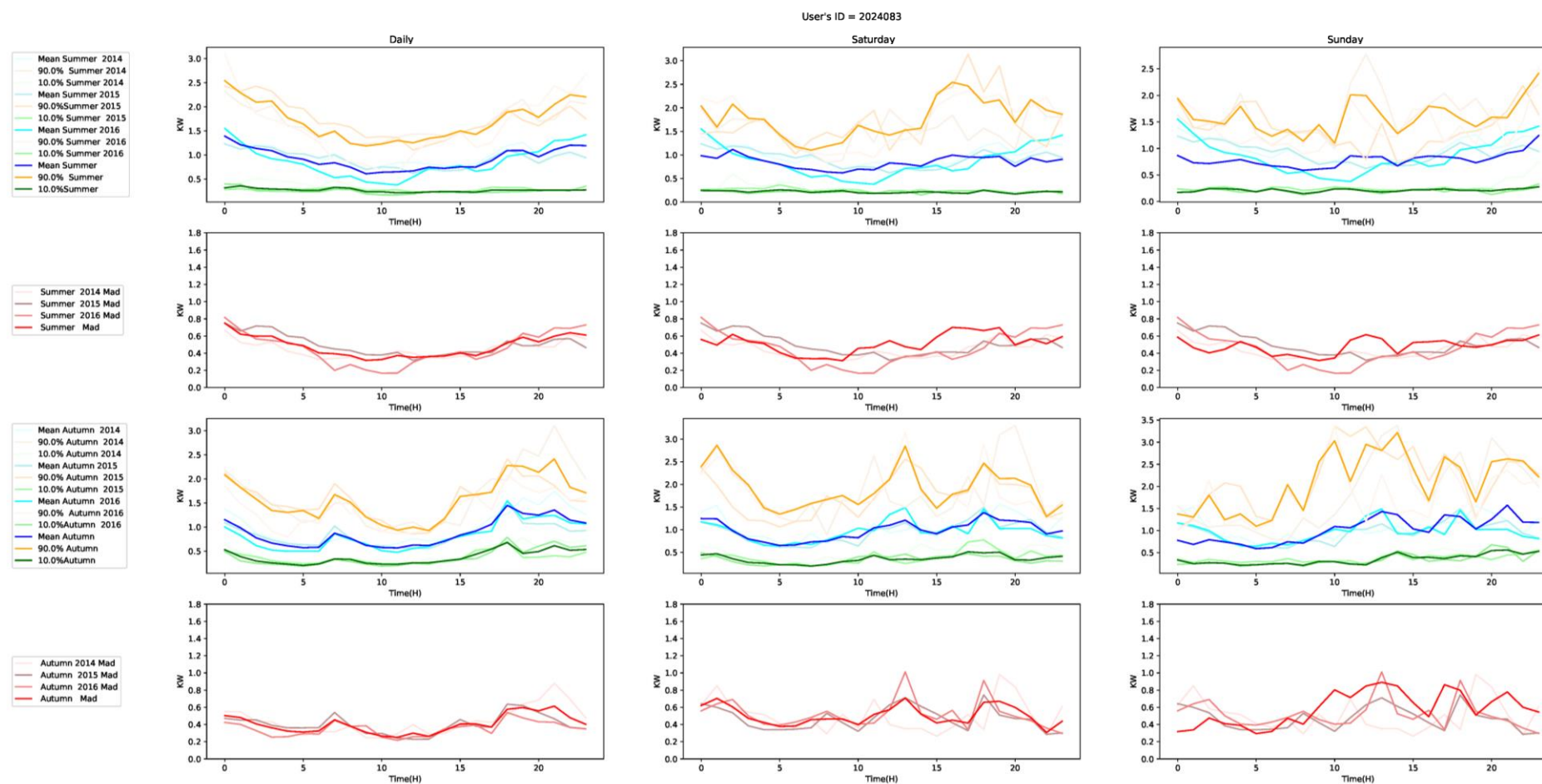
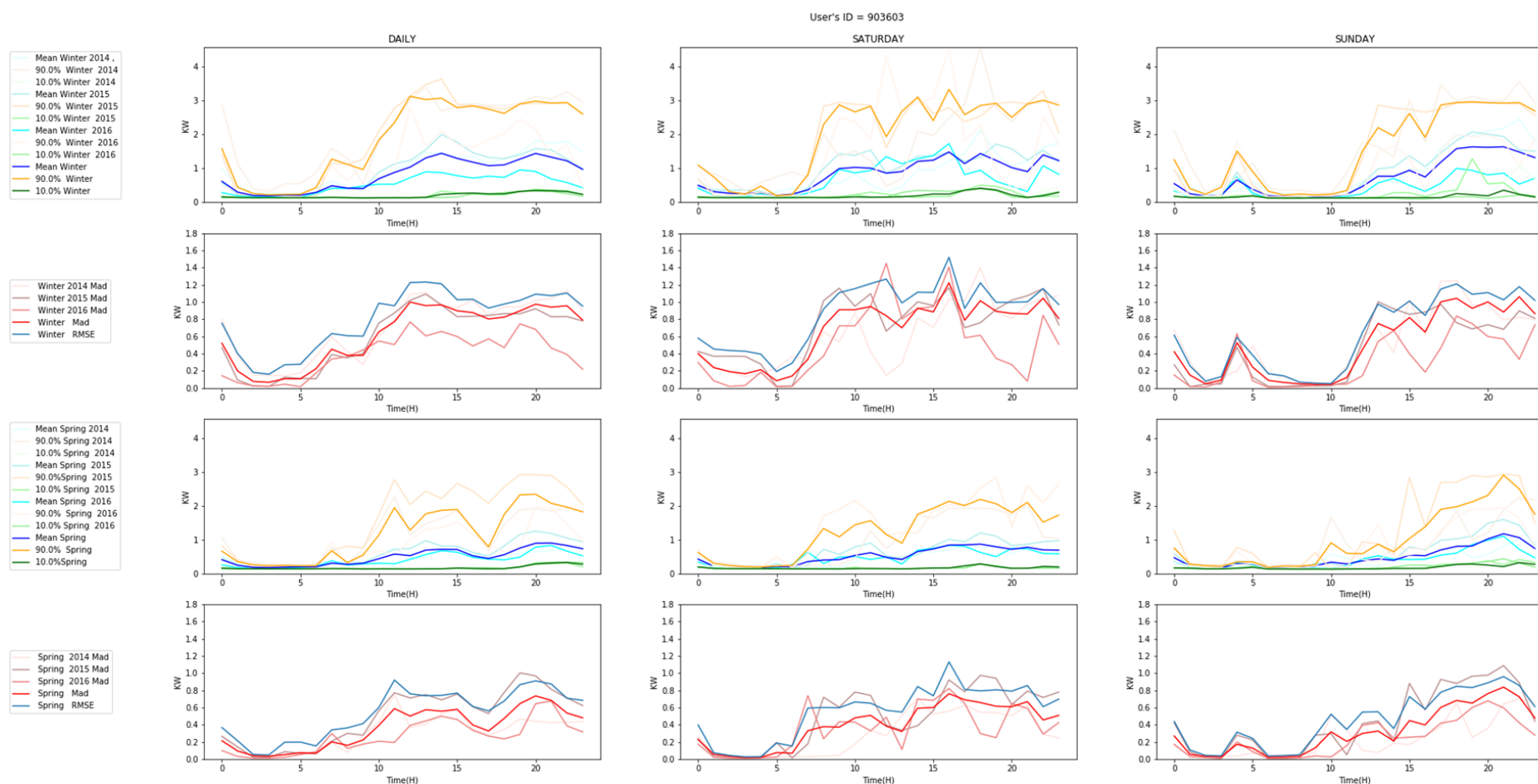


Figure 27. Mean, 10% and 90% percentiles, and MAD of the consumption values for a working day, Saturday and Sunday, at Winter and Spring seasons, in years 2014, 2015 and 2016, of consumer ID 2024083.

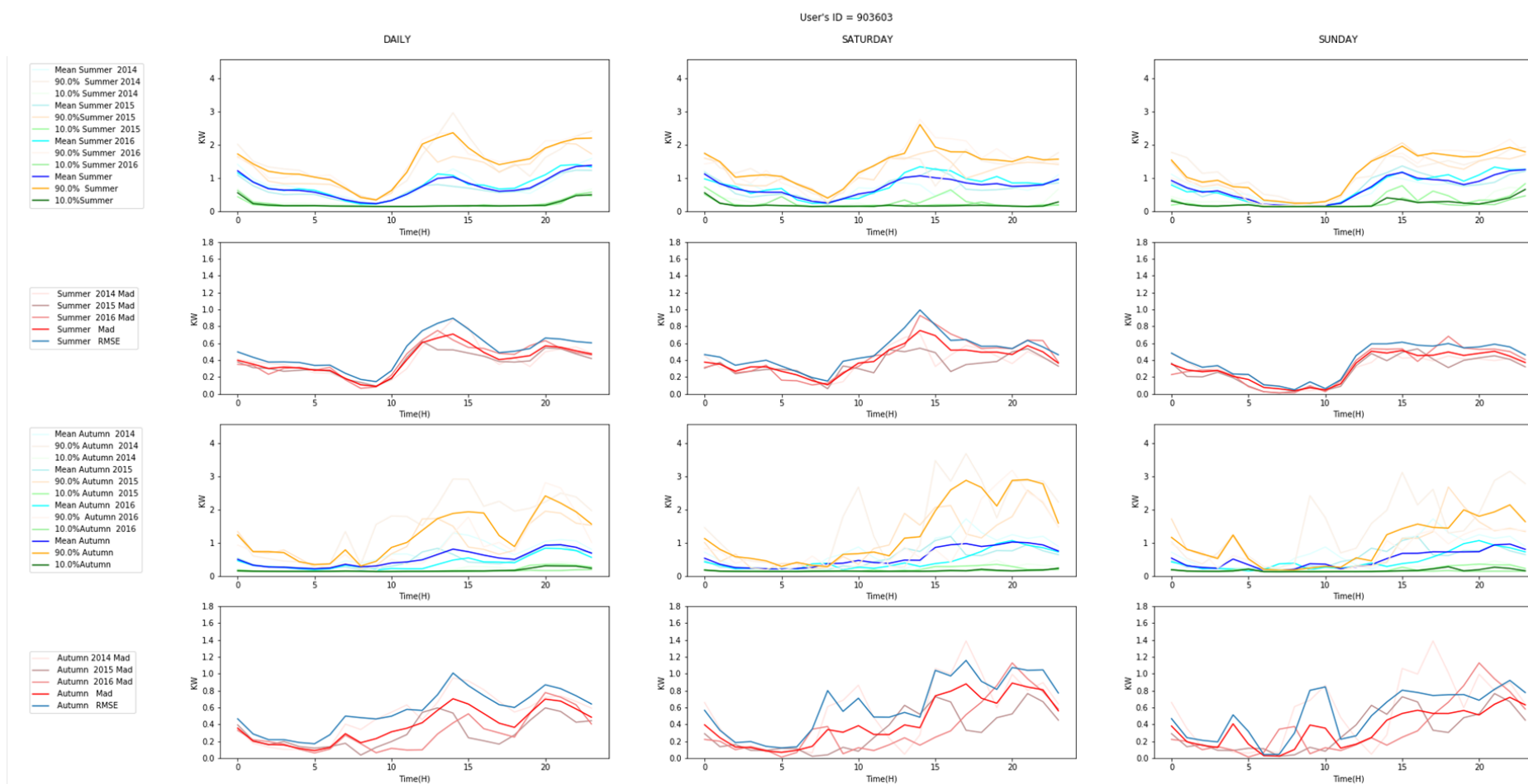


**Figure 28.** Mean, 10% and 90% percentiles of the consumption values for a working day, Saturday and Sunday, at Summer and Autumn seasons, in years 2014, 2015 and 2016, of consumer ID 2024083.





**Figure 29. Mean, 10% and 90% percentiles, and MAD of the consumption values for a working day, Saturday and Sunday, at Winter and Spring seasons, in years 2014, 2015 and 2016, of consumer ID 903603.**

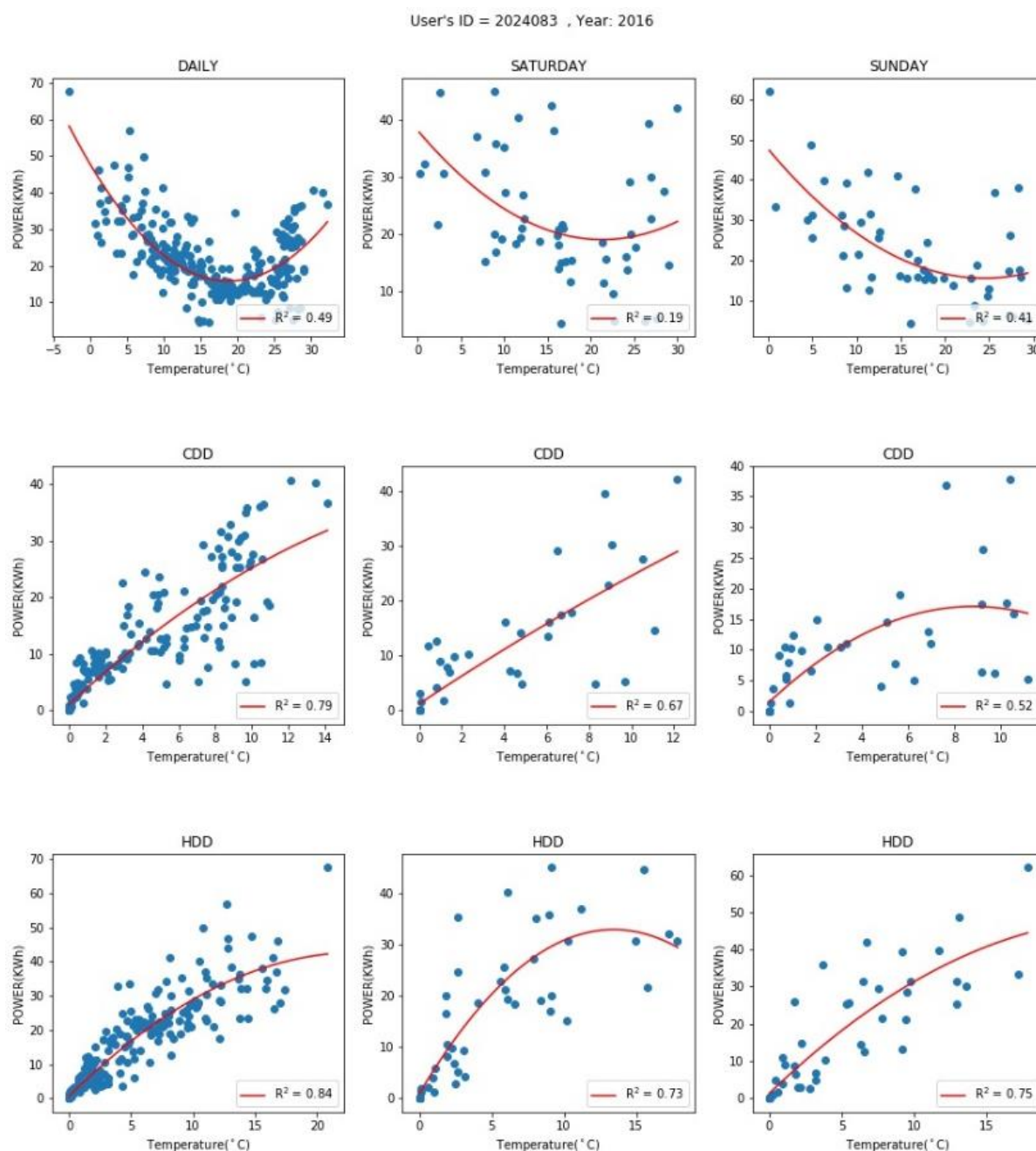


**Figure 30. Mean, 10% and 90% percentiles of the consumption values for a working day, Saturday and Sunday, at Summer and Autumn seasons, in years 2014, 2015 and 2016, of consumer ID 903603.**



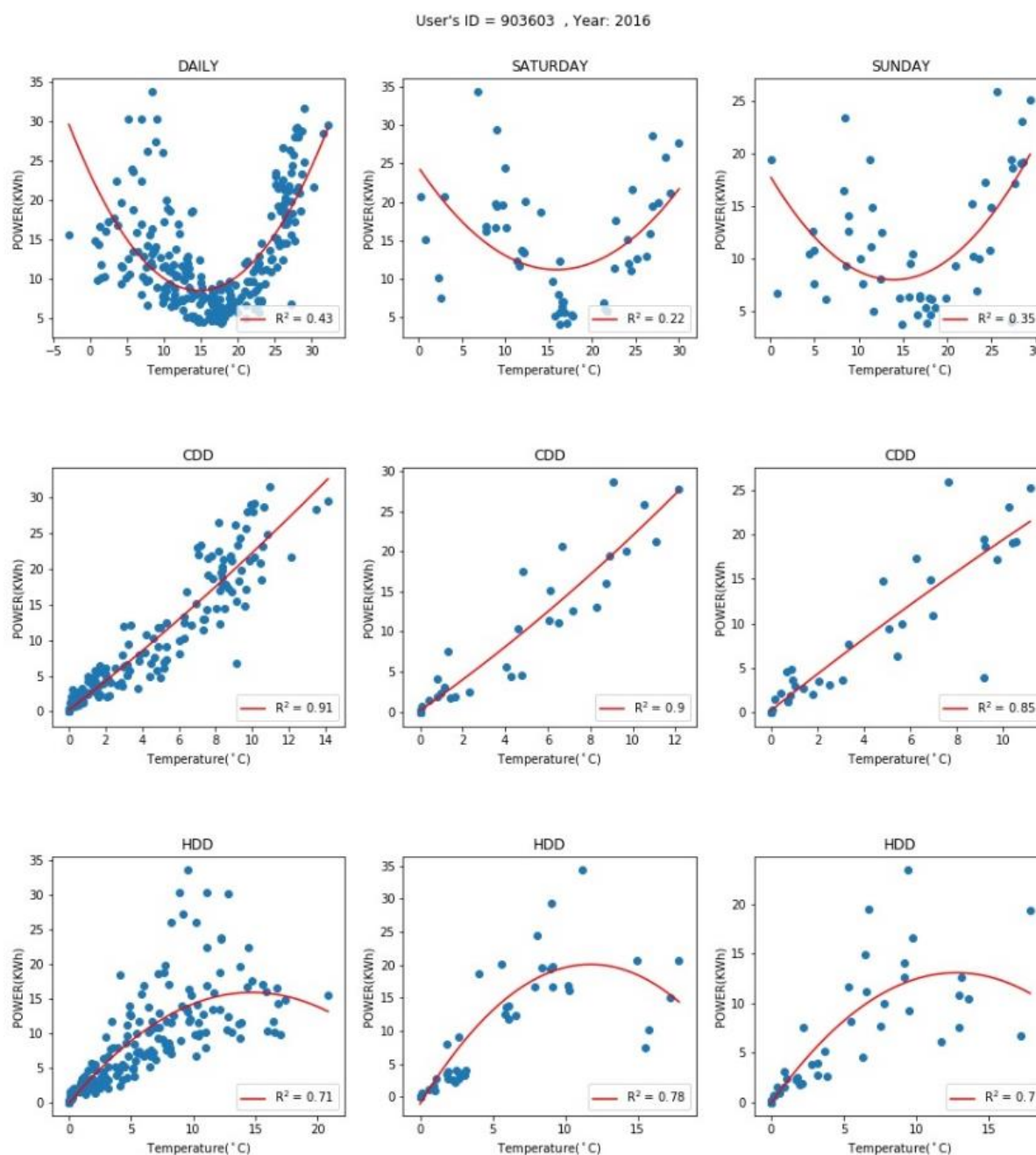
Figure 31 and Figure 32 plot for consumers 2024083 and 903603, respectively, the correlation between power consumption and ambient temperature, Cooling Degree Days (CDD) and Heating Degree Days (HDD).

Consumer 2024083 presents a low consumption/temperature correlation throughout the year, being the  $R^2 = 0.49$  in working days and lower in Saturdays and Sundays. Better correlation values are observed when comparing consumption to CDD and HDD, including working days, Saturdays and Sundays. In addition, the correlation seems slightly better in winter than in summer.



**Figure 31. Correlation between consumption and temperature, CDD and HDD in working days, Saturdays and Sundays of 2016 of consumer 2024083.**

Consumer 903603 presents similar  $R^2$  figures as consumer 2024083 when comparing consumption to temperature, CDD and HDD values. In this case, consumer 903603 presents better correlation in summer than in winter.



**Figure 32. Correlation between consumption and temperature, CDD and HDD in working days, Saturdays and Sundays of 2016 of consumer 903603.**

The above information and correlations between parameters will feed the load/DR forecasting.

### Technical specifications and advances from the existing tools

The tool considers a time horizon of a day, while time steps can be of 15 minutes to an hour, depending on the historical data available.

Regarding I/O data, weather data, mainly temperature and energy/power consumption historical data are to be considered as input, whereas the output is a set of time-series, exported in \*.csv format.

Building Occupancy & Energy Consumption Simulation tool requires consumer's data and connection with an external service to retrieve the weather data.

After data are processed, the tool feeds these data to the load/DR forecasting as well as gamification tool component (i.e. Intelligent Building Control & Flexibility Prediction-Forecasting Tool within inteGRIDy project).

The programming language is Python and it can operate either in Windows 10 or Linux OS. The main libraries utilized from Python are:

- *Numpy* (<http://www.numpy.org/>): utilized for the linear algebra and numerical analysis capabilities, and,
- *Pandas* (<https://pandas.pydata.org/>): utilized for the time-series analysis required.

Within the INERTIA project framework, the tool has been developed mostly to address behavioural patterns and their correlation with the energy consumption of the residents within a facility, being either residential, or commercial [INE14]. Within, inteGRIDy an expansion of the tool has been attempted, to create load profile mechanisms that would aid during the load forecasting process. Moreover, since the load profiles are related mainly to buildings, a correlation between energy consumption and ambient temperature is developed in order to enhance the accuracy of the profile, and thus the load forecasting in power-to-heat cases, e.g. use of HVAC, or air-conditioning.

### Expected advantages compared to commercial products

The main functionality of the tool is to provide load profiling according to historical data of energy consumption. This process is usually an essential stepping stone that leads to more elaborate ones such as a load forecasting or even further to propose an optimized DSM strategy, either in facility level, that is an individual customer, or in aggregated level, that is a DSM portfolio for an aggregator, either with the use of BESS, or in the form of a DR scheme. Thus, a lot of attempts have been made, to tackle this fundamental issue, either in a top-down approach [FAN11], [SAN14], or bottom-up [TSU04], [SWA09], leading to more or less accurate results.

The more accurate the results, though, the more elaborate the load profile process is, the more input parameters it requires, and more complex the algorithm it becomes. Hence, the tool would require to be more intrusive for the end-consumer, needing for example, apart from the energy consumption, motion and occupancy data and less probable to scale it up to aggregated level, since more equipment per facility would be needed leading to non-viable business models, and even more elaborate algorithm for big data analytics. Within inteGRIDy however, simplicity was pursued in order to avoid all those issues, and promote an effective business model and a scalable solution. Moreover, since only the energy consumption is required, along with the weather data, the approach respects the privacy of the end-consumer, being in that way, aligned with the human-centric approach dictated as a main principle of the project and with the GDPR regulations of the EU. Thus, it can operate both for any single individual facility, being either residential, or commercial, and in aggregated level, that is for a DSM portfolio, providing either the end-consumer, or the aggregator, with valuable information.

Additionally, the tool has a modular structure that enables it to expand by adding more features, such as including a simplified model of a facility, in order to determine the energy consumption, and be called upon whenever simulations are to be conducted for various DSM strategy scenarios.



***Implementation features and delivery:***

The tool is applied in the inteGRIDy pilot project of Thessaloniki to generate user consumption profiles for week days, Saturdays and Sundays or Bank Holidays according to the season of the year. The tool can also assess the user's energy consumption flexibility.

Currently a demo of the tool is not available.

A standalone application will be delivered that can be executed as a virtual machine.

The instance of this tool can be downloaded from: <https://varlab.iti.gr:9443>

Code is accessible upon request. Contact info:

Napoleon Bezas : [bezas@iti.gr](mailto:bezas@iti.gr)  
Lampros Zyglakis : [zyglakis@iti.gr](mailto:zyglakis@iti.gr)  
Athanasios Tryferidis : [thanasic@iti.gr](mailto:thanasic@iti.gr)

### 4.3 Demand Response and Demand Side Management

This section addresses the macro-functionality DR and DSM, which according to Deliverable “D1.5 – inteGRIDy Architecture & Functional/Technical Specifications”, includes the following layers:

- Energy DR Matching. This includes models capable to alter the profile of consumption of electricity to match generation.
- Demand Flexibility. Through the characterization of consumer consumption profiles, it is possible to identify the energy that can be reduced, displaced or injected, so that it is possible to match both consumption and generation profiles.
- Prosumer Profiling. Characterization of both generation and consumption profiles of prosumers.
- DR Shifting. Identification and modification of user energy consumption profiles to enable load displacement from peak to off-peak time periods.

The following subsections characterize the inteGRIDy DR and DSM tools:

- Demand Side Energy Profiling, developed by TREK.
- Multi-Carrier Hub Optimization Engine, developed by Engineering (ENG).
- Kisense Energy Management System, developed by VPS.
- Integrated Test Environment, developed by University of Newcastle (UNEW).
- Distributed Energy Management System DEMS, developed by Siemens.

#### 4.3.1 Demand Side Energy Profiling

##### General description of the inteGRIDy functionalities

The Demand Side Energy Profiling (DSEP) tool aims at calculating the available energy demand flexibility of individual end users, enhancing the estimation accuracy through the incorporation of a number of models tuned on raw data collected from end user premises. These models address the DER models of the available HVAC, lighting and DHW systems, visual and thermal comfort profiles, and virtual energy storage (VES) potential of domestic water heaters and building spaces. To generate these profiles, the tool retrieves the following information from the Field Middleware Layer (as described in D1.6), collected locally at the end-user premises:

- Building specific user comfort conditions: temperature, humidity and luminance
- Occupancy information per pilot site
- Operational status/mode of heating, ventilation and air conditioning (HVAC), water heater and lighting devices, and reported interactions of the users with the system
- Energy consumption of HVAC, water heater and lighting devices

The main objective of the tool is to enable the design of context-aware, human-centric, explicit DR campaigns that utilize the available flexibility in an optimal way, while complying with the comfort limitations of the end-users to eliminate any possible nuisance. Furthermore, by incorporating considerations of VES following an energy-to-heat approach, the tool investigates the storage capabilities offered by the available water heaters and the building envelop, further incorporating a building thermal model. In this way, the tool calculates the amount of flexibility that can be dispatch without interfering with the consumer comfort or daily routines.

The comfort profiling mechanism of the tool is based on the extraction of the probability distribution functions describing the visual and thermal comfort of the occupants, determining



the comfort boundaries within which the context-aware demand flexibility is determined. These comfort boundaries are dynamically updated and can be translated to temperature and luminance upper and lower limits, determining the optimal indoor ambient conditions. The DER models of the lighting, HVAC and DHW systems are calibrated on actual data collected from the end-user premises. These models are necessary to correlate the required thermal power and luminous flux with the electric energy of the corresponding device for the determination of the energy demand flexibility. The calculation of the available VES potential, is based on a probabilistic adaptive model that has been developed to estimate the limits of the hot water mass flow required by an occupant based on individually determined DHW usage patterns and the thermal storage capacity of the participating buildings.

More specifically, the main functionalities offered by the tool are:

- Prosumer thermal and visual comfort profiles
- VES potential (based on building thermal modelling and DHW system modelling)
- Context-aware energy demand flexibility

Although the above-mentioned explicit DR campaigns are not defined within the DSEP tool, the extracted energy demand flexibility acts as the basis for their determination within the Visual Analytics Engine (VAE) tool, described in detail in D4.4. In Table 7, the alignment of the tool with three of the four project pillars, Demand Response, Smartening the distribution grid & Energy storage technologies, is presented along with the corresponding use case requirements defined in D1.3 & the use cases defined in D1.5.

**Table 7. Alignment of DSEP with inteGRIDy project pillars.**

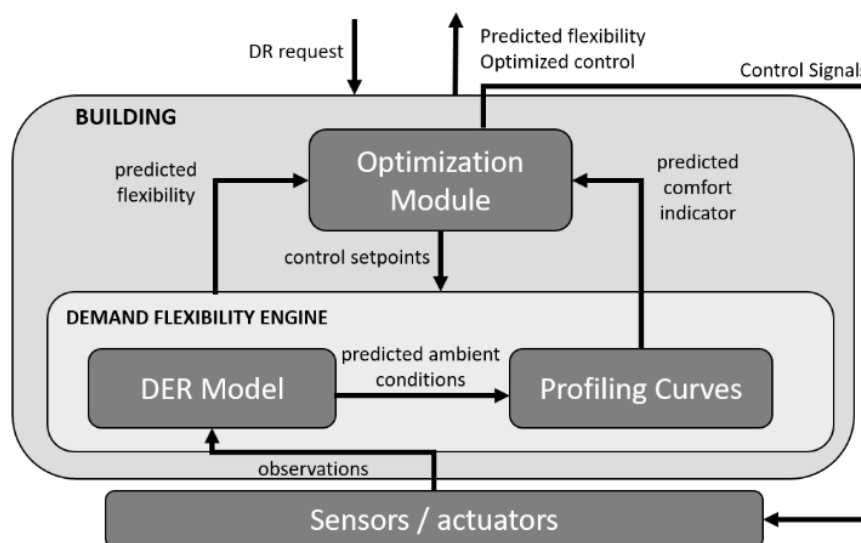
Project Pillar	Use Case (as defined in D1.3 & D1.5)	Comment
Demand Response Smartening the distribution grid	INN_UCA1: Continuous calibration of Prosumer Profiling Models INN_UCA2: Periodic calculation of Context Based Demand Flexibility Profiles	The two project pillars are addressed by the DSEP tool in order to calculate the context-aware demand flexibility of the end-users over a defined time horizon utilising real-time information collected from the end-user premises. The human-centric models addressing comfort, behavioural patterns and demand flexibility are continuously updated.
Energy Storage technologies	INN_UC03: VES in Buildings through optimised HVAC and water heaters control	The concept of Virtual Energy Storage has been included in the demand flexibility calculation by further incorporating the building thermal model and the DHW system model in an energy-to-heat approach.

### Details of the modelling process

The DSEP tool is based on an in-house developed heuristic algorithm that exploits integer non-linear programming techniques to untap the hidden flexibility of HVAC, water heater and lighting devices. The explicit demand response scheme addressed in inteGRIDy requires the continuous computation of flexibility from DR assets and its visualization for the DSO operations. Although the Demand Side Energy Profiling tool embeds a multi-period calculation, a continuous real-time calculation of flexibility will be used in inteGRIDy.

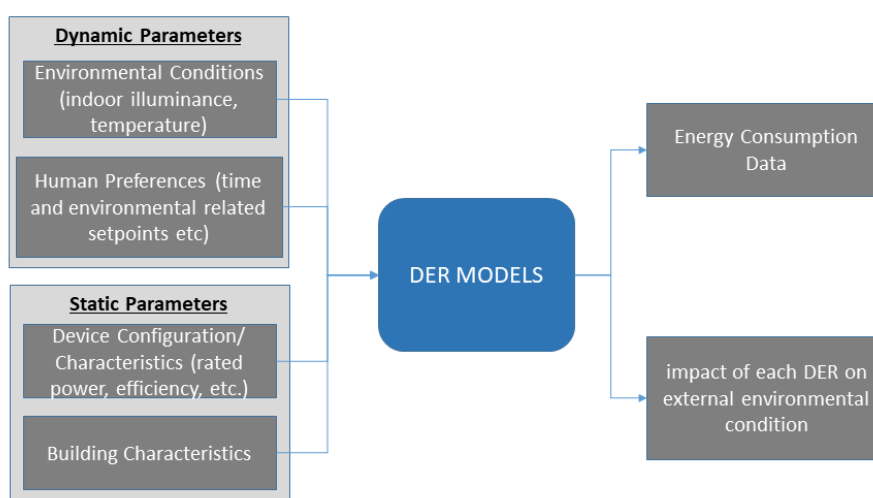
Temperature, luminance and humidity data is collected from the analysed buildings. In addition, HVAC, water heater and lighting consumption data and operational status/mode are collected.

The operation schematic of the Demand Side Energy Profiling is depicted in Figure 33.



**Figure 33. Demand Side Energy Profiling operation schematic.**

In addition to the calculation of energy consumption, the enhanced DER models provide as an output parameter the impact that the operation of each DER has on indoor environmental conditions (Figure 34).



**Figure 34. Inputs and outputs of the DER models.**

Along with the definition of DER model parameters, the proposed framework is considered as context driven, and thus the incorporation of human preferences and environmental conditions is a main prerequisite for the definition of flexibility profiling engine. Therefore, the objective is to define occupants' comfort profiling models that could be further incorporated in the algorithmic process towards the extraction of DER-specific flexibility values. Thermal and visual comfort profiles are defined associated with the operation of the aforementioned controllable devices. In the following subsections, the modelling approaches and techniques implemented in the DSEP tool are presented.



## Comfort

The visual and thermal comfort profiles are generated and are continuously adapted to low-level sensor and consumption data that describe the consumer's ambient environment. The profile extraction related to comfort is based on an inhouse Bayesian algorithm which correlates raw data collected at the premises of the consumer with specific events referring to user interactions with the system. Through this correlation, the distribution functions of comfort and discomfort probability are extracted for the end users. Given that Bayesian classifiers are proven reliable at calculating probabilities, they have been implemented in order to calculate the probability of a certain environment being comfortable or uncomfortable to their occupant. Such a classifier bases its judgment on the physical variables it measures and classifies the examined zone as comfortable or not. In particular, this classifier will look for correlations between different types of discomfort levels and environmental parameters towards the extraction of accurate behavioural profiles.

User comfort and discomfort can be explicitly inferred from the actions taken by the user to readjust the ambient conditions in his/her space. The ambient conditions triggering a user action are considered to be explicit indications of discomfort. In the same way, the adjusted conditions after a user action are considered to be explicit indications of comfort. The lack of any user action is regarded as an implicit indication of comfort, as no further adjustment to the ambient conditions is required. The *visual comfort* is generally expressed by the following formula:

$$p(Disc|Envir) = \frac{w \cdot p(Envir|Disc)}{w \cdot p(Envir|Disc) + (1 - w) \cdot w \cdot p(Envir|Comf)} \quad (75)$$

In this expression,  $w$  represents the weight factor,  $p(Envir|Disc)$  is the probability of a luminance state given the discomfort level, and similarly,  $p(Envir|Comf)$  is the probability of a luminance state given the comfort level. Comfort levels are indicated by the user implicitly through the lack of action to the current ambient conditions. The weight factor is used to balance the contributions of the implicit and explicit comfort information inferred and is readjusted in the duration of the system's training period. The implicit information is generally assigned a significantly lower weight than the explicit one due to its less straightforward interpretation. However, as the training level progresses the weighting factors tend to become more balanced.

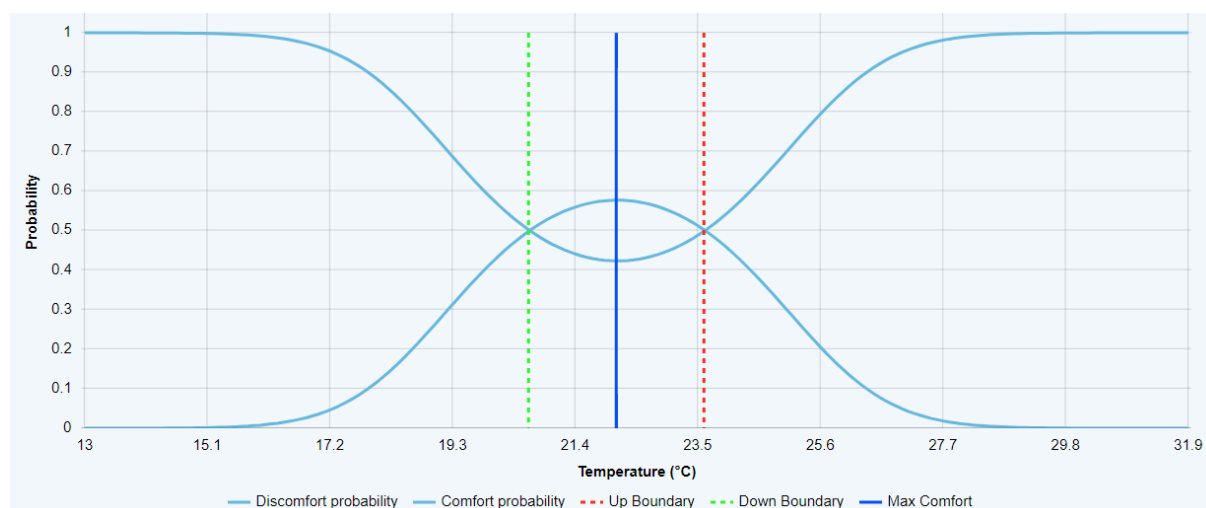
The system performs clustering on the collected raw streams of data to identify the illuminance levels where the users tend to react more often, thus determining the major comfort and discomfort zones. To extract the comfort and discomfort indicators, a Hidden Semi Markov Model (HSMM) is applied. Based on this model, the probability of transitioning between comfort and discomfort depends on the unobstructed duration of the current state and the transition to an observed state when the user interacts with the lighting system. All inferred probabilities are combined to calculate the final calculated comfort and discomfort probabilities as a function of luminance level and time. Through these comfort and discomfort profiles, the boundaries used to identify the end-user flexibility to comfort fluctuations are extracted.

A very similar method, based on a Naïve Bayesian algorithm, is employed to generate the *thermal comfort* profile of the end-user by extracting the comfort and discomfort distribution functions for given temperature and humidity conditions. Just as in the case of the visual comfort, the ambient conditions triggering user interactions with the HVAC system are considered to explicitly indicate discomfort. Subsequently, the user actions to adjust the indoor ambient conditions are considered to be an explicit indication of thermal comfort, while the lack of any action is further considered to be the implicit indicator of comfort. The formula generally expressing the Bayesian thermal comfort model is the following:

$$y_{th} = p(Y_{th} = 0 | x_t, x_h) = kp(Y_{th} = 0)p(x_t \vee Y_{th} = 0) \quad (76)$$

In the above expression,  $y_{th}$  stands for the probability of the user satisfaction with the ambient thermal state when  $Y_{th} \in \{0, 1\}$  is 0, and for  $x_t$  and  $x_h$  being the temperature and humidity inputs respectively. The conditional probabilities  $p(x_t \vee Y_{th} = 0)$  and  $p(x_h \vee Y_{th} = 0)$  are extracted through a Kernel density estimation. Just as explained for the case of visual comfort, two probability distribution functions are extracted, addressing the thermal comfort and the thermal discomfort. Through these functions the temperature boundaries imposed on the system are extracted. It is worth noting that also in the case of thermal comfort, the generated user profiles are dynamically updated based on real life raw data streams from the end-user premises.

Consumer flexibility profiles rely on visual and thermal comfort boundaries as well as a discomfort utility function that indicates the degradation that demand deviations (i.e. flexibility) may lead to consumer's comfort. The correct definition and quantification in real-time of the boundaries and cost of demand flexibility can deliver critical information to the optimization strategy presented later in this chapter. Figure 35 presents an ideal representation of the probability distribution functions of thermal comfort and discomfort, delimiting the corresponding thermal comfort boundaries.



**Figure 35 Ideal thermal comfort and discomfort probability functions**

### DER models

DER models are employed to derive a consumer-centric demand flexibility framework by correlating the electricity requirements of the devices in question and the required luminous flux or thermal output. These models include the mathematical formulations to compute the electricity consumption of each DER type as a function of dynamic input data and static (configuration) parameters that affect their operation. In relation to the consumer thermal and visual comfort, two DER models are developed to describe the lighting system and the HVAC system. As the solution is based on machine learning techniques, the DER model of each device will be independently calibrated per pilot user based on data collected at the end-user premises.

The model implemented for the *lighting devices* takes into account only the cases of dimming lights, as the calculation of electric demand for the on-off lights is a straight-forward procedure, and is based on the average consumption values of the “on” state. For the electric load calculation, it is assumed that there is a direct correlation between the dimming level and the energy consumption of the lighting system. The operation of the lighting system is not affected

by any delays or memory effects. In this simplified approach, the dependency between the input power and the light output of the lighting device is assumed to be linear. This linear behaviour is approximated by the following formula.

$$P_{output} = P_{nominal} \cdot Status \cdot Dim\_level \quad (77)$$

where,  $P_{output}$  is the lighting device consumption and  $P_{nominal}$  is the lighting system's nominal power. During the calibration phase of the lighting system model  $P_{nominal}$  will be extracted through a measurement-based learning process, as discussed above. Linear regression will be used to correlate the dimming level and status of the device to  $P_{output}$ , to identify the parameter  $P_{nominal}$ .

For the *HVAC DER modelling*, the developed model focuses on electric HVAC solutions. More specifically, the model is based on the operational principle of a heat pump, in which the instantaneous efficiency or Coefficient Of Performance (COP) of a heat pump is defined as the ratio of the thermal power delivered to a thermal zone by the heat pump ( $\dot{Q}_{hp}$ ) to the electrical power consumed ( $P_{el}$ ), mathematically expressed as:

$$COP = \frac{\dot{Q}_{hp}}{P_{el}} \quad (78)$$

It is evident that by estimating the COP, the transformation rate of consumed electrical energy to supplied thermal energy of the heat pump and vice versa can be calculated. The most important difficulty in its calculation is that depending on the heat pump type, the supplied thermal power and COP is depended on multitude parameters such as the outlet medium temperature and the ambient temperature (for air sources). This principle is mathematically expressed as follows:

$$\dot{Q}_{hp} = f(T_{outdoor}, T_{HP,out}), \text{ therefore:}$$

$$COP \sim f(T_{outdoor}, T_{HP,out})$$

where  $T_{outdoor}$  is the outdoor ambient temperature and  $T_{HP,out}$  is the output temperature of the heat pump's transfer fluid. The definition of the COP for the modelled system is based on the theoretical expression of the Carnot cycle describing an ideal case without any losses and the COP is expressed as following:

$$P_{el} = \dot{Q}_{hp} - \dot{Q}_c \quad (79)$$

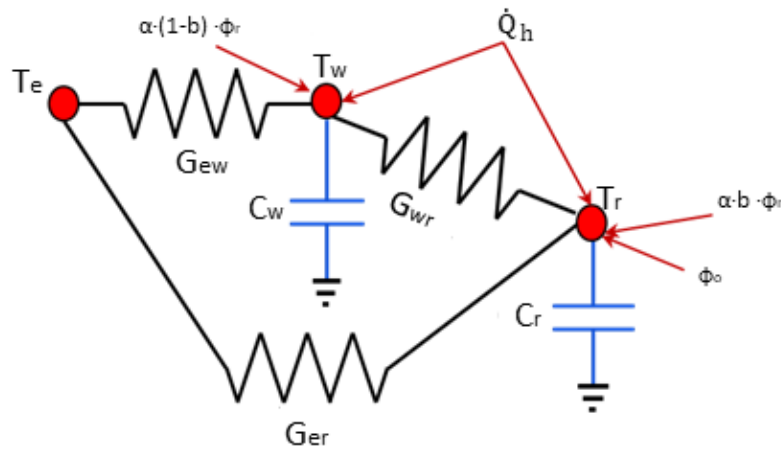
$$COP_{Carnot} = \frac{T_{HP,out}}{T_{HP,out} - T_{outdoor}} \quad (80)$$

Although many complicated expressions have been presented in literature to improve the accuracy of the COP approximation, a simpler approach is implemented in the inteGRIDy flexibility calculation mechanism. In this approach, the output temperature of the system  $T_{HP,out}$  is assumed to be constant within a cycle and is updated at each new iteration. The scenario further assumes the COP to be independent from the  $T_{outdoor}$ , which results to a constant COP over the prediction horizon, that can be calibrated based on real time data collected at each consumer premises. Therefore, the following expression can be assumed:

$$P_{el} = \frac{\dot{Q}_{hp}}{Constant} \quad (81)$$

### Building thermal model

To assess the context aware demand flexibility of the consumers, describing the device behaviour alone is not sufficient. It is also important to describe how the thermal behaviour of the building is affected by changes in the energy usage for heating and cooling purposes. For these reasons, the model of the thermal zone undergoing the effects of heating or cooling must also be included, accounting for the thermal losses and gains within the area of interest. This building thermal model is based on a 3R2C model with one controllable input value, in this case the thermal power provided by the heating system ( $\dot{Q}_{hp}$ ), and three non-controllable inputs, namely: the solar global irradiance ( $\phi_r$ ), the internal gain provided by the occupants and the internal supplies,  $\phi_o$ , and the external temperature,  $T_e$ . Figure 36 presents a representation of the described RC model.



**Figure 36 RC building thermal model**

Two nodes are defined in the system, representing the wall (w) and indoor air (r) and the thermal input from the plant  $\dot{Q}_h$ , is divided between the 2 nodes using the coefficient  $f_w$  as defined in the dynamic equations of the model. There are two state variables, named  $T_r$  and  $T_w$ , which represent respectively the indoor environment temperature, and the external walls temperature. Each state variable is associated with the corresponding heat capacity, namely  $C_r$  and  $C_w$ . The dynamic equations are provided below:

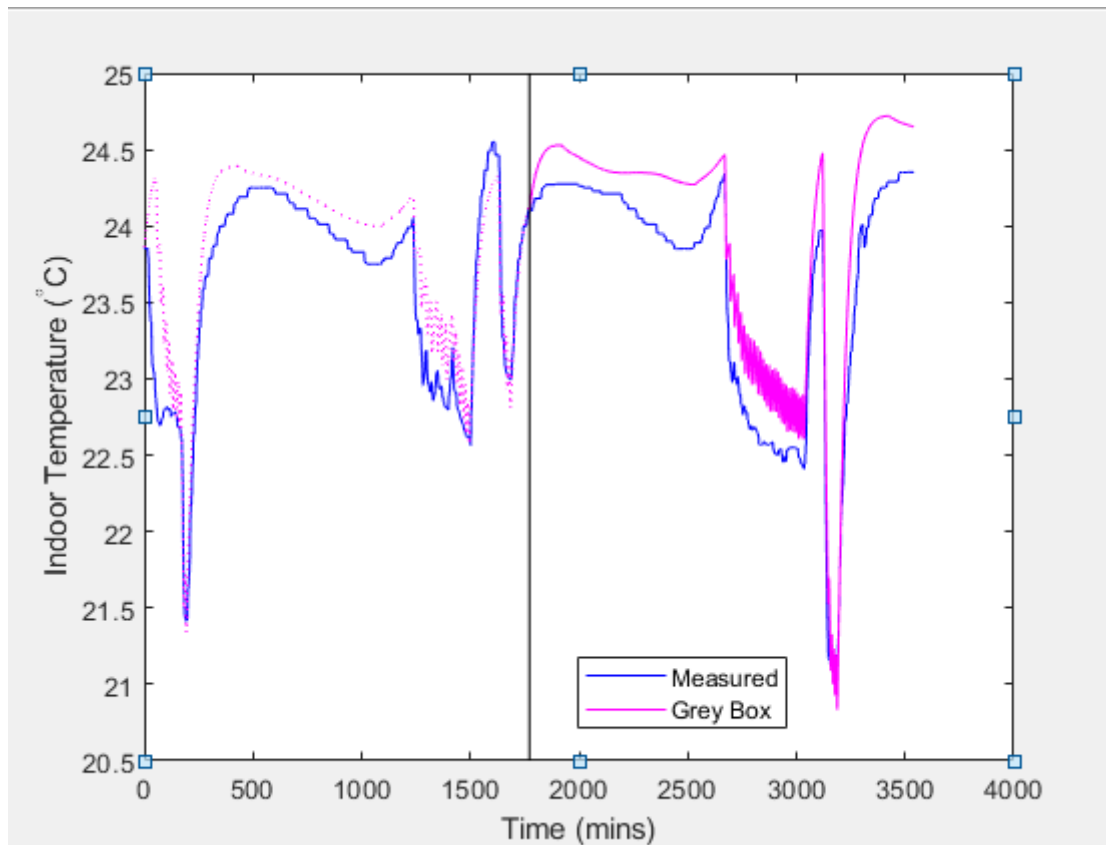
Room temperature:

$$C_r \frac{dT_r}{dt} = -(G_{rw} + G_{re})T_r + G_{rw}T_w + \phi_o + ab\phi_r + G_{re}T_e + (1 - f_w)\dot{Q}_h \quad (82)$$

Wall temperature:

$$C_w \frac{dT_w}{dt} = -(G_{wf} + G_{wr} + G_{we})T_w + G_{wr}T_r + a(1 - b)\phi_r + G_{we}T_e + f_w\dot{Q}_h \quad (83)$$

The parameters  $G_{xy}$  define the thermal conductance between the temperature expressions  $T_x$   $T_y$  (where x & y define the interface between r: room, w: wall, e: external),  $\alpha$  and  $b$  are parameters related to the solar input. The parameters  $G_{xy}$ ,  $\alpha$ ,  $b$ ,  $C_w$  and  $C_r$  are trained parameters, using the System Identification toolbox. The model is considered to be a Grey-box model. In Figure 37, the evolution of the indoor temperature predicted by the described model is presented and evaluated against real data collected at TREK's premises.



**Figure 37 Building thermal model results against measured data**

Once the state space model has been defined, a cost function is formulated to define the optimal thermal demand that results to the context-aware flexibility related to the HVAC usage. The cost function is expressed as:

$$J = \int_{t_0}^{t_f} f \dot{Q}_h + (1 - f)(T_r - T_{set})^2 \quad (84)$$

where  $f$  is a parameter from 0 to 1 that determines the influence of the energy consumption with respect to thermal comfort. The function is subject to the following constraints:

$$\dot{Q}_{h_{min}} \leq \dot{Q}_h \leq \dot{Q}_{h_{max}}$$

$$T_{min} \leq T_r \leq T_{max}$$

where  $T_{min}$  and  $T_{max}$  are the comfort boundaries extracted from the thermal comfort profiles described above. To solve this problem numerically a quadratic programming algorithm is employed since the system is linear, but the cost function it's quadratic. From the obtained  $\dot{Q}_h$  and the heating technology used the temperature profiles for the radiators can be found.

#### *DHW model*

In order to investigate the VES potential of the pilot users that can be utilised in the cases when load shifting is necessary, the available water heaters are investigated as controllable loads offering energy storage possibilities. The investigated strategies must comply with the user's

comfort requirements and daily routines, while also be energy efficient in the sense that no new demand load peak occurs outside the controlled time frames. For these reasons it is important to not only properly model the DHW device but also the DHW demand.

To accurately model the DHW demand, a bottom-up and data driven, modular approach is followed to maximize the accuracy of the DHW demand per building on a short-term basis. The model inputs are limited to mass flow measurements and activity patterns; however, sensing data including occupancy status is also included for the model calibration and the development of the activity model. The model is dynamically updated to account for changes concerning occupant behaviour, seasonal changes and environmental conditions. The model's output will be a timeseries that when introduced to the DHW model will provide the VES potential related to water heaters.

The DHW demand module incorporates the necessary stochasticity given the uncertainty inherent to the consumption of DHW, which is primarily induced by the activity modelling but is not limited to it. The output of the model is based on time-series based as it feeds the DHW model (described below) to generate the electrical consumption time-series. The activity model comprises of the following parts:

- Generation of a matrix containing normalised, conditioned data from sensing equipment, namely: mass flow rate ( $\dot{m}$ ) vs timestamp.
- Screening of the above described matrix for the detection of water\_draw events (G) characterized by two characteristics: the event duration and the average mass flow throughout the duration.

$$G = [\bar{m}, dt]$$

- Assignment of the detected water\_draw events  $\{G_1, G_2, \dots, G_n\}$  to a larger array correlating each event ( $G_n$ ) with information concerning the season of the year, the day-type (working day/weekend), the time of event occurrence, and the corresponding "Activity\_ID" that represents an output of the "DHW-activity" modelling.

Based on the correspondence of the "Activity\_ID" to "water\_draw" events, the forecast generator will be able to estimate the DHW demand profile given the outcome of the activity model.

The DHW modelling approach implemented in the DSEP tool combines the DER model of the available water heater and the water tank model in a unified model. This unification is made under the assumption that the DER model of the water heaters comprises of an electric resistance model which is considered to be fundamental. Moreover, as the sensorial equipment installation for the needs of the project has been designed to be non-intrusive, the amount of data collected in relation to the water tank is limited. For this reason, the model assumes no stratification of the water temperature within the tank.

The DHW model is expressed by the following energy balance equation:

$$\rho \cdot c \cdot V \cdot \frac{dT_{tank}}{dt} = \dot{Q}_{el} + \dot{Q}_{in} - \dot{Q}_{loss} - \dot{Q}_{demand} \quad (85)$$

where,  $V$  represents the tank volume ( $m^3$ ),  $\rho$  is the water density ( $\rho=1 \text{ kg/L}$ ),  $c$  is the water specific heat capacity ( $c = 4.184 \text{ kJ/(kg} \cdot ^\circ\text{C)}$ ),  $\dot{Q}_{in}$  is the input energy flow rate (W),  $\dot{Q}_{loss}$  is the energy flow rate indicating the thermal losses (W),  $\dot{Q}_{demand}$  is the output energy flow rate,  $\dot{Q}_{el}$  is the electrical consumption of the water heater.

A number of assumptions have been made for the sake of model simplicity and applicability, and are listed below:

- $\dot{m}_{inlet} = \dot{m}_{outlet} = \dot{m}$ ,  $\dot{m}$  being the water mass flow



- The temperature of the water within the tank is uniform
- $\dot{Q}_{loss} = \gamma(T_{tank} - T_{amb})$  - assuming that  $\gamma$ , thermal conductance W/°C, is constant,  $T_{tank}$  is the temperature within the tank and  $T_{amb}$  is the ambient temperature

Based on these assumptions the energy balance equation is transformed in the following way:

$$\rho \cdot c \cdot V \cdot \frac{dT_{tank}}{dt} = \dot{Q}_{el} - \gamma(T_{tank} - T_{amb}) + c \cdot \dot{m}\gamma(T_{in} - T_{tank}) \quad (86)$$

Regarding calibration and validation of the DSEP tool, the calibration of the described model based on data collected at individual prosumer premises allows the extraction of the parameters  $\gamma$  and  $V$  that express the characteristics of the available DHW system.

Within the DSEP tool, the derived comfort, DHW usage, building thermal model, and DER profiles are user-specific rather than described by a “one-fits-all” model. Therefore, the calibration of the models will be done individually per end-user and based on the available equipment and context information of the pilot users. In this context, the extrapolation of the profiles to a wider population is out of scope for the specific pilot demonstration, and hence no calibration and validation of the system models as a whole can be performed.

### Technical specifications and advances from the existing tools

The time horizon accepted by the DSEP tool can be any time window within a day, i.e. between the 00.00 and the 23.59 of every day of operation using 15-minute intervals. It is however empirically setup to be of maximum 2 hours in order to minimise the amount of error in forecasting of the flexibility calculations.

A tailored human machine interface, namely the VAE tool (presented in D4.4 and D4.5), will be provided to allow the DSO/aggregator to monitor and dispatch the required flexibility in the pilot premises.

In terms of I/O data, DSEP tool requires the following input data:

- Real-time measurements from local/remote sensors such as energy meters and environmental sensors
- Status of local devices collected by actuators installed at the end-user premises.

Data exchange within the tool includes setpoint, timestamp, status, control mode and luminance of HVAC, water heaters and lightings.

At the moment, the current version of the tool does not expose interfaces/data to other commercial solutions.

There are no dependencies with other software components for the tool's DR functionality layer. The tool operation however, requires the installation of a hardware infrastructure at the end-user premises including a set of environmental conditions sensors (lighting, temperature, humidity), energy meters, and control devices (controllable thermostats, lamps, smart plugs) in order to acquire real-time consumer/group data that feed the decision-making algorithm.

The DSEP outputs are further fed into the Visual Analytics Engine (VAE) platform, described in detail within D4.4 and D4.5, in order to provide graphical representations of asset (referring to both residential and commercial customers) performance, flexibility and other analytics as well as to extract optimized DR campaign and perform implementation operations.

The tool is developed in Java/Spring programming codes. In addition, Json is used as a data exchange format. The database management system is based on MySQL.



Given that the programming language is Java, the tool does not present any constraint in the operating system where it is run.

Interfaces with environmental conditions sensors and actuators (e.g. controllable thermostats, HVAC systems, water heaters, controllable lamps) installed at the pilot installations have been considered for the tool deployment.

### **Expected advantages compared to commercial products**

Within InteGRIDy and with focus on the St. Jean pilot, the calculation of demand flexibility only addresses domestic and commercial loads. In general, Domestic load consists of lights, fans, refrigerators, heaters, television, small motors for pumping water etc. It is the type of electric load mainly corresponding in residential and tertiary buildings. Most of the residential load typically occurs only for some hours during the day (i.e., 24 hours) e.g., lighting load occurs during night time and domestic appliance load occurs for only a few hours. Commercial load consists of large HVAC units, lighting for shops, fans and electric appliances used in restaurants, fridges and refrigerators for market shops, etc. This class of load is operational for more hours during the day as compared to the domestic load. The commercial load has seasonal variations due to the extensive use of air-conditioners and space heaters.

In general, a number of forecasting methods have been proposed in research projects to assess demand flexibility focusing on forecasting the consumption of flexible devices based on historical energy consumption data collected at the prosumer premises. However, no commercial systems have been established to this day. So far, a number of proposed methodologies for the prediction of energy demand flexibility have implemented diverse machine learning techniques [BUN00] [COT03] such as: Artificial Neural Networks (ANNs), Fuzzy Logic, Support Vector Machine (SVM), statistical modelling and other.

More device-specific methodologies propose the extraction of flexibility based on energy consumption data collected at the end-user premises using smart meters and focusing on major residential loads [DON13]. More specifically, heat-pumps have been defined as a significant source of flexibility [KOU15] and have been used as an indicator of demand flexibility. A probabilistic model for predicting the device status, operation time, and duration is proposed in [BAR11]. However, the majority of the identified frameworks have been case specific, customised to specific problems and modelling assumptions, and small variations are expected to significantly influence the model performance. Moreover, user comfort is most often reduced to pre-determined schedules for defined user types which leads to inaccurate account of end-user behaviour.

As the InteGRIDy project aims at contributing to the investigation of novel DR strategies implementing explicit/implicit DR, energy storage management and further ancillary services, it is deemed important to develop reliable methodologies for the dynamic prediction of demand flexibility. In specific, the tools demonstrated within the St. Jean pilot activities focus on explicit DR strategies in residential and tertiary buildings. This renders the accurate assessment of demand flexibility essential since no interaction between the end-user and the system is foreseen. As the system aims at implementing explicit DR in a non-intrusive manner to avoid any disruptions to the end-user comfort and daily routines, it is evident that comfort, flexibility sources and building characteristics should be the three main factors (along with occupancy which can be integrated within the comfort calculations) that lead to the estimation of the available flexibility, which can be offered by a building/asset. Under these considerations, the flexibility forecast adopts a human-centric and context-aware approach to ensure the user satisfaction.

In general, flexibility sources can be categorized to load devices, storage devices and generators according to how they cope with electric power. In principle, every device could potentially be considered as a source of demand response. However, based on their

properties, availability and operational patterns only a limited number of a systems has been deemed appropriate for participating in demand response services. The DSEP tool developed within the context of InteGRIDy, utilizes the flexibility offered by HVAC and lighting systems as well as the VES potential of domestic water heaters and the building through trainable models. The training of the DER and building thermal models implemented in the DSEP tool is conducted on data collected at the prosumer premises, lifting the constraints of previous methodologies imposed due to model specificities.

Moreover, the Comfort Profiling implemented in the DSEP tool is considered a major advantage compared to existing systems as it identifies and dynamically updates the comfort preferences per prosumers in a stochastic manner. As in the case of the DER models, the Bayesian approach used for the estimation of comfort conditions eliminates case-specific parameters required by detailed thermal comfort models traditionally used in literature (e.g. Predicted Mean Vote (PMV) model and its modified versions). The underlying Bayesian algorithms estimate the end-user preferences through his/her continuously monitored behaviour and ambient conditions. Thus, comfort considerations are explicitly addressed ensuring the more accurate and effective estimation of demand flexibility.

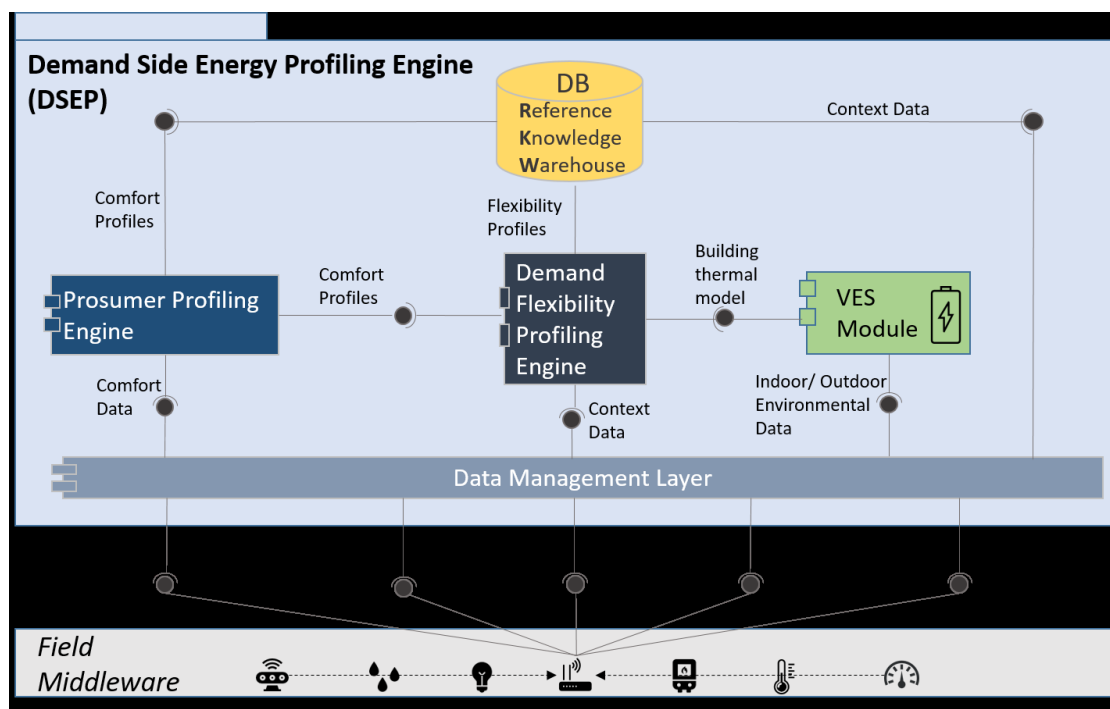
The DSEP tool further incorporates considerations of thermal storage encompassing the thermal storage capabilities of existing domestic water heaters and building spaces (building thermal inertia). This allows the shifting or modification of their energy consumption to dispatch desired amounts of flexibility with minimized influence on occupant comfort, always satisfying specified upper and lower comfort limits and without disrupting to unacceptable levels the daily routines and operations. The DHW system and building envelope can participate in DR events where an increase from the baseline consumption is requested, or, in the case of a DR request for reduction of demand, as supplementary energy sources for loads, to reduce grid consumption.

Nevertheless, although load modification in every single building cannot be large enough, the aggregated modification of demand for several buildings, which are part of demand response services via their aggregator, can be significantly large for participating in electricity markets provided that necessary legislation and technical modalities exist.

### **Implementation features and delivery**

Demand Side Energy Profiling tool is applied to the inteGRIDy St Jean pilot project, where comfort and device profiles (i.e. lighting, HVAC and water heaters) are generated. These profiles are processed to evaluate the given flexibility towards a DR event.

The conceptual architecture of Demand Side Energy Profiling tool is depicted in Figure 38, where the core features and interfaces supported by the tool are presented.



**Figure 38. Conceptual architecture of Demand Side Energy Profiling tool.**

The development of the DSEP Engine has been based on the THOR Occupant Profiling Framework (as indicated in the DoA, section 1.3.3. Positioning of the project). These mechanisms have been updated and customised to fulfil the requirements set by InteGRIDy and have been incorporated in the Prosumer Profiling engine for the extraction of the comfort profiles and the behavioural modelling. Moreover, significant development has been performed for the establishment of necessary information flows between the building infrastructures and the profiling engine (data collection, cleansing, normalization and event detection regarding ambient conditions and operational status of relevant demand loads). Moreover, within the project, the DSEP tool has been appropriately extended by incorporating the respective VES models developed on top of the THOR DER modelling engine, described in the previous section. All the models included in the tool are context-aware and human-centric and are calibrated based on raw data streams collected from the end-user premises.

The DSEP tool will be deployed in an Apache Tomcat container at the cloud server at TREK's premises. Furthermore, well defined REST interfaces are available to accommodate the various interactions between the different InteGRIDy components (as described in D1.5) while flexible distributed deployment of specific DSEP components can be performed when and if necessary, according to the needs of the InteGRIDy deployment and validation scenarios.

DSEP tool does not have available user manuals or tutorials available since it is a back-end component and profiling and flexibility estimations are not operations to be directly carried out by end-users.

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### 4.3.2 Multi-Carrier Hub Optimization Engine

#### General description of the inteGRIDy functionalities

The Multi-Carrier Hub Optimization Engine manages and optimises the energy flows inside smart microgrids. The main goal of the tool is to provide flexibility services to the DSO responsible of the MV grid to which the microgrid is connected to. The flexibility is provided by modulating the power consumption and generation patterns in accordance to the requirements set by the DSO. The tool includes the following functionalities:

- Collects all the data generated from the microgrid devices and suitably conveys them to the microgrid database employed to exchange information between the equipment installed and the Information and Communication Technology (ICT) platform
- Processes all the data coming from the field monitoring devices matching them with the DSO requests and the technical and operational constraints for optimising the energy microgrid operation
- Provides a Decision Support System that allows the operator to properly choose the most suitable solution and microgrid configuration
- Sends back the optimised profile in order to make the evaluated configuration effective by means of setpoints towards the microgrid equipment

The tool provides also a graphical user interface (GUI) that shows the most significant energy flows, price trends and process parameters to the microgrid operator.

As for the modelling functionalities, the Multi-Carrier Hub Optimisation Engine needs to handle data about the energy behaviour of controllable energy devices within the microgrid. These devices have the capability of modifying their energy profile adopting a scheduled optimised behaviour made up by setpoints for the entire time horizon. In order to do so, the tool has to know the flexibility limits of these resources, that in the case of Terni pilot microgrid are the CHP and the battery system, for properly performing the optimisation process. The models of these two systems allow to simulate, time stamp by time stamp, their energy behaviour and their statuses relying on the latest updated optimised results, configuring a parallel process that takes into consideration the operation of all the controllable energy units. Moreover, a first implementation of the economic modelling has been set up: the models are able to derive an estimated flexibility cost for the provision of this kind of service based on the time windows over a 24 hours time-horizon. In view of a future extension in a context where the information about flexibility economics are more reliable, further extension of the features could be implemented.

The functionalities of the Multi-Carrier Hub Optimisation Engine modelling layer cover three of the inteGRIDy pillars. As reported for the forecasting functionalities, the Demand Response pillar is involved in this case because the possible flexibility services provided as Demand Response services are assessed by calculating also the energy behaviours mentioned above. The presence of modelling capabilities and the corresponding information gathered from them allow to improve the knowledge of the modelled components and the possible smart application offered; in this view Smartening the Distribution Grid pillar is directly involved by these aspects. Finally, also the Energy Storage pillar is affected by the modelling functionalities presented in this section: the possibility of modelling the behaviour and the technical features of the battery system is crucial for their management and thus their exploitation in smart grid contexts.

#### Details of the modelling process

As state above, the Multi-Carrier Hub Optimisation Engine includes a module dedicated to the modelling and simulation tasks of microgrid equipment that can modify their energy behaviour,

in terms of power flexibility. In this view, a proper modelling allows referring to the actual capabilities of the considered systems.

This section details the battery and CHP models that feed the optimization process run by the Multi-Carrier Hub Optimisation Engine.

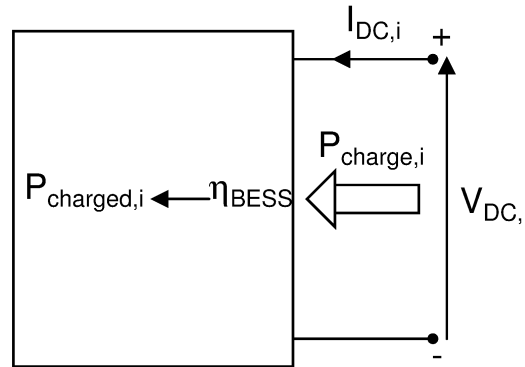
### Electric battery

The electrochemical energy storage is a key element to provide flexible availability to the optimisation algorithm. Relying upon its rated values, such as maximum and minimum charge/discharge power, ramp response, self-discharge, capacity, etc., and upon monitoring data retrieved from the field, such as current SOC and power flow, the model allows, firstly, to evaluate the proper flexibility capability of the battery system itself, in terms of maximum and minimum power in discharge/charge phase that can be reached in that particular operational configuration. Finally, the model, running in parallel with the optimisation process, allows to update the SOC of the battery system once the optimised solution is chosen and adopted; this value will be employed by the subsequent steps of the optimisation itself.

In the following, the battery model employed based on [JAC07] is outlined. In the model, the battery is considered as a “black box”, characterized only by its overall DC efficiency  $\eta_{BESS}$ . Measured electrical parameters are voltage, current and power at the battery DC terminals.

#### Charge of the battery

In case the battery is charging in the time interval  $i$ , quantities measured at the battery DC terminals are as depicted in Figure 39, where  $I_{DC,i}$ ,  $V_{DC,i}$  and  $P_{charge,i}$  are current, voltage and power.



**Figure 39. Schematic representation of the battery model in charging mode.**

The power actually absorbed by the battery in the time interval  $i$  is  $P_{charged,i}$ , which is lower than  $P_{charge,i}$  and may be evaluated as:

$$P_{charged,i} = P_{charge,i} \cdot \eta_{BESS} \quad (87)$$

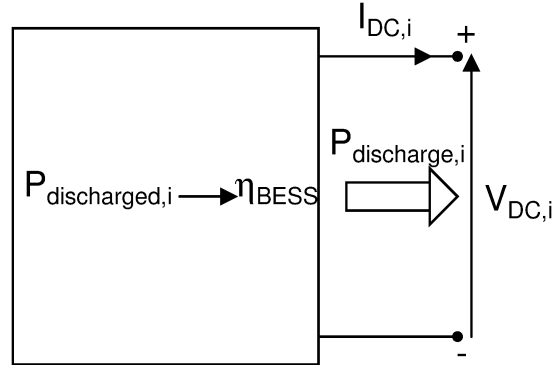
The SOC at the time interval  $i$  can be estimated as:

$$SoC_i = SoC_{i-1} + P_{charged,i} \cdot Dt_i \quad (88)$$

where  $Dt_i$  is the duration of the time interval  $i$ . If  $P_{charged,i}$  and  $Dt_i$  present units of kilowatt (kW) and hours respectively,  $SoC_i$  is expressed in kilowatt hours (kWh).

#### Discharge of the battery

In case the battery is discharging in the time interval  $i$ , quantities measured at the battery DC terminals are as depicted in Figure 40, where  $P_{discharge,i}$  is the discharge power measured at the battery DC terminals.



**Figure 40. Schematic representation of the battery model in discharging mode.**

The power discharged by the battery in the time interval  $i$  is  $P_{discharged,i}$ , which is larger than  $P_{discharge,i}$  and can be evaluated as:

$$P_{discharged,i} = \frac{P_{discharge,i}}{\eta_{BESS}} \quad (89)$$

The SOC at the time interval  $i$  can be estimated as:

$$SoC_i = SoC_{i-1} - P_{discharged,i} \cdot Dt_i \quad (90)$$

where  $Dt_i$  is the duration of the time interval  $i$ . If  $P_{discharged,i}$  and  $Dt_i$  presents units of kW and hours respectively,  $SoC_i$  can be then expressed in kWh.

#### Main assumptions of the model

- The evaluation of the SOC at each time interval by Eqs. (47) and (49) requires that the value of the SOC at the time interval  $i=0$  is known.
- The evaluation of  $P_{charged,i}$  and  $P_{discharged,i}$  at each time interval by Eqs. (46) and (48) requires the value of the overall DC efficiency of the battery,  $\eta_{BESS}$ . In principle, DC efficiency is not a constant value, but depends on the Joule losses of the internal resistance of the battery at the time interval  $i$ , i.e. depends on  $I_{DC,i}$  and the internal resistance value  $R_{int,i}$ , which in turn depends on  $SoC_i$  and the internal temperature of the battery  $T_{int,i}$ . The evaluation of  $T_{int,i}$  would require a thermal model, whose inputs would be the ambient temperature  $T_{amb}$ , the thermal resistance  $R_t$  of the battery and the thermal capacitance  $C_t$  of the battery. In order to minimize the complexity of the model, two options are available: use a constant value for  $\eta_{BESS}$ , taking into account that common  $\eta_{BESS}$  values for lead-acid batteries range from 0.75 to 0.85; or alternatively derive through experiments a lookup table linking  $\eta_{BESS}$  with  $I_{DC}$ , which could be further refined including whether the battery is in charging or discharging mode.
- Due to the errors introduced by the model in the approximated SOC evaluation, a recalibration of the SOC should be periodically performed. One way to perform this



recalibration is by assigning  $V_{DC}$  values to both  $SOC_{max}$  and  $SOC_{min}$  through experimental tests.

### *CHP model*

The other system appointed for being modelled is the CHP, representing the controllable generation source of the microgrid. In this case, the rated parameters of this device and the corresponding power monitoring data feed the modelling of the system energy performance. First, the evaluation of flexibility limits with respect to the actual status of the CHP is performed, providing the optimisation algorithm with information to undertake the management strategies.

The model of the CHP is based on collected technical and operational parameters. The energy units modelled consist of two CHP units able to supply 31 kVA with a power factor of 0.8 and associated operation control system, biomass feeding, master-control system for the generated energy flux regulation and grid stabilisation. The biomass-based generator is a three-modules system: the GEK fuel gasifier able to convert the wooden pellets into syngas, which is then fed to the internal combustion engine supplied by ALL POWER LABS Co. The engine is connected to an AC electrical generator supplied by Mecc Alte (model NPE 32-F/4). This multi-module fully automated machine can produce 400V (3 phase) electrical energy at 50Hz steadily and with a maximum thermal power of about 50 kW.

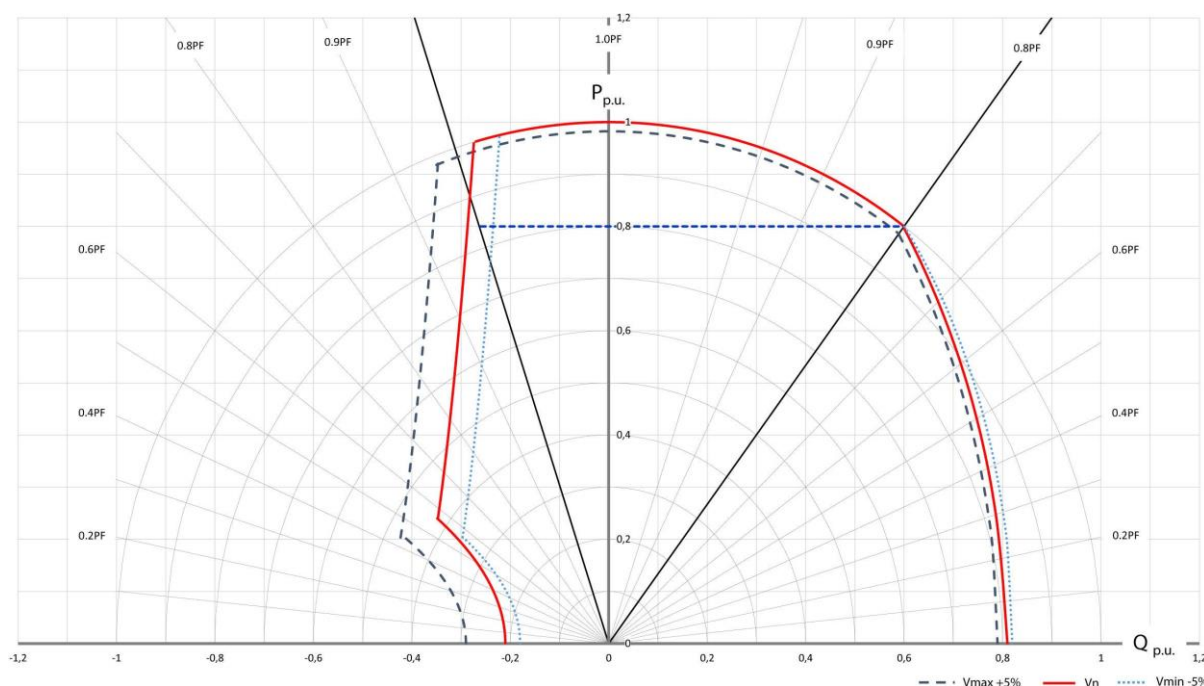
### *The electric generator*

The synchronous generator connected to the CHP is designed and produced within an ISO 9001 environment. It is a 4-pole alternator characterized by a robust mechanical structure built on the following materials: FEP12 steel for the frame, C45 steel for the shaft, cast iron or aluminium pressure die cast for the end-brackets, and fan is aluminium die casted either nylon fibre glass loaded, UL compliant materials. Rotors are dynamically balanced according to grade 2.5 of ISO 1940-1. All the windings are 2/3rds pitch to eliminate triple harmonics within the voltage waveform and to avoid eddy currents.

### *Model of generator*

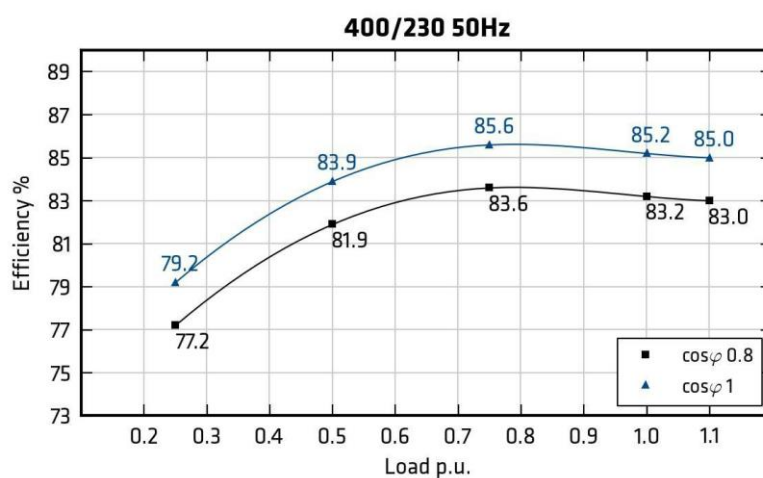
In the following it is presented a simplified model of a CHP focusing on the synchronous generator, since only electrical data are available from the field. Electrical data include measured voltage, current and power at the terminals of the generator. It is assumed that the whole system would be able to work continuously without any stop due to fuel absence. In addition, since the generator is already equipped with voltage and power regulators, it is assumed that the system is always able to provide the requested active power output. Technical limits are provided in Figure 41, where the blue line defines the maximum active power that the CHP generator is able to produce, while it also shows the active and reactive power limits for the electric generator. Minimum power that the system is able to provide is 25% of maximum power. Furthermore, the output of the CHP generator is set manually by the operator who defines the limit of the active power and the power factor is set accordingly.





**Figure 41. Active vs reactive power diagram of the CHP model.**

The efficiency of the synchronous generator is characterized in Figure 42 as a function of the load and power factor.



**Figure 42. Efficiency curve of the synchronous generator as a function of the load and power factor.**

The model characterization is completed with the inclusion of an electric model of the generator, the well-known Behn-Eschenburg model, that could be applied to evaluate power flow (i.e. evaluate voltage and current value in the network) as shown in Figure 43. Furthermore, Table 8 and Table 9 present the physical and electrical characteristics respectively of the synchronous generator equivalent circuit.

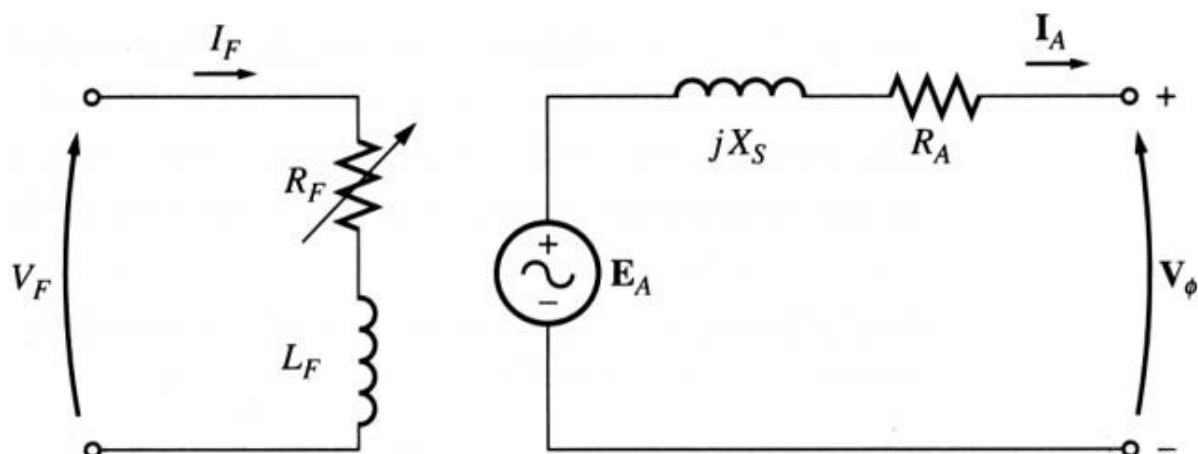


Figure 43. Synchronous generator electric equivalent circuit.

Table 8. Physical characteristics of the synchronous generator equivalent circuit.

Element		Data
<b>Damper cage</b>		<b>Copper</b>
Stator Winding Resistance (20°C)	$\Omega$	0,11
Rotor Winding Resistance (20°C)	$\Omega$	1,853
Stator Exciter Resistance (20°C)	$\Omega$	11,05
Rotor Exciter Resistance (20°C)	$\Omega$	0,32
Weight of complete generator	kg	132,0
Unbalanced magnetic pull	kN/mm	4,5
Air flow	m <sup>3</sup> /min	6,9
Noise level at 1m/7m	dB(A)	64/54

Table 9. Electrical characteristics of the synchronous generator equivalent circuit.

<b>S<sub>n</sub></b>	Rated Power (kVA)	31
<b>P<sub>n</sub></b>	Rated Active power (kW)	24.8
<b>V<sub>n</sub></b>	Rated voltage (V)	400
	Number of poles	4
<b>Unsaturated (ref. EN60034-4)</b>		
<b>X</b>	Direct-axis synchronous reactance %	379.9
<b>X<sub>d</sub>'</b>	Direct-axis transient reactance %	18.7
<b>X<sub>d</sub>''</b>	Direct-axis subtransient reactance %	13.3
<b>X<sub>q</sub></b>	Quadrature-axis synchronous reactance %	121.9
<b>X<sub>q</sub>'</b>	Quadrature-axis transient reactance %	121.9
<b>X<sub>q</sub>''</b>	Quadrature-axis subtransient reactance %	40.7

$X_2$	Negative-sequence reactance %	27.7
$X_0$	Zero sequence reactance %	3.47
<b>Saturated</b>		
$X_d$	Direct-axis synchronous reactance %	322.9
$X_d'$	Direct-axis transient reactance %	15.9
$X_d''$	Direct-axis subtransient reactance %	11.3
$X_q$	Quadrature-axis synchronous reactance %	103.6
$X_q'$	Quadrature-axis transient reactance %	103.6
$X_q''$	Quadrature-axis subtransient reactance %	34.6
$X_2$	Direct-axis synchronous reactance %	23.6
$X_0$	Zero sequence reactance %	3.47
$K_{cc}$	Short circuit ratio sec	
$T_d'$	Transient time constant sec	0.061
$T_d''$	Subtransient time constant sec	0.082
$T_{do}$	Open circuit time constant sec	1.08
$T_a$	Armature time constant sec	0.021
$I_o$	Excitation current at no load	0.75
$I_c$	Excitation current at full load	2.2
	Overload 1 hour in a 6 hours period 110% rated load	
	Overload per 20 sec %	300
	Heat dissipation W	4,442

Related to the calibration and validation of the tool, the battery model requires the calibration of the SOC estimate against the voltage measured at DC terminals of the battery ( $V_{DC}$ ):  $V_{DC,max}$  and  $V_{DC,min}$  values are associated to  $SOC_{max}$  and  $SOC_{min}$  values, respectively. Experimental tests will be thus performed at the beginning of the pilot operation. CHP model does not require any calibration, since all the model parameters are provided by the manufacturer.

Validation of the tool will be experimentally assessed, during pilot operation, in terms of effectiveness of setpoints provided to the microgrid equipment.

### Technical specifications and advances from the existing tools

The modelling tool within the Multi-carrier hub optimisation engine runs in parallel to the optimisation process. The time horizon is a day or less and time steps can be 10 min, 15 min, 30 min or 1 hour.

Addressing the I/O data, in case of the Multi-carrier hub Optimisation Engine, the most used data structure is the power profile. The modelling module of the tool uses as input data the monitored data from the field and the rated values of the equipment as configuration parameters. Moreover, operational and technical constraints are taken into account. The outputs are the simulated power profiles regarding the reference behaviour of the simulated system and its flexibility boundaries.

The input data of the optimisation tool are:

- Requests from the DSO
- RES and load forecast
- Economic signals
- Monitoring data

With the exception of the real time monitoring data, the information has to be structured as profiles providing data for each time stamp of the optimisation time horizon.

The results of the optimisation process are:

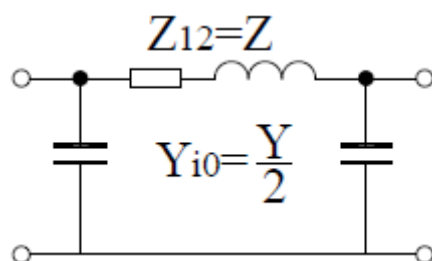
- Setpoints for the microgrid equipment
- Power absorption and generation profiles of the flexible energy units, namely the battery and the CHP
- Data about DSO rewards and costs related to the provision of flexibility actions

While the data about generation and injection are structured in power profiles, the setpoints are written into a text file to be implemented and actuated in the field.

The optimisation framework needs to receive input data from different actors. Monitored data from field devices are sent through MQTT protocol, while power profiles data are exchanged by REST services among the tools deployed in the Pilot.

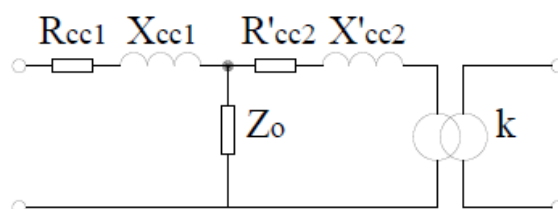
The Multi-carrier hub optimisation engine needs data from the external tool Microgrid monitoring tool, responsible of the monitoring tasks at the connection point of the microgrid. In addition, in order to model and simulate the behaviour of the microgrid infrastructure, a load flow tool is required as an external tool. This tool is already developed by UNIROMA1 and reflects the physical infrastructure of the microgrid. In the following it is briefly described.

Electric lines are modelled based on the parameters normally provided by the manufacturers (resistance, reactance and capacitance), as shown in Figure 45:



**Figure 44. Parameterization of electrical lines.**

Likewise, the transformer is modelled according to the equivalent circuit that is normally described by the parameters of the network as depicted in Figure 45.



**Figure 45. Parameterization of transformer.**

Loads are described as sinks of active/reactive power already known, generators are described as nodes in which both injected power and voltage are fixed. The simulated network is connected to a node of the MV network that it will be considered as a slack node.

The problem is a set of non-linear equations that can be solved through Newton-Rapson method.

The integration and installation of the entire optimisation framework tool need third-party components:

- Java JDK 1.8
- MATLAB Runtime for version R2016b or later (and/or MATLAB R2016b or later)
- PostgreSQL database v10.0 or later
- Apache Tomcat 9.0 or later
- Eclipse Mosquitto 1.5.4 or later

The main languages adopted are MATLAB and Java, which have been employed respectively to code the multi-objective optimisation algorithm and to perform the framework to exchange data among the tools of the ICT framework and the database. The simulation modules are developed in Java programming language.

The model is compatible with the operating systems Windows 7 or later and Linux.

The Multi-carrier Hub Optimisation Engine tool has no direct connection with physical hardware devices.

Regarding the innovations developed within inteGRIDy, the modelling approach presented earlier is a brand-new feature of the Multi-carrier Hub Optimisation Engine (ENG) tool, developed for the specific purpose of the inteGRIDy project. The previous implementation of the optimisation tool in the INGRID project, relied on the evaluation of system behaviour mainly based on static constraints that did not allow the availability of updated flexibility data of the managed energy resources.

### **Expected advantages compared to commercial products**

There are many tools that address the simulation of energy systems in order to have available a useful set of data to be used for smart microgrid application analysis of further mathematical computations. energyPRO tool from EMD international [ENE101] addresses the models of a very wide set of different energy technologies, such as CHP, PV, heat pumps, etc., providing insights not only regarding the energy behaviours of the appointed technology, but also economic consideration and investments/feasibility study. Another relevant tool is provided by Simulation X, ESI [SIM102], which handles most of the energy storage models, from electrical to mechanical ones, allowing to have information on the energy behaviour and related performances. This tool also provides comparison between two different storage technologies, highlighting the corresponding advantages.

This modelling module cannot be considered as a stand-alone application since it has been designed to be a supporting component of the optimisation process. Therefore, it is difficult to compare it against well-established commercial products. In any case, this approach brings some advantages. The modelling component of the Multi-Carrier Hub Optimisation Engine addresses directly a lightweight simulation process that runs in parallel with the optimisation process, and for this reason has to be reliable and cannot require large amount of computational effort. All the information about the models are gathered and discussed directly with the owners of the components, that are also responsible for their operations; this allow a very precise evaluation of their energy behaviour. Moreover, these models also implement an economic matching between the modelled flexibility capabilities and the corresponding flexibility costs, to the claimed and taken into consideration during economic comparison with other money sources, such as DSO rewarding for service provision.

## Implementation features and delivery

The Multi-Carrier Hub Optimisation Engine is deployed in the Terni inteGRIDy pilot project, where it models the energy microgrid equipment that can modify their performance or output, which in this case are the CHP and BESS systems.

The core of the optimisation framework is a component developed in MATLAB environment implementing the algorithm, properly compiled and exported as a Java Archive.

This is imported and invoked by a Java program, which receives the data from the Pilot database employing tailored libraries, and processes this information and structures them so that these are evaluated by the optimiser. On a final stage, the setpoints are written into the database and also structured in a text file. The tool can be considered as a standalone application and is deployed as a Docker container. The source codes are stored in a tailored GitLab repository; codes are accessible on request.

Within this tool, the simulation and modelling components are designed and structured in a way that can run in parallel with the optimisation process. As such, they are Java module integrated into the core of Multi-carrier hub optimisation engine (ENG) and exchange data time stamp by time stamp internally with the optimisation module of this tool.

A demo version of the modelling modules is available.

The tool can be considered as a standalone application. It is released as a module of the entire Multi-carrier hub optimisation engine (ENG) tool as a Docker container.

The source codes are stored in a tailored GitLab repository; codes are accessible on request.

Contact info:

Giuseppe Paternò (ENG): [giuseppe.paterno@eng.it](mailto:giuseppe.paterno@eng.it)



### 4.3.3 Kisense Energy Management System

#### General description of the inteGRIDy functionalities

Kisense is an Energy Management System that integrates energy measurements (such as electrical and thermal), environmental data (such as temperature and humidity), forecasts (such as electrical generation and load consumption), and energy prices and tariffs to deliver demand response solutions and flexibility services.

The main features offered by this comprehensive tool are:

- Multi-parameter monitoring (current, voltage, active and reactive power, renewable generation, water, gas, fuel, temperature, humidity, air quality, occupation, presence, among others).
- Multi-site aggregation per parameter, per circuit, per floor, per building and other user defined attributes.
- KPIs definition (ex.: consumption per consumer, per area, per employee in each department) and calculated variables from generic formulas.
- Energy savings baselines definition and tracking.
- Time-of-use tariff analysis.
- Alarm and event management to detect abnormal consumptions and significant changes in normal consumptions.
- Remote control of appliances and flexible loads.
- Demand response programs implementation.

The Data Processing Module (DPM) provides a homogenised view (storage and access) of data collected from different devices (smart meters, sensors, actuators and others) and data sources (weather info and forecast, energy prices and others) in terms of types of variable, units of measurement and aggregation mechanisms. The module functionalities are further enhanced by the possibility to associate general metadata attributes to a data series (Figure 46).

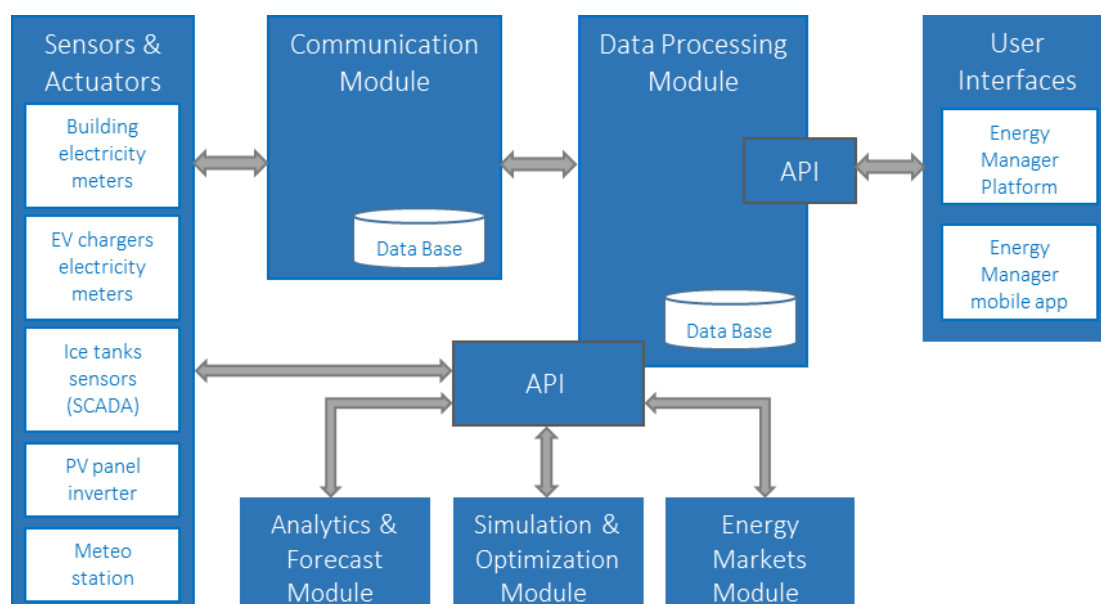


Figure 46. Kisense EMS Modular Architecture.

The Kisense EMS addresses three inteGRIDy pillars:

- Demand Response: the optimization algorithm recommends load shifting of certain flexible loads to adjust the energy use in accordance with dynamic tariffs and 'local' renewable energy production, thus balancing supply and demand in coordination with energy production and consumption forecasts.
- Energy Storage: the building manager can use the optimization results to set the schedules of EV charging and the ice tanks storage to maximize PV self-consumption and to reduce the energy cost.
- Electric Mobility: the EV fleet management team can access data from the different types of EV chargers and their operation schedules.

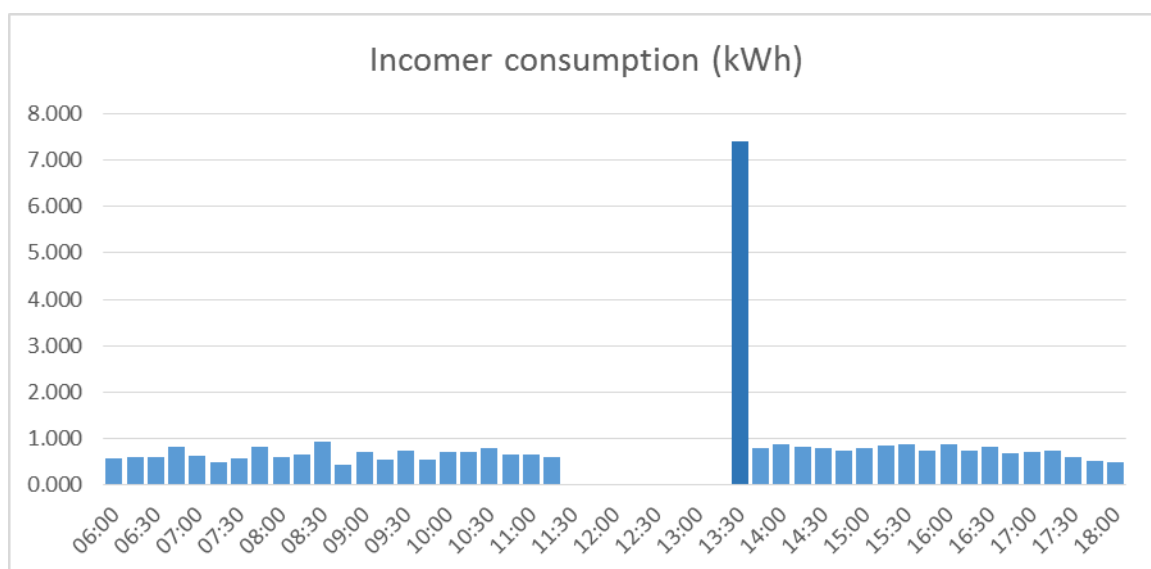
### Details of the modelling process

In general terms, the tool is able to apply conversion factors, calculate consumptions and costs from applying tariffs, validate readings, and calculate hourly, daily, monthly and yearly aggregations of the raw data and forecast.

The existing data validation mechanisms were very basic and consisted of checking plausible limits and repetitions. Since invalid readings or communication faults are inevitable and may have a strong impact on the calculation of profiles, a new data validation mechanism was developed. This mechanism associates one or more data inspection algorithms to a data series. These algorithms (validator plugins) can be updated or added to the platform as needed and be developed to check either general or specific conditions. As an example, a validator for meter readings was developed that detects and invalidates readings that sudden "peaks" or "valleys".

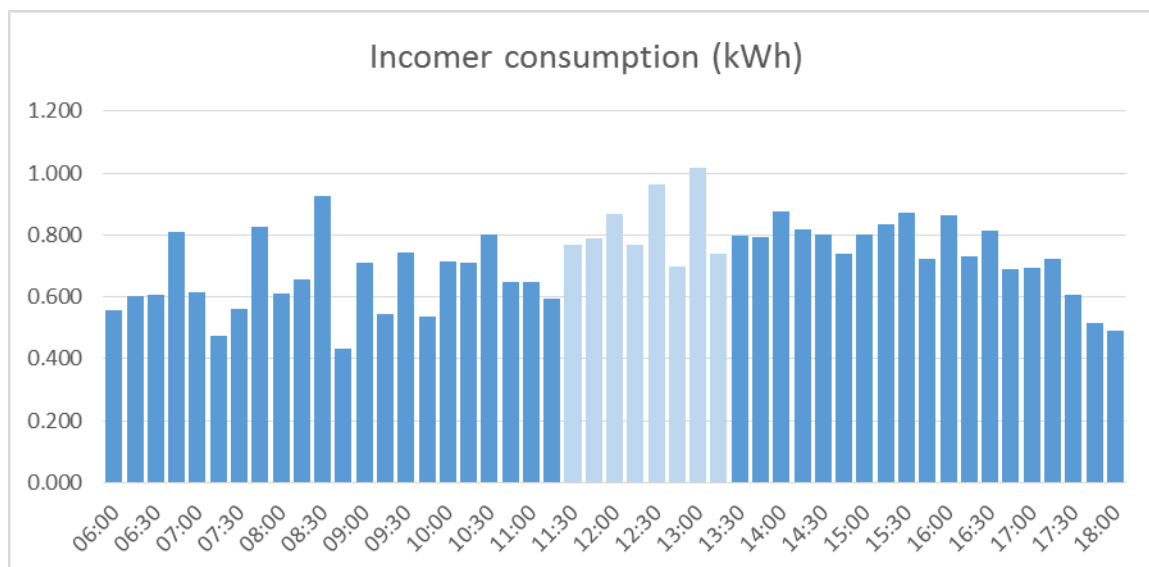
Another problem that persisted was to estimate consumptions when there is a communication fault that leads to a peak consumption, corresponding to a data gap, being registered as a single raw value. This problem arises more frequently when radio devices are used but can also occur with wired meters due to communication interferences (see Figure 47).

The approach selected to "distribute" a peak consumption was to analyse de consumption during the last 3 weeks (or other selected time interval) and estimate the consumption over the fault period based on an average of the homologue periods that is on the same days of the week scaled by the average day consumption.



**Figure 47. Measured consumption with a data gap.**

Regarding the calibration and validation of the tool, Figure 48 shows the estimation based on a three weeks profile of the peak shown previously due to a reading transmission (communication) fault that lasted around 2 hours. The estimated data is marked with a distinct flag, color on the chart.



**Figure 48. Incomer consumption with a data gap estimation.**

This estimation algorithm is only applied if the fault occurs during a short period of time (less than 6 hours) and if the peak consumption is (3 times, for example) higher than the average consumption for that period. Only historical data is used to calculate a profile that match the fault period.

### Technical specifications and advances from the existing tools

The process of data estimation uses collected raw data (typically 15 min samples) and requires at least 3 weeks of historical data. On the other hand, the maximum estimation interval is also limited to 3 days although different setting can be defined.

The input data and the estimated data are retrieved and stored on the main database that is the KRW. Other tools access these data using the application programming interfaces (API) in JSON or XML format.

As stated above, this tool (module) is part of Kisense EMS and for this reason depends on the other modules of the system but has no external dependencies.

The programming language is C# and Kisense EMS can be installed on a Windows Server 2016 or later. Furthermore, the DPM does not access any hardware device directly. The communication with the physical devices is managed by a communication service.

Regarding the progress made in Kisense EMS through the inteGRIDy project, the functionalities of this module regarding data validation, estimation, and profiling were much enhanced or developed from scratch for the implementation of the Lisbon pilot. In fact, the use of automatic data validation mechanisms is the basis for the generation of accurate profiles and thence the implementation of demand and supply matching algorithms and flexibility services.

### Expected advantages compared to commercial products

By implementing advanced data validation and estimation mechanisms, Kisense EMS solutions gain in reliability and efficiency when compared to other market solutions. The level of integration and flexibility of the implemented mechanisms is also not usually found on other solutions that rely on separate data validation/certification procedures.

On the other hand, this functionality reduces significantly the cost of support since fewer “incidents” are reported or need manual examination and intervention. Moreover, the relation with the user is also improved since it is largely based on the perception of the quality of the data.

In conclusion, the developments reported help the successful deployment of Kisense EMS based solutions for micro-grid installations and energy communities.

### Implementation features and delivery

Kisense EMS is the core tool for the Lisbon pilot, being responsible for the implementation of all the use-case scenarios. DPM, in particular, estimates consumption data when these are missing due to failure in data collection under certain circumstances and provides generation and consumption profiles from measured and forecasted data.

Kisense EMS consists on a set of windows services (modules) and web application (user interfaces). The Data Processing Module is set of services that communicate through a common bus in a standard service-oriented architecture.

The model is an internal process and runs in parallel with save data and aggregation process.

For more information on the Kisense EMS code, please contact:

Jorge Landeck: [jlandeck@vps.energy](mailto:jlandeck@vps.energy)

#### 4.3.4 Integrated Test Environment

##### General description of the inteGRIDy functionalities

The Integrated Test Environment [CHU97] [JYI16] consists of energy storage and demand side response models. The energy storage model considers real and reactive power ratings, energy capacity and efficiency of energy storage systems. Two types of DR model are available in the Integrated Test Environment: the first mimics the behaviour of domestic customers through the reduction of the consumption by a certain percentage; the second captures the characteristics of industrial and commercial customers who have a backup generator or a microgrid, and can reduce their consumption to zero or by a certain amount.

The power system simulation environment is able to model different types of power systems in steady state and perform power system control and optimization tasks with different algorithms, feature that falls under the Network Modelling macro-functionality category described in Section 4.2. The multi-agent system is implemented in Java.

The Integrated Test Environment has the following capabilities and functions:

- The test environment has a range of distribution network models including IEEE standard networks and validated real distribution networks. IEEE standard networks include IEEE 14, 33, 57, 69, 118 and 300 bus networks. Real network models have been validated through UK smart grid trials (Aura-NMS and Customer led network revolution). New network models can be easily integrated into the Integrated Test Environment.
- A range of smart grid technologies and techniques have been modelled in the Integrated Test Environment and can be easily implemented in test networks. Smart grid technologies and techniques included in the Integrated Test Environment are:
  - Residential and Industrial and commercial demand side response
  - Energy storage systems
  - Real time thermal rating
  - Soft open point
  - Enhanced distribution generation control
  - On load tap changer
  - Capacitor bank
- The Integrated Test Environment has a number of control algorithms implemented on the test networks including:
  - Rule based control
  - Fuzzy logic
  - Optimal power flow with different solvers

The Integrated Test Environment can be used in inteGRIDy to assess the impact of different solutions to smarten the networks in the different pilots. The tool supports the inteGRIDy pillars of Demand Response, Smartening the Distribution grid and Energy Storage Technologies.

##### Details of the modelling process

This section outlines the methods employed in Integrated Test Environment to model [distribution networks](#), energy storage systems (ESS) and residential-industrial-commercial DR [BAR14] [IBR08].

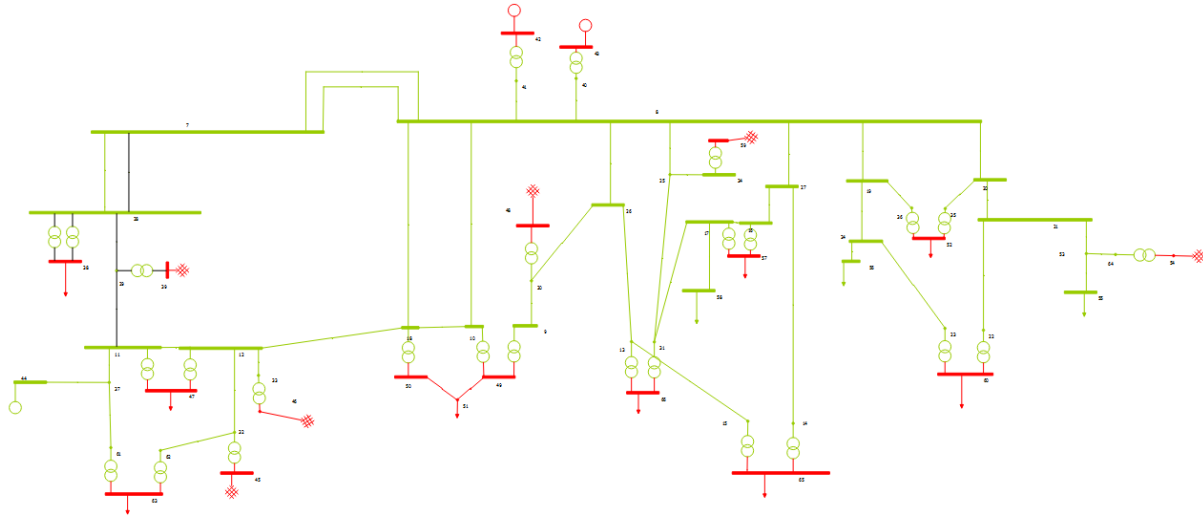
##### *Model of the Isle of Wight distribution network*

Isle of Wight is supplied from the mainland by three subsea interconnectors and distribute power through 132/33kV primary substations. A 140MW oil-fired power station provides emergency supply for the Island and operates primarily as a STOR facility. At 33kV level, a

number of DGs including PV have been connected or accepted. Distributed PV systems have been installed on over 3,000 domestic and commercial buildings.

The steady state model of 132kV and 33kV networks of the IoW is modelled in IPSA2 and MATPOWER. The modelling of the network is based on the  $\pi$  model in transmission and distribution modelling and as the length of the lines are significantly smaller than the limits mentioned in references for the short lines, the shunt capacitances are neglected and the single line diagram of the network achieved is depicted in Figure 49. In Figure 49, substations and load/generation connection points are modelled as electric buses.

As such, the distribution network is represented as a connected graph  $G = (B, L)$ , where  $B$  represents a set of individual nodes (i.e. generations and loads), and  $L$  represents the set of connection lines in the network (distribution circuits).



**Figure 49. Schematic of the IoW distribution network model in IPSA2 environment.**

### Energy storage model

In Integrated Test Environment ESS is represented by a generator. When the battery is charged, the command sets the output of the generator to negative. ESS model is stored as a structure array. The SOC calculation assumes that the efficiency is the same for charge and discharge operations:

Charge:

$$SoC^{t+1} = SoC^t + \Delta SoC^t = SoC^t + \Delta T \cdot P^t \cdot \eta \quad (91)$$

where  $t$  is the timestamp,  $SoC^t$  is the SOC at time  $t$ ,  $\Delta SoC^t$  is the SOC change from time  $t$  to time  $t + 1$ ,  $\Delta T$  is the time interval,  $P^t$  is the charge power and  $\eta$  is the ESS efficiency

Discharge:

$$SoC^{t+1} = SoC^t + \Delta SoC^t = SoC^t - \frac{\Delta T \cdot P^t}{\eta} \quad (92)$$

### Residential DR

Residential DR is modelled as a percentage of reduction of load. Assuming the load at the location of the customer is  $P_t$  before DR service is delivered. and denoting the reduction



percentage as  $\eta$ . When DR service is provided, the consumption of the customer is calculated as:

$$P'_t = (1 + \eta)P_t \quad (93)$$

where  $P'_t$  is the consumption of the residential customer when the customer is providing DR service,  $P_t$  is the consumption of the residential customer when the customer is not providing DR service, and  $\eta$  is the percentage of reduction in consumption.

#### *Industrial and commercial DR*

Industrial and commercial DR is modelled as a reduction of load during a certain time period. It should be noted that only real and reactive power reduction input will be used by MATPOWER, and that apparent power and power factor is used for information only. The industrial and commercial DR is applied to a specific busbar for the defined period of time. Load will be restored at the end of the given duration.

Addressing the calibration and validation of the models, the network models have been validated against other power system simulation models. The effects of energy storage and DR on voltage and power flow have been validated as well. DR models uses real trial data so no validation is required.

The distribution network in Isle of Wight (IoW) has been benchmarked against IPSA Power software [TNE16] and Integrated Test Environment. Appendix A includes the power flow in the IoW network's branches calculated using IPSA and Integration Test Environment. The difference between the results of two tools is almost 0% (it varies only for 7 branches between 1% and 3%).

#### **Technical specifications and advances from the existing tools**

Power flow and optimal power flow is carried out only for single time step. Formulation can be revised to carry out scheduling studies. Time step can be decided based on the time required for each optimization. For large networks with a large number of control variables, the computation time taken for each time step will increase. Typically, the simulation is carried out with data at half-hour intervals but can be reduced to 5-minute intervals.

The time horizon range can be change according to the provided load and generation profiles. The resolution of the power flow and the optimal power flow calculations depend on the resolution of provided profiles.

Regarding I/O data, these are exchanged, imported and exported in CSV format in the Integrated Test Environment.

The following results are given by the Integrated Test Environment for each time step:

- Energy storage: real and reactive power setpoints
- Capacitor bank: reactive power output
- On load tap changer: tap change/tap position
- Demand side response: demand side response request
- Distributed generation: curtailment signals
- Generator output: real and reactive power

Input data

- Network information including topology, ratings, components, impedance
- Demand profiles
- Generation profiles
- Energy storage efficiencies and ratings

#### Output data

- Load flow results including busbar voltage, branch power flow
- Energy storage SOC change
- Distributed generation output

The Integrated Test Environment can interact with other software through CSV, excel and .mat files. The Integrated Test Environment is based on:

- MATLAB, version 7 (R14) or later
- MATPOWER, an open source software package in MATLAB to solve power flow and optimal power flow problems
- Java environment, which requires Java development kit and NetBeans. NetBeans is an integrated development environment for Java. Java Agent Development library should also be included.

The Integrated Test Environment focuses on technical optimization aspects of power system considering the following market signals:

- Cost of using energy storage: charge and discharge £/kW, £/kVAr
- Cost of demand side response: £/kW, £/kVAr
- Cost of tap change: £/operation
- Cost of capacitor bank operation: each tap change (£)
- Cost of distributed generation curtailment: £/kW, £/kVAr
- Cost of conventional generator: £/kW, £/kVAr

Monitoring data required by the Integrated Test Environment include:

- Demand for each bus for each time step including real and reactive power
- Generation profile for distributed generation for each time step including real and reactive power
- Initial SOC of energy storage
- Initial tap position of on load tap changer
- Initial position of capacitor bank
- Consumption and availability of demand side response enabled customer

The Integrated Test Environment has been developed in Java and MATLAB, and it can be extended to interact with Python. The tool is compatible operating systems are Windows 7 or later, and Linux. Furthermore, the tool does not require any additional hardware device and it is not connected to any external hardware.

The ITE has been extended after the start of inteGRIDy where IPSA power software has been added. The software has been used as a visual interface to model the network. In addition, it has a huge database of the main assets used in Smart Grids. This will facilitate hugely the modelling task of the user. The automatic translation from IPSA to MATPOWER is established. On the other hand, more control algorithms have been implemented in MATLAB to control and smarten the different assets in the network. These control algorithms are based on E-variables [DAM18] and automata [YAR19].

## Expected advantages compared to commercial products

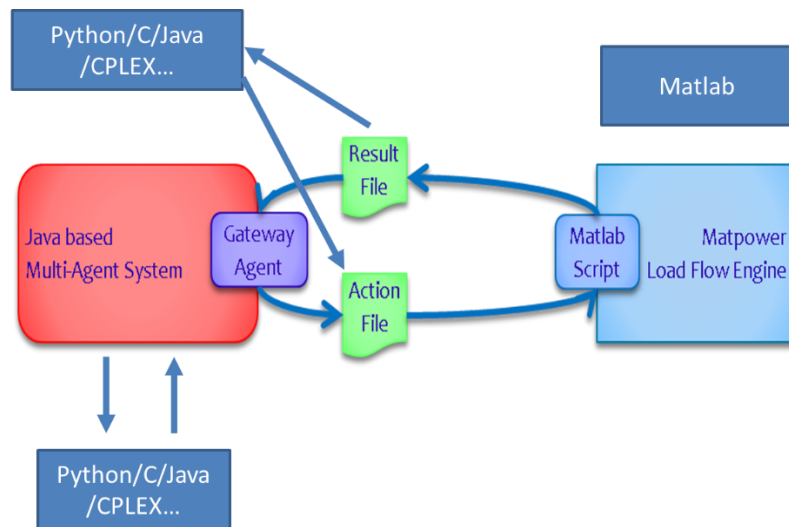
There is no commercial product that can do all the functionalities of the ITE such as the assessment of the smart solutions by integrating the impact of control algorithms on the functionalities of power networks. The existing power software such as IPSA power software or PSS/E do only the power flow and they cannot consider the impact of control algorithms.

## Implementation features and delivery

The Integrated Test Environment is used in the IoW inteGRIDy pilot project to model the distribution network of the IoW, as well as to model energy storage systems and demand response events occurring in the network. The energy storage facilities will be located and sized by using the heat map of the distribution network. Then, the optimal power flow technique will be used to define the optimal scheduling of renewable resources and the energy storage, with different time horizon. Other types of storage can be considered by link the Integrated Test Environment with the model of FC. More scenarios to show the interaction between the control side and power side can be developed according to the use cases of IoW. This requires developing appropriate gateway to facilitate the communication between the power side and control side. Some control methods have been already developed by using fuzzy control theory and they can be used to control the power side facilities.

The framework consists of two simulation approaches running simultaneously, sharing common CSV-based files containing network properties and modelling results. At the start of a simulation, the Gateway Agent within the java environment calls MATLAB to initiate the MATPOWER simulation, which is supported by its model file and a series of profiles. Once initiated the MATPOWER simulation will work through its set of time series data performing load flow calculations. The result of these calculations is then stored in the Result File – the gateway agent processes this result file and distributes the contents across the agent population. If an agent within that population discovers an anomaly or wishes to conduct any degree of control activity – it will write the control command(s) into the action file. When all actions are written into the action file, MATPOWER simulation will read the actions and carried out the action in the next time-step. Control algorithms can run on the Java based Multi-agent system as an agent. Alternatively, the Integrated Test Environment can be used to interact with any other platforms with the same principle as shown in the figure below.

The architecture of the Integrated Test Environment is shown in Figure 50. There are two options to run the Integrated Test Environment: the first one involves running the Integrated Test Environment as a standalone system by implementing control functions within MATLAB; the second one involves the interaction with other programming language such as Python, C, Java and CPLEX. Furthermore, control algorithms developed in other programming languages can exchange information by reading and writing CSV files.



**Figure 50. Architecture of Integrated Test Environment.**

The Integrated Test Environment can be released as software packages. It is currently stored locally on the machines at UNEW. The intellectual property of the environment needs to be respected by the citation and acknowledge.

An example and demo of the Integrated Test Environment as well as a detailed user manual with case studies are available [JY116].

For more information about the Integrated Test Environment, please contact:

Adib Allahham: [Adib.Allahham@newcastle.ac.uk](mailto:Adib.Allahham@newcastle.ac.uk)

### 4.3.5 Distributed Energy Management System

#### General description of the inteGRIDy functionalities

Demand response (DR) has been defined as "...action taken to reduce electricity demand in response to price, monetary incentives, or utility directives so as to maintain reliable electric service or avoid high electricity prices." DR Programs are designed to take specific actions to influence the load profiles of facilities that participate in the DR Programs (that is, participant premise) at peak consumption times on the grid. These peak consumption periods may cause critical grid reliability issues or may be caused when the price of electricity is too high. The Utility/ISO tries to influence the demand by requesting participants to reduce (or shed) the load. These critical periods in which the Utility/ISO needs to influence the load profile of a participant premise are referred to as DR Events. Electric consumers are encouraged to be participants in a DR Program designed by the Utility/ISO by entering into a contractual agreement that describes how they would be compensated by participating in the DR Events.

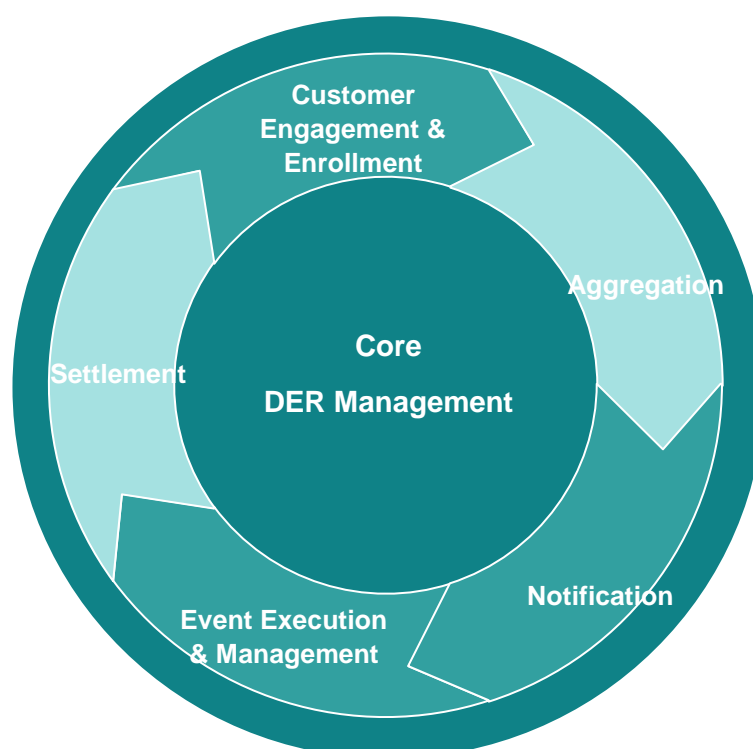
The tool Distributed Energy Management System (DEMS) presents the following energy related capabilities:

- Energy DR matching
- Demand flexibility
- DR shifting
- Predictive DR algorithms
- Analytics/cross-domain big data
- Scenario-based dynamic simulation
- Flexibility optimized management
- Forecasting tools

DEMS includes a number of applications working together and supporting a wide variety of use cases. At a high level, the application consists of several main components: forecasting, optimization, scheduling, baseline and settlement, DR event management and dispatch, control module (online monitoring and control), reserve call processing and control area aggregations.

DEMS provides a web-based GUI as well as flexible interfaces using industry standards and published APIs to allow integration with multiple systems. In DEMS it is possible to create and manage different market rules and constraints. DEMS can provide demand reductions through the use of a flexible load engine that groups loads by defined fields including for example substation, feeder line, zip code, map interface, or others defined by the use.

The DEMS Control Module manages the real time execution of power and power flexibility commitments, based on the use of the system assets as virtual power plants (VPP) to participate in energy or flexibility markets. The scheduling process determines the virtual power plant's capabilities and assigns assets as required to the appropriate control area to fulfil commitments.



**Figure 51. DEMS core cycle.**

Figure 51 shows core DR DEMS functionalities and these are detailed below.

#### *Customer Engagement & Enrolment*

- Integration with CIS or CRM Systems for managing customer enrolment
- Ability to interface with 3rd party enrolment tools and providers
- Ability to create and manage programs and constraints for all customer classes, for both economic and reliability dispatch

#### *Aggregation*

- Flexible ability to group consumer loads via a rules-based engine
- Load groups can be based on feeder, substation, geography, customer class, etc.
- The heart of “surgical” DR

#### *Notification*

- Voice, Text, and Email based notifications
- Configurable messaging templates
- Notification for event scheduled, start, stop, cancelled, and extended

#### *Event Execution & Management*

- Traditional Event Execution Model – select program and loads then schedule event
- Events can be triggered by external systems like EMS/DMS
- Event Wizard utilizing forecasting algorithms and analytics to provide load reduction recommendations

#### *Settlement*

- Integration with MDM system to automate customer billing and settlement



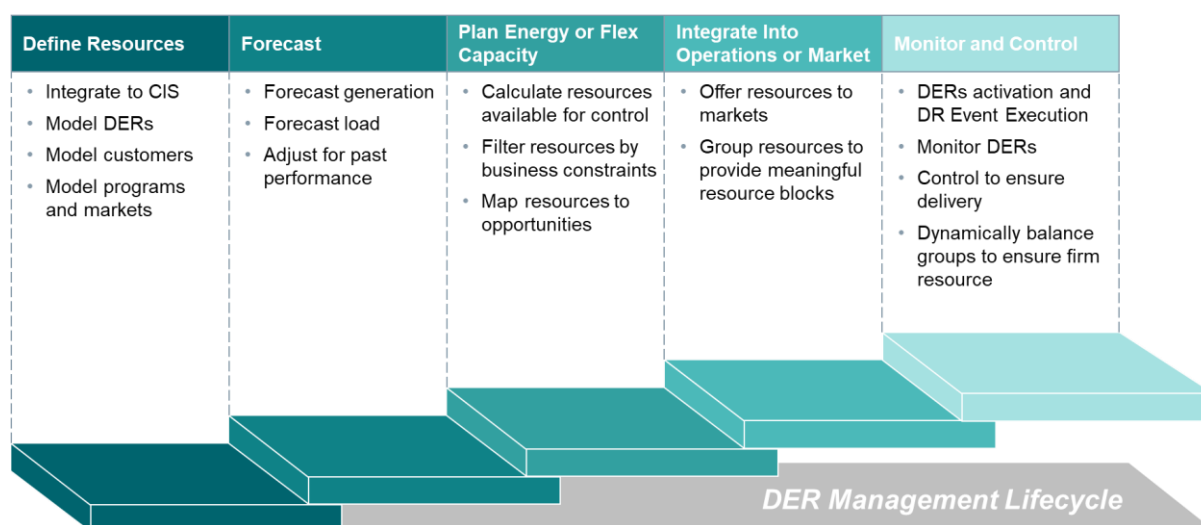
- Settlements performed in minutes when data is available
- Full reporting capability from SDP to required hierarchy

DEMS support Demand Response/Demand Side Management pillar providing functionality for the operation and settlement of DR Programs. A Privileged User is able to schedule the distribution of DR Events using the DEMS interface when a DR Program is needed (that is, the DR Program is "called"). The DEMS sends DR Event signals to controllable end devices, such as water heaters, thermostats, and switches through the Advanced Metering Infrastructure (AMI) or an OpenADR compliant device installed at the participant's premise. The DEMS calculates the settlement data, which is the basis for the DR incentive payment to the participant used for billing. Settlement occurs after the DR Event when meter data is available in the EnergyIP platform. The settlement data that the DEMS calculates is the difference between the calculated baseline and the actual load during a DR Event. Different baseline computation algorithms are selectable when defining a DR Program. The DEMS allows privileged users to manually edit baseline calculation results in case of inconsistencies, and then re-computes the settlement data based on the edited baseline values.

DEMS has the ability to not only support DR programs for load curtailments but can also support programs that require end nodes to consumer power. This feature enables DEMS to provide real time load balancing against renewable generation and provide regulation services for Ancillary market as well supporting the Smartening the Distribution Grid pillar.

### Details of the modelling process

Figure 52 shows a general overview of DERs management workflow process.



**Figure 52. DERs management workflow process.**

#### Define Assets

An asset represents a fundamental building block in the DEMS DR/VPP system. It is connected to an endpoint that represents a home or a business. A Distributed Energy Resource (DER) asset can be represented by a generator, battery, load, or a gateway device. These assets are represented by a service point on the EnergyIP platform. DEMS DR/VPP works with several types of service points, which are defined in the reference data provided with the product (see Table 10).

Table 10. Types of service point classes addressed in DEMS.

Service Point Class	Subtype	Relate Devices	Purpose
Service Delivery Point	Electric	Meter	Represents a load that connects to the grid and communicates through smart metering.
Consumer Premise Equipment		Controller	Represents a communication gateway that is similar to those that are used for Open Automated Demand Response (OpenADR) controllers. Open ADR or Demand Responses (DR) represent a communications data model that is designed to facilitate sending and receiving DR signals from a utility or independent system operator to electric customers.
Consumer Premise Equipment	Realtime Data Provider	Controllable Resource	Represents an endpoint that communicates through a Consumer Premise Equipment/Controller endpoint, such as a thermostat, a baseboard heater, or a generator.
Virtual Power Plant	Generation	Wind Solar Energy Plant Small Hydro Power Plant Geothermal Plant Biogas or Biomass Dump gas or mine gas Emergency power generator Combined heat and power	Represents a power-generating or power-consuming DER that you can use in a virtual power plant. A device needs to be associated with a VPP asset at all times for the VPP algorithms to work correctly.
Virtual Power Plant	Load	P2HorP2G  Load	Represents a power-consuming DER resource that you can use in a virtual power plant. A device needs to be associated with a VPP asset at all times for the VPP algorithms to work correctly.
Virtual Power Plant	Storage	Battery  Other Storage	Represents a power-storing DER resource that you can use in a virtual power plant; it includes additional technical parameters that are required for modelling energy storage. A device needs to be associated with a VPP asset at all times for the VPP algorithms to work correctly.

### Programs/Markets

The DEMS DR/VPP allows you to manage various programs to handle specific requirements set up by the operator to enable privileged users to set up service points, and to manage the enrolment of service points in the programs by creating contracts. The product tracks and enforces the execution state of programs, whereby the state may determine if service points are allowed to enrol in the program or the program may be used for event-based management, schedule execution, or reserve capacity dispatches. Programs provide many functions and details including notifications, constraints, opt outs, pricing incentives, market rules, and more. Table 11 shows a list of all Demand Response (DR) programs defined within the current organization.

**Table 11. List of Demand Response programs.**

Field Name	Description
Name	The name of the DR Program is shown in this column. The name is unique within the organization.
Type	The type associated with the DR Program, this can be either: Demand Response Energy Market Capacity Market
Dispatch Mode	The DR Mode can be Notification Only or Direct Load Control:  Notification Only: DR Programs with DR Mode set to Notification Only will only send notifications (email messages, voice messages, and/or text messages) to the participant contacts. When DR Events are called for a DR Program with DR Mode set to Notification Only, no control signals are sent to service points.  Direct Load Control: DR Programs with DR Mode set to Direct Load Control indicates control signals are sent to service points. Additionally, notifications will be sent to the contacts.
Nominations Required	This column indicates if the DR Program has nomination enabled for Offer bidding
TSO	This column indicates the Transmission System Operator associated with the DR Program
DSO	This column indicates the Distribution System Operator associated with the DR Program
Status	The status of a DR Program could be:  <b>Active:</b> This allows DR Events to be scheduled and dispatched for the DR Program. <b>Inactive:</b> This disallows DR Events to be scheduled or dispatched for the DR Program. <b>Decommissioned:</b> This takes the DR Program offline and does not allow any more participants to sign up for the DR Program. All participants of a DR Program must be un-enrolled in order for a DR Program to be decommissioned.  Note that the status of a program can be set by selecting the DR program and clicking on Activate/Deactivate/Decommission as required.

Open for enrolment	This column indicates if the DR Program currently allows service points to sign up for the program (meaning, open for enrolment). The value of the field can be either true or false.
Settlement Required	This column indicates if the DR Program has been set up to require settlement. Possible values: Yes or No.
Priority	This indicates the priority ranking of a DR Program relative to all DR Programs registered in the system.

### *Device Communication*

Communication with end devices represents a critical ingredient in the operation of DEMS DR/VPP. The application supports communication with end devices through the following pathways:

- AMI meters
- OpenADR VENs (gateway devices or cloud-based systems)
- RTUs

Each device type uses different communication protocols, provides different end device control functionality, and returns different types of data to the system. Each type of device communication uses a different type of implementation and architecture.

### *Forecasting*

One of the core functions of DEMS DR/VPP is to provide an actionable forecast of an asset's expected generation or consumption for a future time period. DEMS provides a collection of forecast algorithms that you can associate with an asset depending on the operator's preferred forecast output, as well as the physical and data characteristics of an asset.

Forecasting is implemented as a periodic process that calculates the forecast time series separately for each asset; it is based on the configuration and historical data of an asset.

DEMS provides load shifting or DR and asset flexibility or VPP capabilities. Based on the load forecast and historical event participation data, DEMS can generate a prediction of the sheddable load and band of flexibility to adjust accordingly the load relative to the forecast for sites and aggregations.

For those assets that are defined as "flexible", the forecasting process involves the computation of the upward and downward power flexibility of an asset. The power flexibility forecast calculates an asset's power flexibility based on power production limits and the computed forecast.

The positive power flexibility forecast is calculated as follows:

- Generating assets: The difference between maximum power and the basic forecast
- Loading assets: The difference between the basic forecast and minimum power
- Storage assets: The difference between maximum discharging power and the basic forecast (for storage assets, a positive basic forecast schedule means discharging). If the difference is less than zero, the positive power flexibility forecast is zero.

The negative power flexibility schedule is calculated as follows:

- Generating assets: The difference between the basic forecast and minimum power
- Loading assets: The difference between maximum power and the basic forecast

- Storage assets: The difference between the basic forecast and (negative) maximum charging. If the difference is less than zero, the negative power flexibility forecast is zero.

Consequently, the flexibility values are always positive values regardless of the positive or negative direction indication.

### Forecast Demand Response Assets

DEMS DR/VPP generates a load forecast for sites and aggregations in the system. If triggered when using the jobs engine, a forecast algorithm generates load forecasts that leverage historic consumption data in the system. You can configure any forecast algorithm for use with Demand Response assets, such as Service Delivery Points and Consumer Premise Equipment service points, even though forecast algorithms behave differently for Demand Response assets.

If you use the load forecast and historical event participation information that is available in the system, DEMS can then predict the sheddable load for sites and aggregations. You can produce a consumption capacity forecast. When combined with the load shed forecast, the system generates a “Load Corridor” of capacity and shed capabilities.

The following forecasting functions are available:

- Visualization of the expected consumption for a service point or group of service points (Figure 53)
- Visualization of the load corridor or band of flexibility to adjust load up and down relative to the forecast
- Dynamic determination whether curtailment or consumption is required to comply with a set point at a given interval in time for schedule-based events
- Prediction of the shed functionality, which is used when an event is defined
- Making a forecast and load corridor available to external systems with a REST API

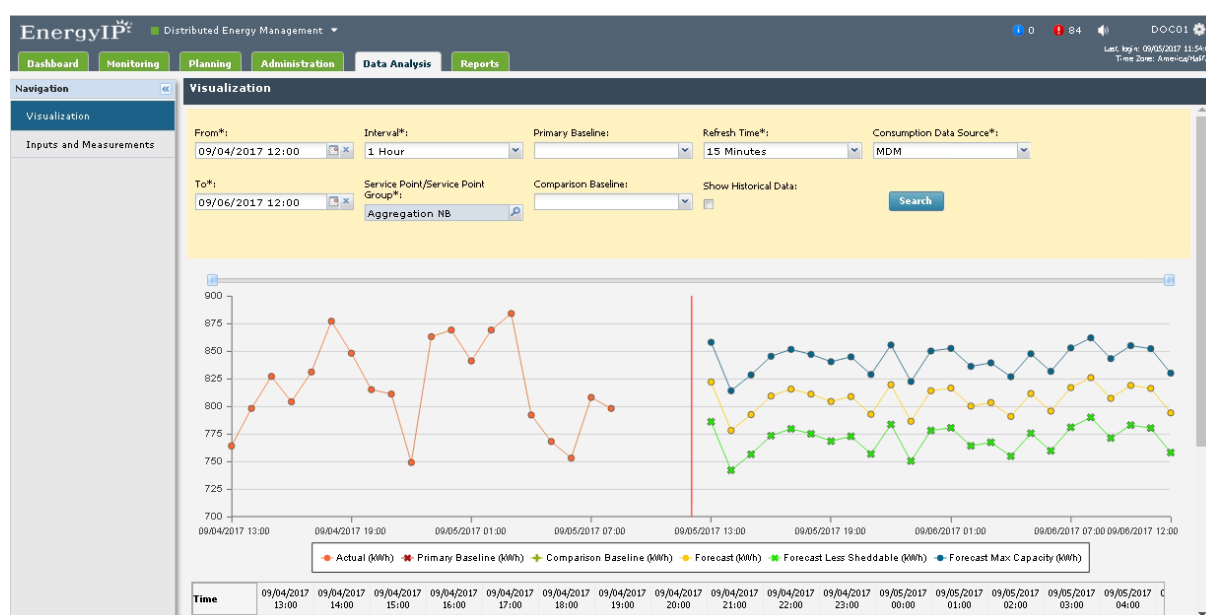


Figure 53. Visualization Graphs.

### Consumption Forecast

DEMS DR/VPP forecasts Demand Response service points that are based on the configuration of the associated forecast service. You can choose any of the available forecast algorithms for a Demand Response service point.

Calculations are performed at a service point level on a scheduled basis and triggered by using the Drms-Compute-Forecast job. Aggregation level summation calculations can be recalculated on the fly because aggregation contents can also be changed on demand. Any new summations are based on previously calculated service point data.

The forecasting mechanism can also include weather data information, specifically temperature, in the forecast algorithm. You can activate the forecast mechanism as part of the

Weather API specification. The forecast can be displayed on the Dashboard and Analysis Visualization at a site or at an aggregation level.

#### *Load Shed Forecast*

Leveraging the load forecast and historical or real-time information that is available in the system, DEMS can also generate a prediction of the sheddable load for aggregations. Calculations are performed at a service point level on a scheduled basis and triggered by the Drms-PredictedShed-Precompute job. The predicted load shed is calculated based on the enrolled curtailment and then adjusted based on historical event performance if a service point is enrolled in multiple programs, then the average enrolled curtailment is applied. The load forecast calculation does not take into account if any event is shorter in duration than the available meter read intervals and if any event occurs between data points. For example, if an event only lasts for 15 minutes and the meter reads are recorded hourly, then the predicted shed cannot be calculated.

#### *Load Capacity Forecast*

Leveraging the load forecast and historical or real-time information that is available in the system, the system can also generate a prediction of load capacity for aggregations. Calculations are performed at a service point level on a scheduled basis and triggered by using the Drms-Maxcapacity-Precompute job. The load forecast calculation does not take an event into account if any event is shorter in duration than any available meter read intervals and if any event occurs between two data points

#### *Load Corridor*

The DR Load Corridor represents the band of consumption at a service point (or aggregation of service points) for a forecast. It is defined by the enrolled capacity, the ability to increase consumption, and the enrolled curtailment, the ability to decrease consumption. This load corridor reflects the range of control that the DEMS system has over the power consumption of a collection of assets.

You can use the load corridor to analyse the ability to balance grid conditions with a group of service points. The load corridor also represents an important part of the schedule that is based on events functionality. When you import events as a schedule, each interval of time has a target power value. When the system loads the schedule and then groups each interval according to the max duration property, it compares the target power value to the forecast for the same time interval. If the target power is higher than the forecast, the resulting event is used to consume power or increase consumption. If the target power is lower than the forecast, the resulting event is used to decrease consumption.

#### *Configure Schedule-based Events*

DEMS system provides operators the ability to create events based on imported schedules. In addition to defining the time of an event, an imported event schedule defines the following:

- The load target for a specific period of time.



- The configuration used to define the aggregation and program targeted in the event.

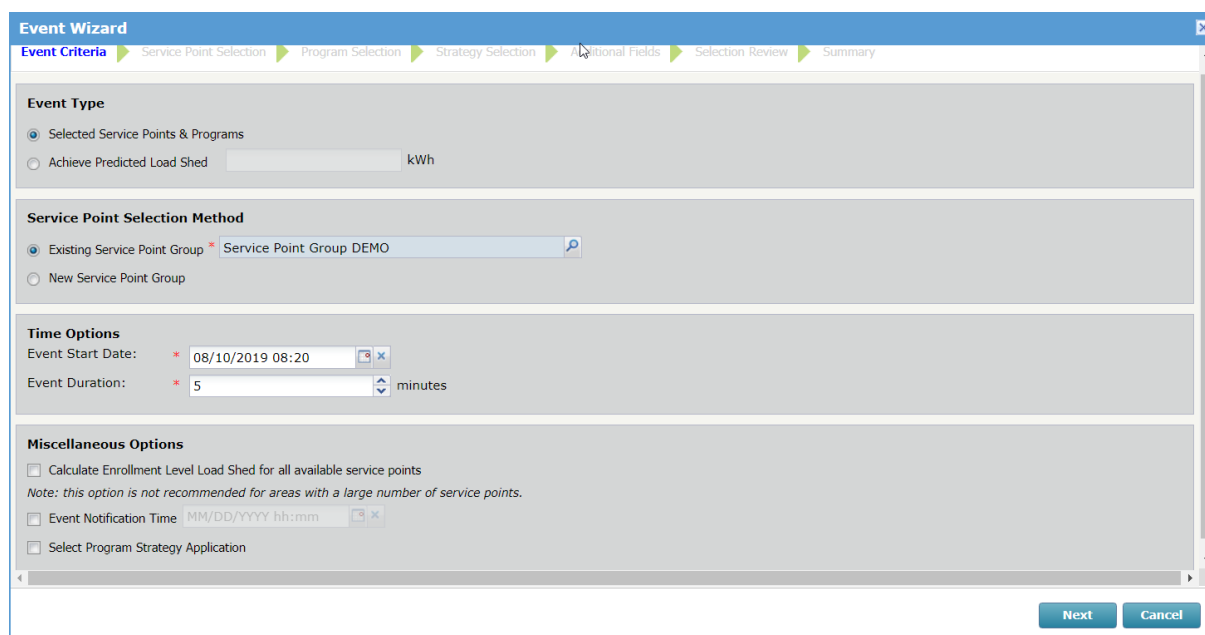
Schedule based events can be used to increase or curtail load within the DEMS load corridor. When importing events as a schedule, each interval of time has a target power value. When the system loads the schedule in and groups each interval according to the max duration property, it compares the target power value to the forecast for that same time interval. If the target power is higher than the forecast, the resulting event is used to consume power/increase consumption. If the target power is lower than the forecast, the resulting event is used to decrease consumption.

#### *Demand Response Event Distribution Algorithm*

The DEMS system provides operators the ability to create events based on schedules. In addition to defining the time of an event, an event schedule defines the following:

- The load target for a specific period of time
- The configuration used to define the aggregation and program targeted in the event

Schedule based events can be used to increase or curtail load within the DEMS load corridor. Event scheduling is initiated from the Event Browser screen when you select Create from the Action menu. The Event Wizard (Figure 54), which appears, is used for the setup and configuration of surgical DR events. The wizard enables great control over the definition of a DR event.

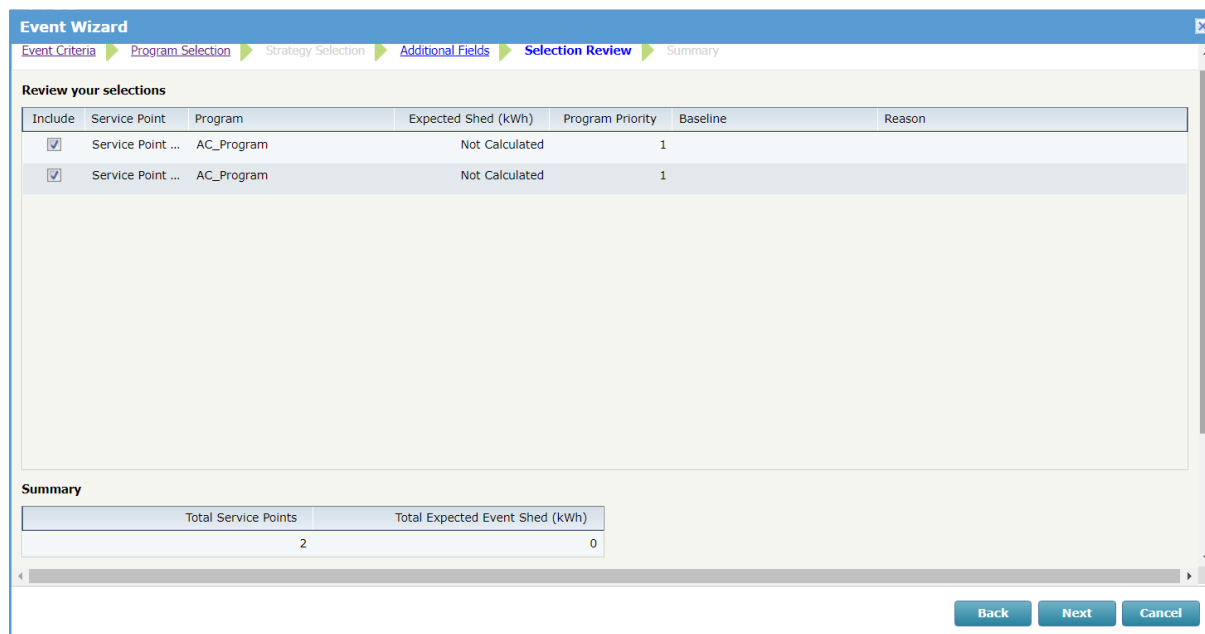


**Figure 54. Event Wizard - Event Criteria.**

There are two options for selecting an Event Type.

- **Selected Service Points and Programs:** You need to select the programs being called for an event. All service points, as selected in the Service Point Selection step, are available for inclusion/exclusion from the event pending the application of program constraint rules.
- **Achieve Predicted Load Shed:** This method enables you to leverage options of multiple programs and multiple service points to achieve a specific level of load shed. Data in the system, historical DR event performance, and DR program enrolment information supports algorithms that aid in predicting the target load shed.

The Selection Review screen (Figure 55) provides you with the final determination of which service point and program combinations are to be included in a DR Event. If you selected the "Event Type of Selected Service Points & Programs" option in the Event Criteria phase, then this review selects all eligible premises to be included in an event, subject to program constraint restrictions. Otherwise, on the Achieve Predicted Load Shed path, the review displays a list of selected service points optimized via the DR Event Distribution Algorithm to obtain the requested kWh amount specified.



**Event Wizard**

Event Criteria | Program Selection | Strategy Selection | Additional Fields | **Selection Review** | Summary

**Review your selections**

Include	Service Point	Program	Expected Shed (kWh)	Program Priority	Baseline	Reason
<input checked="" type="checkbox"/>	Service Point ...	AC_Program	Not Calculated	1		
<input checked="" type="checkbox"/>	Service Point ...	AC_Program	Not Calculated	1		

**Summary**

Total Service Points	Total Expected Event Shed (kWh)
2	0

Back Next Cancel

**Figure 55. Event Wizard - Selection Review.**

The Review your selections table offers the following information and capability.

- **Include:** If the check box is selected, it indicates that this service point/program combination is called (included) in the DR Event being created. You can manually override the inclusion of a service point and program combination by clearing the check box. Service points can likewise be manually included into an event pending application of system rules and program constraints.
- **Service Point:** The premise name and service point name to be included in the event.
- **Program:** The DR program name of the service point and program combination to be included in the event.
- **Expected Shed (kWh):** A number in kWh that has been expected to be shed for the given device. This value is determined based on historical information for the specific service point or program participation. This prediction becomes more accurate as more event participation load shed history is accumulated. This field is only calculated when the "Achieve Predicted Shed" is entered at the beginning of the event wizard.
- **Program Priority:** When defining DR programs, a priority value can be specified. When multiple programs are being called in a single event, this value determines the order in which programs are used.
- **Baseline:** The baseline calculation that is associated with the program. Note that the system does not allow simultaneous participation in program events which employ different baseline calculations.
- **Reason:** Various information notes regarding the non-inclusion of a premise or program. For example, this can be the exclusion of a premise due to the application of program constraints or attaining of an "Achieve Predicted Load Shed" kWh target, or if programs have conflicting Holiday Calendars.

The Summary table offers the following information and capability.

- **Total Service Points:** This represents the total number of service point and program enrolments that are included in the event. This is not necessarily a raw number of service points, as a premise may be enrolled in more than one program.
- **Total Expected Event Shed (kWh):** This represents a running total of the chosen service point's Predicted kW Shed amounts included in the event.

The following information is displayed on the Achieve Predicted Load Shed path only:

- **Requested kWh:** the kWh value specified when embarking on the Achieve Predicted Load Shed path.
- **Buffer %:** A configurable value which represents a buffer that is applied to the requested kWh when selecting premises to be included in a DR event. You configure this value to meet the results experienced in your system
- **Delta:** This represents the sum of the expected shed (kWh) of the included premise/program combinations less the buffer amount. Note that when premises are removed, and the Total Expected Event Shed (kWh) falls below the requested kWh, this value will no longer include the buffer.

Details of the optimisation algorithm/decision making process.

The DR Event Distribution Algorithm is deployed in the DEMS application by the event wizard for event scheduling optimization.

Once commanded to execute an event to achieve a target kW, the Demand Response Event Distribution process runs an algorithm to provide a proposed list of service point/program enrolments that should be executed to achieve that target kW shed.

The inputs into this algorithm are described below:

- **Target kW:** The Target kW that you want to shed.
- **Service Point Group Node Identifier:** Identifier of the service point group node that you have previously selected in the event wizard.
- **List of Program IDs:** A list of program IDs that you have previously selected in the event wizard.
- **Event Start Time:** Start time of the event.
- **Event End Time:** End time of the event.
- **Process All Enrolments:** This is a Boolean value represented on the event wizard interface by a checkbox. This value determines if the program constraints are evaluated for all eligible service points that are based on the evaluation criteria or if the evaluation of constraints only continues until the target kW and a predefined buffer value is achieved. This option is available for performance purposes as evaluating constraints for a large number of service points can be a time consuming and resource intensive process.

The event distribution algorithm performs the following steps to compute a list of enrolments that can be selected:

- Ensure that there are predicted shed forecasts for the event period. If not, return an error.
- For all the service points in the specified service point group, retrieve all the current enrolments in each of the specified programs. Order this list based on the following criteria:
  - Order ascending by associated "program priority" value.
  - Order ascending by the number of previous events that the service point has participated in within their enrolment window.
  - Order descending by the length of the service point enrolment window.
- Loop through each enrolment in order as defined above:

1. Check if the predicted shed sum already exceeds the specified target kW plus buffer:
  - i. [processAllEnrolments = false] Skip this enrolment with a message of "Not validated".
  - ii. [processAllEnrolments = true] Continue processing with a message of "Target kW already reached" (will be overwritten by any other error message that occurs in the further processing).
2. Check if the current service point is already included in the list of selected service points.
  - i. If yes, verify the baseline associated with this program matches the baseline associated with the previously selected program enrolments. If they do not match, reject this enrolment with a message of "Mismatched baselines."
  - ii. If no, continue processing.
3. Check that the enrolment and program constraints are validated.
  - i. If constraint check fails, reject this enrolment and use the constraint check result as the message (for example, "Maximum number of events would be exceeded").
  - ii. If constraints are not violated, continue processing.
4. For each non-rejected enrolment, calculate the kW that will be shed by including that service point. For each service point:
  - i. Find the average of all predicted shed records within specified event period.
  - ii. Using the average hourly shed, calculate the shed for the entire event period based on the length of the event. For example, for a 2.5 hour event, find the 2 predicted shed values and average them, then multiply the average by 2.5.
  - iii. Add this value to a running total of kW to shed.
- d. Return a single list of all enrolments containing the following groups:
  1. The first group will be the recommended enrolments ordered as specified in step 3 above.
  2. The second group of enrolments in the list will be:
    - i. [processAllEnrolments = false] All enrolments that were not processed. Each of these entries will have a message of "Not validated".
    - ii. [processAllEnrolments = true] All enrolments that were processed and recommended after the target kW plus predefined buffer has been reached. These entries will have the message "Target kW already reached" and are fully processed like the first group, except for the fact that they are not selected.
  3. The third group of enrolments contains the rejected enrolments, each of which will have a message indicating why the enrolment was rejected.

The algorithm will look ahead in the number of records specified to best achieve the specified target.

#### Predicted Shed Calculation for Events and Service Points.

Predicted shed data represents the expected curtailment (in kWh) for a service point between a time interval. Each interval is represented by an end time and an interval length in seconds. Under most circumstances, predicted shed data for a service point should be a continuous set of shed data intervals with an interval length between 5 and 15 minutes. This topic covers how predicted shed values are calculated for service points and Demand Response (DR) events, which is used during event creation and event modification.

When calculating total predicted shed for a service point, predicted shed data is only considered in the calculation if the shed interval end time falls within the time range for the event. For instance, predicted shed data between 11:00 am - 12:00 pm for an event with an end time of 11:30 am is excluded since the end time of the shed interval falls outside the event time range. However, the same predicted shed data will be included if the event has a start time of 11:30 am and end time of 12:30 pm.

Figure 56 includes all predicted shed data in the calculation with the exception of the last shed interval since the end time of the interval falls outside the event range.



**Figure 56. Event Shed**

The predicted shed data that overlaps the entire length of the event is not considered in the total shed calculation, resulting in an expected shed value of zero kWh for that service point. In other words, predicted shed data between 11:00 am and 12:00 pm for an event with a start time of 11:15 am and end time of 11:45 am is excluded in the calculation.

During event creation through the event wizard, total predicted shed is calculated for the entire demand response event. Individual shed values are calculated for each service point enrolment in a program then added together to produce a total kWh shed. Individual total predicted shed values for each service point enrolment is calculated as the weighted average of any eligible predicted shed records between the effective start and end time of the event. So, each predicted shed data value is scaled based on the length of the interval to ensure that longer shed intervals are weighted more heavily in the total shed value.

If the service point is only able to participate in the event for a portion of the event time due to constraints on the program, the predicted shed is expected to decrease since only the predicted shed data that falls within the start and end of the time of the event participation is considered.

If no predicted shed data exists for the service point, a value "zero" is returned.

Example Calculation:

Consider an event with a start time of 12:00 pm and end time of 2:00 pm. Assume there are also four predicted shed records for the event (to highlight the calculation, the shed data is not continuous and does not have regular time intervals).

Interval Start Time	Interval End Time	Expected Shed (kWh)	Duration (minutes)
11:50am	12:10pm	13	20
12:20pm	12:40pm	25	20
12:50pm	1:30pm	15	40
1:45pm	2:30pm	6	45

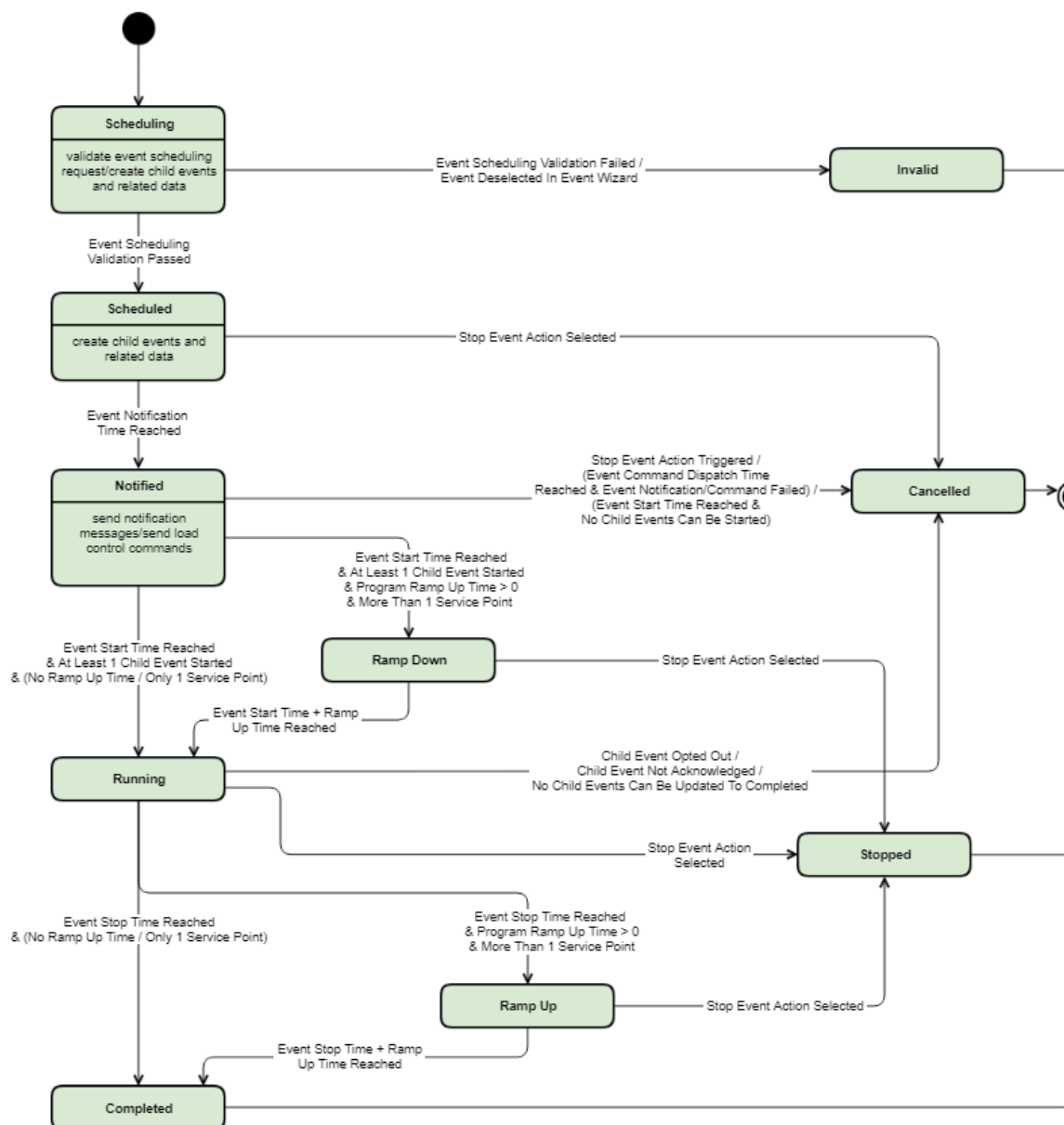
The last predicted shed record is filtered, since the end time of the interval is after the end time of the event. The first record is included since the end time of the interval falls within the start and end time of the event. The other two are fully within the bounds of the event.

The total predicted shed for that event will be the weighted average of the three predicted shed records.

$$\begin{aligned} \text{total predicted shed} &= ((13 \text{ kWh} / 20 \text{ minutes}) + (25 \text{ kWh} / 20 \text{ minutes}) + (15 \text{ kWh} / 40 \text{ minutes})) / 3 * (\text{length of child event, 120 minutes}) \\ &= 91 \text{ kWh over 120 minute event} \end{aligned}$$

## Event Lifecycle

DEMS manages demand response events a series of transitions from state to state. Figure 57 includes a diagram of the flow between states in the event lifecycle.



**Figure 57. DEMS Event Life Cycle State.**

A DR event can have the following states, that are shown to the user:

1. Scheduling: The event is being scheduled and going through validation. In order to pass the validation, a DR event must:
  - Have at least one service point that
    - Is of type ServiceDeliveryPoint or CustomerPremiseEquipment
    - Is associated with an account
    - is associated with a premise
    - Is enrolled in the programs



- Not violate program and enrolment constraints
- Not overlapping with other events that are associated with different baselines
- Not overlapping with other events that are associated with different configurable holiday calendars. A missing holiday calendar conflicts with any holiday calendar.

This is the first state of an event when it is displayed on Event Browser screen after the event scheduling request is submitted. The event would progress to Scheduled state if it passes validation.

2. **Scheduled:** The event has been scheduled and its child events and related data have been or are being created. Child events are visible on Event Details screen.
3. **Notified:** The contacts of the event have been successfully notified, or there is no need to send notification messages when one of the following conditions is met:
  - a. There are no message templates associated with the program with Event Notified event action.
  - b. There are no contacts associated with the event.
  - c. The contact methods (for example, Email) of related contacts do not match the message formats (for example, Voice) of the message templates associated with the program.
  - d. No consumer or contact method entered for the service point in the event
  - e. Consumer does not have a preference set to receive the relevant notifications

At Event Command Dispatch Time, load control commands will be sent. A child event is triggered when its load control command has been successfully sent to the AMI system. A child event that does not need load control commands is considered triggered by default. Event enters this state at Event Notification Time.

4. **Ramp Down:** The event has started and is ramping down. The event can enter this state when at least one of its child events can be started. A child event can only be started when it is notified, triggered and not opted out, except when it is an OpenADR event in which case it will always be started at Event Start Time. This state would only be available when the Ramp Up Time (Minutes) of the program is greater than zero and there is more than one service point involved. Event enters this state at Event Start Time.
  5. **Running:** The event has started and is running. The event can enter this state when at least one of its child events can be started. Event enters this state at Event Start Time or Event Start Time + Ramp Up Time when the event went through a Ramp Down state.
  6. **Ramp Up:** The event is ramping up. This state would only be available when the Ramp Up Time (Minutes) of the program is greater than zero and there is more than one service point involved. Event enters this state at Event Stop Time.
  7. **Completed:** The event is completed. Event enters this state at Event Stop Time, or Event Stop Time + Ramp Up Time when the event went through a Ramp Up state. This is a final state and the event will no longer be updated.
  8. **Cancelled:** The event is cancelled. The event enters this state when one of the following conditions is met:
    - a. No child events can be started at Event Start Time.
    - b. Child events failed to be notified before Event Command Dispatch Time.
    - c. Event commands for child events failed to be generated or dispatched at Event Command Dispatch Time.
    - d. Child events are opted out at Event Stop Time.
    - e. Child events are not acknowledged at Event Stop Time.
    - f. No child events can be updated to Completed at Event Stop Time.
- Stop action is selected on the Event Browser screen when the event is in Scheduled or Notified state.

Load control commands will be sent to cancel previous commands if necessary. This is a final state and the event will no longer be updated.

9. **Stopped:** The event is stopped. The event enters this state when Stop action is selected on the Event Browser screen when the event is in Running, Ramp Down or Ramp Up state. Load control commands will be sent to cancel previous commands if necessary. This is a final state and the event will no longer be updated.

Regarding the calibration and validation of the tool, due to the nature of the tasks performed by DEMS, in this case the process of calibration and validation does not apply.

Although not required, to maximize the accuracy of the forecasting algorithms, it is recommended that six months of historical consumption data per asset be available for analysis. If available, the algorithm uses up to two years of trailing historical data. Fewer data can be provided, however, as the volume of historical data decreases, the less reliable the forecast becomes.

### Technical specifications and advances from the existing tools

The algorithm checks each 15-minute archived value for validity based on quality indications. Selected forecasts can be generated at the beginning of the following hour.

From smart meter data will be collected at 15-minute interval period.

In terms of I/O data, the tool provides an asset time series REST API (see Table 12) to import time data series such as forecasts or historical data.

Before data is imported using this API, it is necessary to create asset service point and measurement types specifics for the data to be imported.

The data file format must be CSV containing two columns: timestamp and value, as shown below.

```
2015-12-04 00:00,33.171993
2015-12-04 00:15,23.148043
2015-12-04 00:30,50.02202
2015-12-04 00:45,52.47753
2015-12-04 01:00,87.66069
2015-12-04 01:15,22.260231
```

**Table 12. DEMS REST APIs.**

API	Description
Retrieve Compute Data	Timeseries output providing load, baseline, forecast, predicted shed, and capacity information
Event Schedule Import	Import API used to create events targeting a DR Load Commitment definition
Import Asset Time Series	Import timeseries data such as forecasts or historical data
Market Transactions - Offer and Order	Retrieve offers and import orders related to virtual power plan capacity or energy

Market Transactions - Schedule Adjust	Used for updating the power schedule for an asset and the control area to which it is assigned.
Market Transactions - Activations	Import reserve calls as a schedule
CTS Data	Request common timeseries data
Enrolment API	Create or Update a new enrolment

The flexibility forecast does not consider market specific limitations or usage information. External forecasts need to be imported into the system if utility operators choose to import a forecast rather than compute the forecast using DEMS' algorithms. External forecasts must include basic power forecast, as well as the flexibility up and down forecasts.

Meter read data is necessary to track the performance of the service point against the baseline that is calculated for the service point during demand response events as well as an input data for forecasting algorithms.

To set up and conduct a successful OpenADR Pull/Push service, the following preconditions should be met: One or more Virtual End Nodes (VEN) should be available that support Pull or Push mode of OpenADR profile 2.0a or 2.0b and obey the relevant OpenADR profile 2.0a or 2.0b VEN conformance rules. This functionality is supposed to be implemented by the NEMO tool.

In case it is necessary the IEC 104 Master Protocol Adapter works with the platform to connect IEC 104 slave devices. The protocol adapter collects measured values from, and transmits setpoints and commands to, devices in the field.

An EnergyIP application is one that is built using the EnergyIP platform. Specifically, the application must fulfill the following conditions to be called an EnergyIP application:

- It is a Java application that uses the basic common classpath provided by the EnergyIP platform.
- It uses the application bootstrap framework provided by the EnergyIP platform.
- It uses the security framework provided by the EnergyIP platform.
- The technical configuration of the application resides in the configuration schema defined by the EnergyIP platform, and is
- created/edited through the EnergyIP Configuration Management and System Console.
- From System Console, the application can be started, stopped, and its runtime status is available.

The EnergyIP platform requires application servers running Java and a database server running Oracle with two databases. Table 13 depicts the technical characteristics of these servers.

**Table 13. Technical characteristics of Energy IP application servers.**

Component	Version information
Operating System	RHEL 7.2 (64-bit), RHEL 6.7 (64-bit) <sup>1</sup>

<sup>1</sup> Included in the EnergyIP build artifact and installed by the eMeter Installer

<b>Database Client</b>	Oracle 12c JDBC driver (ojdbc7.jar) <sup>2</sup>
<b>Web/Application Server</b>	Apache Tomcat 8.0.42 <sup>2</sup> (or higher sub-version v8.0.xx) - Required for EnergyIP 8.5 SP6 and lower SP  Apache Tomcat 9.0.10 <sup>2</sup> (or higher sub-version v9.0.xx) - Required for EnergyIP 8.5 SP7 and higher SP Apache ActiveMQ 5.11.3 <sup>2</sup>
<b>Java</b>	Sun Java 8 (64-bit) <sup>2</sup> Java SE Development Kit 8u45 (JDK 1.8.0_45 or higher sub-version (v1.8.0_xx)), Sun HotSpot JVM
<b>IDE for Reports Development</b>	Eclipse BIRT 4.5.0 <sup>2</sup> Download BIRT Designer <a href="#">birt-report-designer-all-in-one-4 5 0.zip</a> from Eclipse.org.
<b>Java Cryptography Extension</b>	EnergyIP requires 128-bit encryption algorithms, which are only possible with the Java Cryptography Extension (JCE) with unlimited strength jurisdiction policy. Download the latest version of Sun JCE with unlimited jurisdiction policy at <a href="#">JCE Unlimited Strength Jurisdiction Policy Files 8 Download</a> .
<b>Shell</b>	Bash

The EnergyIP platform is supported by browsers Google Chrome (version 58 or higher) and Microsoft Internet Explorer (version 11.0).

The DEMS application requires the EnergyIP platform, Cassandra, and the Cassandra Common add-on application to be installed and fully configured. Each version of DEMS is developed and tested against a specific EnergyIP release. In the Barcelona pilot, DEMS will use Energy IP 8.5 SP6, Cassandra's 3.9 and Cassandra Common 1.2 SP2.

A Cassandra-less deployment is possible but in the Barcelona pilot project a Cassandra database has been installed for Common Time Series data model that supports the Connected Device Communication Infrastructure (CDCI).

While moving data in and out of EnergyIP and its applications, such as DEMS® DR/VPP, the system uses CDCI to leverage the CTS infrastructure as the backbone for data persistence and management. The Common Time Series schema exists in two different online data stores: Cassandra and Oracle. EnergyIP provides an archiving application that transforms and moves data from the Cassandra data store to Oracle or it purges data from the Cassandra data store to file (depending on the configuration) to reduce data volumes.

No hardware devices are required for the operation of DEMS.

The advances delivered by DEMS tool with respect to the functionalities provided for the previous release in the context of the InteGRIDy project introduces new features in the following areas:

- **Configurable Holiday Calendar:** This feature now allows operators to configure holidays, using business calendars. These holidays are used when creating Events, Visualizing baselines, and Settlement calculations.

<sup>2</sup> Customer responsibility to procure, install, and upgrade

- Custom Fields for Events: Previously, it was not possible to view custom fields (parameters) on events. DEMS now introduces the feature where the operator can configure these fields and populate them during the creation of an event.
- OpenADR Tracking: DEMS and OADR are now able to determine the communication status of gateways and the VEN below them. You can enable the tracking of OpenADR devices to indicate if they are connected.
- Custom Universal AMI Adapter (UAA): The Universal AMI Adapter (UAA) is a two-way interface with the AMI data collection systems that sit between the data collection systems and other applications in EnergyIP. The UAA will transform the information data and format coming from the smart meters to a common format so that DEMS application can interpret and process it.

### Expected advantages compared to commercial products

The Energy Decentralization is rising and will create new challenges, but also new opportunities. For example, the Grid Evolution from unidirectional and top-down to bi-directional and distributed triggers two major challenges for the energy industry. First, how to manage loads and ensure grid reliability with distributed grid assets? And second, how to bundle distributed generation and optimize it?

A demand side management system ensures that power is consumed or stored when needed. Reaction of prosumers based on requests, device commands or market prices is called Demand Response (DR). Industrial, commercial enterprises or households which stand for "demand", respond in real-time on production situations, power fluctuations and power market changes ("response"), which gives them additional revenues.

DEMS supports explicit Demand Response e.g. request to decrease/increase energy demand during peak period) or Implicit Demand Response (e.g. higher energy prices during peak period).

DEMS has the ability to execute both notification-only and automated demand response programs using a direct connection to the asset or reusing the smart meter capabilities. Operator can allow one or more types of devices to be associated with a DR Program. Device types include: Programmable Communicating Thermostats (PCT), (Building) Energy Management Systems ((B)EMS), EVSE, IHD, inverter, rectifier, energy storage, and other DLC devices not listed above that support OpenADR, Multispeak or IEC60870-5-104. Electric vehicle programs can be created and administered for electric vehicle supply equipment (EVSE) DLC programs in which the event parameters are set by the utility user.

DEMS has the ability to create and administer energy storage, smart inverter, grid-interactive water heating (GIWH) DLC programs in which the event parameters are set by the utility user.

It furthermore has the ability to create and administer regulating reserves programs, capacity programs for dispatchable generation and storage resources, ancillary services program including ramping programs or ancillary services program including non-spinning reserves programs, in which the event parameters are set by the utility user.

For the billing purposes, DEMS supports a variety of standard customer baseline load (CBL) algorithms using historical non-event loads or can create a customer own defined CBL algorithms.

EnergyIP DEMS is the answer in one single system to manage demand and supply of distributed energy resources for a wide variety of use cases presenting advantages with other available tools on the market such as Autogrid Flex [AUT20], OATI Web Distribute [OAT20] and Demand Response Solution [DEM20].



- Market-leading breadth and depth of functionality – The DEMS application is intuitive, easily-deployed, and packed with pre-built functionality across the DR value chain. These functions include rules-based participant management, event management, audit, reporting, analysis, forecasting, settlements, and dispatch management.
- Powerful and flexible support of DR business processes – The Siemens DEMS includes an embedded workflow, data driven configurations, declarative and role-based security, and integration with back office systems that enables utility business processes to be followed in a cost-effective manner.
- Integration Capability – DEMS has the ability to interface with other control room, back office and customer facing applications through bi-directional communications so that DER-related assets and data are always accessible. Billing and settlement are accurate and accelerated because DEMS integrates to meter data management and customer information systems. DEMS also has a SCADA interface to enable real time demand monitoring and automated surgical control of substations.
- Immediate and future-proofed system performance – The Siemens DEMS has been designed, tested, and proven with both scale and functionality in mind. This is unique in the DERMS software market where top-down design or one-off customization can lead to performance limitations. Siemens has developed the DEMS application to be able to provide additional functionality by leveraging information from other utility systems like GIS, SCADA, outage management, MDM and CIS. As the application continues to evolve, additional interfaces can be supported based on business needs. DEMS as an application meets utilities' current needs and easily supports dynamic future needs.
- Cost savings through operational efficiency – DEMS can be configured to support existing and future business processes. Additionally, costs can be reduced through centralized business process management and synchronization of systems across all programs and market segments. The high availability of data, program metrics and key performance indicators with DEMS create efficiencies. The potential improvement in business processes enhances the customer experience and results in increased participation, leading to operational efficiency. Surgical DR – the capability to create flexible aggregations – enables customers to identify and employ DR resources within the transmission and distribution networks in a localized manner to increase asset lifetime and reduce operations and maintenance costs.
- Surgical Demand Response – A user can provide targeted demand reductions through the use of a flexible load aggregation engine that allows aggregations to be defined by substation, feeder line, postal code, map interface or several other associations. This “surgical” approach uses DR Program resources more efficiently and enables utilities to “condition the load” so that grid conditions are more favourable to safe and reliable operations. In a utility's case, DEMS can be configured to automatically execute DR events on loads serviced by specific substations or feeder lines when they are under operating stress and threaten reliability. This capability provides the ability to limit or avoid outages, restoration costs and contributes to longer, better performing assets. This might be of interest for the USEF Activities in the Netherlands or other parts in Europe.
- Flexible Integration – Siemens can integrate DEMS with the existing utility enterprise architecture. DEMS can be integrated to MDM, CIS, SCADA, AMI, and other systems. DEMS is also designed with flexible interfaces to make system integration cost effective and to deliver the solution on time.
- Workflow Management – DEMS provides the ability to configure workflow processes so that demand response customers, events, and settlements are managed according to utility business processes and program guidelines. This structure ensures that business objectives are achieved by executing events in a consistent manner with a defined workflow process.



- DEMS Product Road Map - Siemens uses the agile model for product development. The agile model allows the DEMS team to be flexible and accommodating to specific needs while also ensuring DEMS is in tune with current and future market- based requirements. Each DEMS customer can choose to join the DEMS product advisory board to help guide and validate future feature development.

### Implementation features and delivery

DEMS is deployed in the Barcelona pilot project. The tool will perform the following activities:

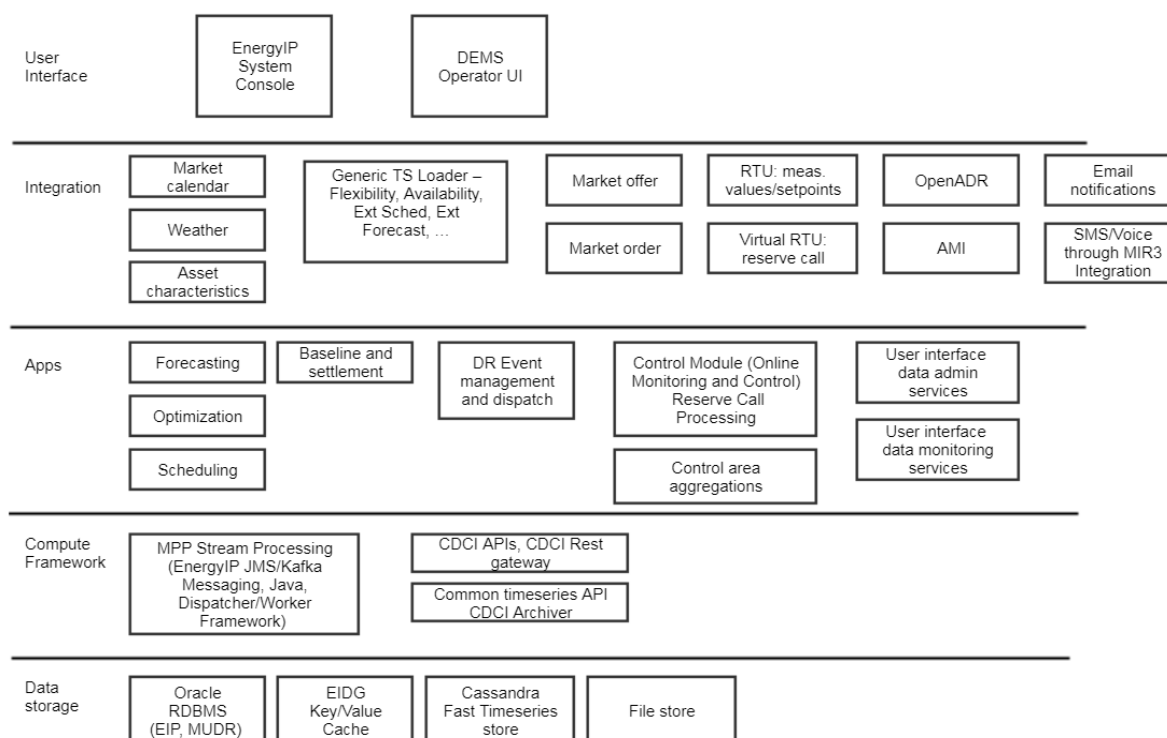
- Assess the power and energy flexibility of the swimming pool system to employ it to shift the load, in DR mechanisms.
- Import the Consumption and Load Shed forecast of the swimming pool system for use with Demand Response.

DEMS DR/VPP is hosted in the EnergyIP platform. The product leverages several platform components and consists of a number of different applications that work together to enable DER management use cases.

At a high level, DEMS DR/VPP includes the following architectural components:

- User interface
- Integration, device, and end customer communication components
- Functional applications
- Computational framework
- Data storage

Figure 58 presents the multi-level architecture of DEMS and the modules included at each level.



**Figure 58. Multi-level architecture of DEMS and modules included at each level.**

The Distributed Energy Management Systems (DEMS) add-on applications requires additional third-party components:

- Cassandra no-sql database (Table 14)
- Kafka stream processing message broker (Table 15)

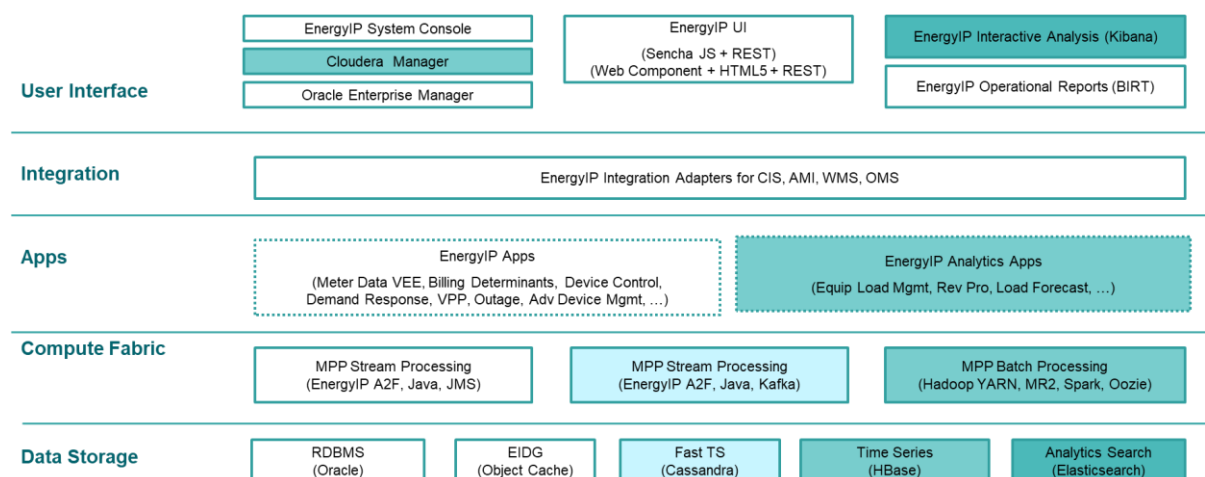
**Table 14. Cassandra database technical features.**

<b>Database</b>	Cassandra
<b>Database Version</b>	Apache Cassandra 3.9 or 3.11.2 <sup>3 4</sup>
<b>Operating System</b>	Cassandra server can run on any platform that is supported by Apache

**Table 15. Kafka database technical features.**

<b>Message Broker</b>	Kafka
<b>Version</b>	Apache Kafka 1.0.0 or 2.0.0 (kafka_2.11-1.0.0 or kafka_2.11-2.0.0) which includes Apache ZooKeeper <sup>3 4</sup>
<b>Operating System</b>	Kafka server can run on any platform supported by Sun Java

Figure 59 shows a EnergyIP high level technology stack (Transactional + Big Data)



**Figure 59. EnergyIP high level technology stack.**

<sup>3</sup> Customer responsibility to procure, install, and upgrade

<sup>4</sup> Used only in certain optional applications



In regards source code EnergyIP applications are deployed on EnergyIP servers, that is, servers where EnergyIP has been installed and is running. An EnergyIP deployment may be a single server deployment where all applications run on a single machine, or a multi-server deployment where applications run across multiple machines.

For an EnergyIP application to be deployed on a server the application jar file must be present in the \$EIP\_HOME/core-lib for core applications or the \$EIP\_HOME/opt/lib directory for optional applications. A soft link to this jar file must exist in the \$EIP\_HOME/lib directory. Any other jars that the application uses (above and beyond the class path provided by EnergyIP platform) must also be placed in the lib directory along with the application jar file.

EnergyIP releases software packages for the applications including functional modifications, improvements and enhancements.

The environment deployed in the Siemens private cloud in Seville for the Barcelona pilot could be virtualized in virtual machines for deployment in any other infrastructure compatible with the installation requirements of the EnergyIP platform.

A demo of DEMS application is not yet available. The application is currently being upgraded to a newer release and the OpenADR adapter is being installed.

For more information about DEMS, please contact:

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#### 4.4 Storage Systems

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The macro functionality Storage Systems includes the following layers as defined in Deliverable “D1.5 – inteGRIDy Architecture & Functional/Technical Specifications” and shown in [IND15]:

- Virtual Energy Storage. Use of swimming pools or buildings as virtual heat storages to displace energy demand.
- Thermal Storage. Typically, this includes tanks that use water as storage fluid.
- EV Charging Profiling. Characterization of the electrical vehicle use patterns and electric balance with the grid.
- Battery Cycling. Charge and discharge effects over the performance of project relevant battery technologies.

The following subsections characterize the inteGRIDy tools that include functionalities related to Storage Systems:

- TRNSYS Swimming Pool Model, implemented by AIGUASOL.
- Supervisory Model Predictive Control for Energy Systems, developed by CETH-CPERI.

#### 4.4.1 TRNSYS Swimming Pool Model

##### General description of the inteGRIDy functionalities

Transient System Simulation Tool, also known as TRNSYS, is a commercial energy simulation software developed in Fortran imperative programming language, by the University of Wisconsin [THE18]. It is a flexible graphical based software that simulates the behaviour of transient systems, mostly focused on thermal and electrical energy systems. However, it can be used to model different types of dynamic behaviours, such as traffic flow or biological processes.

TRNSYS has two parts, the first one is an engine (called kernel), which reads and processes the input file and iteratively solves the system. The second one, an extensive library with components from vastly different areas such as weather data processors, energy generation technologies, multizone buildings, HVAC equipment and economic routines. This has been the tool chosen to model the behaviour of the main elements that make up the swimming pool and the sport centre.

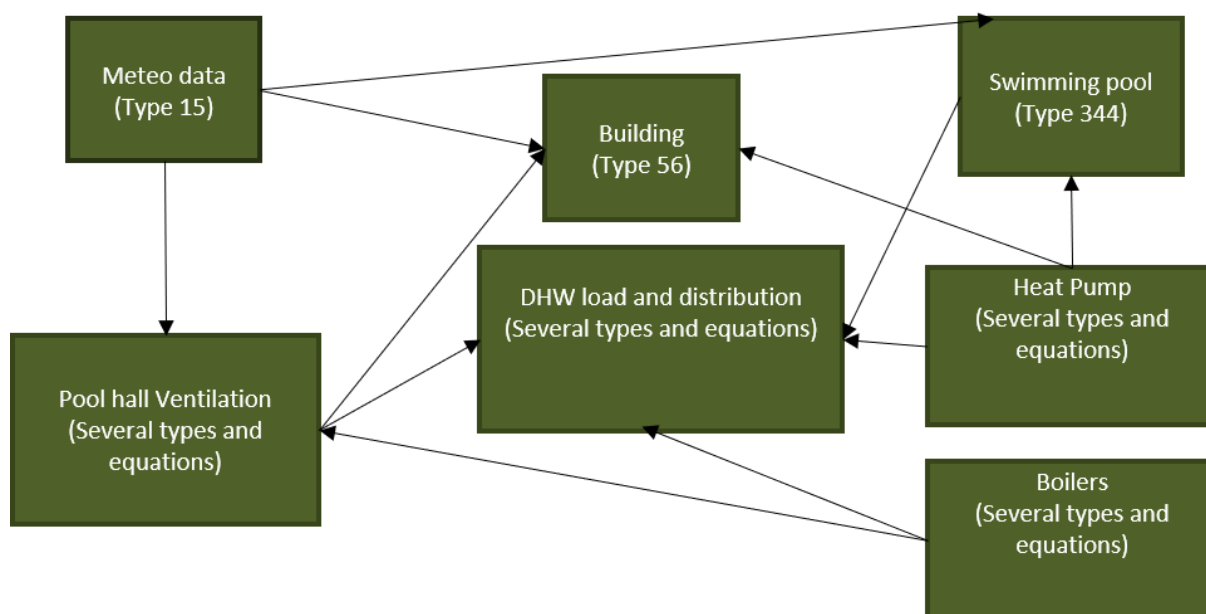
The TRNSYS model addresses the Project pillars Smartening the Distribution Grid and Energy Storage, through the assessment of the thermal behaviour and energy system of a building and a swimming pool. The model characterizes the heat production at low and high temperature via heat pumps and boilers respectively. Air handling unit is included in the model. A detailed swimming pool model is included to assess the adequacy of employing the swimming pool to virtually store energy.

##### Details of the modelling process

This section describes the TRNSYS model of the Claror Sports Centre, where the Barcelona inteGRIDy pilot project is deployed. The system modelled consists of the following main elements:

- Sports Centre building
- Swimming pool hall and pool
- Swimming pool hall ventilation system
- Swimming pool water heating system
- Meteorological data
- Domestic hot water (DHW) loop and heating system
- HVAC system of the building including generation system, composed by a heat pump and boilers

These subsystems are coupled and simulated as a whole system taking into account the dependencies between subsystems as shown in Figure 60.



**Figure 60. Main elements and dependencies between modules of the TRNSYS swimming pool model.**

The dependencies and interactions between the modules account for the following effects:

1. Meteo data-> Swimming pool
  - Solar radiation through windows incident at the pool surface
  - Fresh water renovation
2. Meteo data-> Building
  - Radiation incident in the building
  - Thermal losses due to conduction through building envelope
  - Outdoor air infiltration
  - Fresh air ventilation of building areas
3. Meteo data-> Pool hall ventilation
  - Outdoor air temperature
4. Pool hall ventilation->Building
  - Swimming pool hall heating
  - Swimming pool hall dehumidifying
5. Pool hall ventilation -> DHW load
  - Air handling unit (AHU) condensation preheating system (if active)
6. Heat pump->Swimming pool
  - Pool water heating
7. Heat pump->Building
  - Building space heating
  - Building cooling and dehumidifying
8. Heat pump->DHW load



- DHW preheating
9. Boilers->Pool hall ventilation
- Pool hall heating hot water generation
10. Boilers->DHW load
- DHW heating (in series with the heat pump preheating)

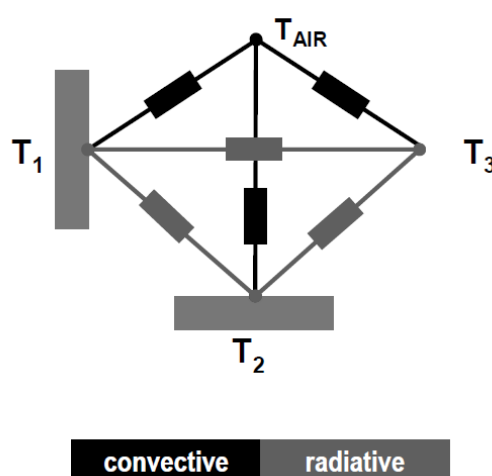
In addition, below are listed other components in the model that present specific purposes:

- Schedule and occupancy profiles of the building
- Activity and internal gains of the building
- Infiltration calculation models
- Ventilation system control
- Simulation results visualization and printing

In the following a more detailed description of the main model components is provided.

### *Sport Centre Building*

The model of the building uses the type (routine) 56 of TRNSYS, which simulates the building as a multi-zone energy balance. For each thermal zone, the air temperature is calculated after performing a convective and radiative energy balance within the zone. As an example, Figure 61 depicts the energy exchanged through convection and radiation between three surfaces (1,2 and 3) in a zone.



**Figure 61. Convective and radiative energy exchanged between three surfaces in a zone (source: [AUE96]).**

The convective energy balance considers the following phenomena:

- Convective heat gains from all surfaces
- Infiltration gains
- Mechanical ventilation gains
- Convective heat gains from internal sources (people, equipment, lighting...)
- Fraction of solar radiation through windows converted in convective gains

The radiative energy balance for each surface considers three terms:

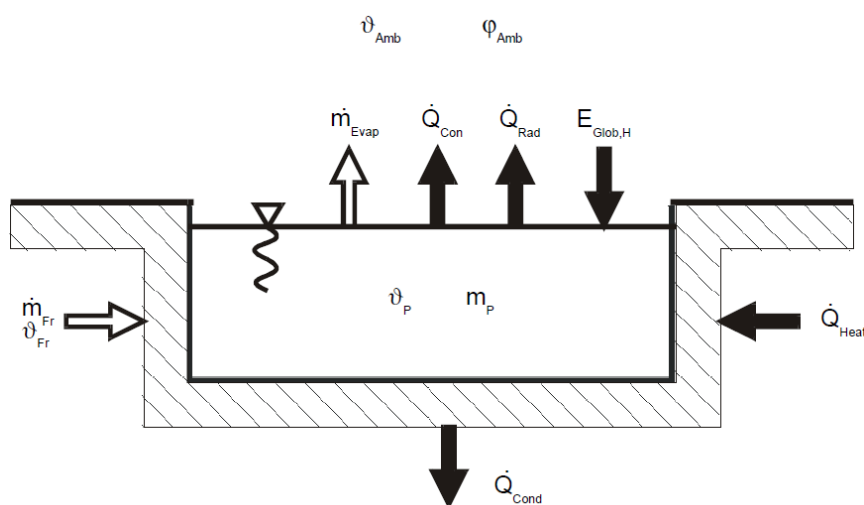
- Radiative gains from internal sources

- Solar gains through windows
- Long wave radiation exchange between surfaces based on the Gebhart model [GEB59]

Each wall temperature is determined by the transfer function method of Mitalas and Arsenault [MIT72]; for the calculation of thermal and optical properties of the windows, type 56 incorporates the method of the WINDOWS 4.1 software, developed by National Berkeley Laboratory [ARA94].

### Swimming pool

The model of the swimming pool is a commercial component available from Transsolar [AUE96]. Figure 62 presents the energy balance of the swimming pool.



**Figure 62. Energy balance of swimming pool as considered in Transsolar (source: [AUE96]).**

The heat exchange with the surroundings includes the following terms:

- Heat flow rate by evaporation
- Heat flow rate by convection
- Heat flow rate by short-wave radiation
- Heat flow rate by long-wave radiation
- Heat loss by fresh water supply
- Heat flow rate from heating

The heat loss by evaporation  $Q_{evap}$  can be calculated on the basis of the evaporated mass flow rate as follows:

$$Q_{evap} = m_{evap} \cdot \Delta h_{evap} \quad (94)$$

where  $\Delta h_{evap}$  is the water enthalpy of evaporation. The evaporated mass flow rate  $m_{evap}$  is computed from the difference in pressure of the water steam between the water surface and the surroundings, which is considered as the main driving force. In this case it is assumed that a layer just above the water surface is at the pool water temperature  $T_{pool}$  and has a relative humidity  $RH_{amb}$  of 100 %. For an indoor pool the evaporated mass flow rate can be calculated with the following equation:

$$m_{evap} = \varepsilon \cdot A_{total} \cdot (p_{sat}(T_{pool}) \cdot p_{steam}(T_{amb})) \quad (95)$$

where  $A_{total}$  is the contact surface of the pool,  $p_{sat}$  is the water saturation pressure and  $T_{amb}$  is the ambient temperature. The steam pressure  $p_{steam}$  in ambient conditions can be calculated using the relative humidity as:

$$p_{steam}(T_{amb}) = RH_{amb} \cdot p_{sat}(T_{amb}) \quad (96)$$

The total evaporation coefficient  $\varepsilon$  for a choppy water surface is taken from the VDI Guideline 2089 [VDI94].

The heat flow rate by convection  $Q_{conv}$  can be calculated on the basis of Newton's formula as:

$$Q_{conv} = \alpha \cdot A_{total} \cdot (T_{pool} - T_{amb}) \quad (97)$$

where  $\alpha$  is the convection coefficient, which is computed based on Lewis's formula for mass and heat transfer, and the relation between the heat and mass transfer coefficients can be determined as:

$$\frac{\alpha}{D} = \frac{\lambda}{\rho \cdot D_{mix} \cdot c_p} \quad (98)$$

where  $D$  is the thermal diffusion coefficient,  $\lambda$  is the thermal conductivity,  $\rho$  is the density,  $D_{mix}$  is the mixed-average diffusion coefficient and  $c_p$  is the thermal capacity.

The heat transfer with the walls by long-wave radiation exchange  $Q_{rad}$  is computed based on Stefan-Boltzmann law as follows:

$$Q_{rad} = A_{total} \cdot \varepsilon_{water} \cdot \sigma \cdot (T_{pool}^4 - T_{walls}^4) \quad (99)$$

where  $\varepsilon_{water}$  is the water emissivity and  $\sigma$  is the Stefan-Boltzmann constant.

The short-wave radiation gain is determined through the computation of the data of radiation striking the pool based on the window model and the view factors determined by Gerhardt model [GEB59].

The energy flow due to the heating circuit and the fresh water renovation is characterized as:

$$Q = m \cdot C_p \cdot (T_{in} - T_{pool}) \quad (100)$$

where the flows are set according to the design values of the pool filtering loop and the temperatures correspond either to the heating water coming from the heat pump or the mains water temperature, depending on the term considered.

Finally, the pool temperature is determined according to:

$$\sum Q_i = m_{pool} \cdot C_p \cdot (T_{pool}^{prev} - T_{pool}) \quad (101)$$

where  $T_{pool}^{prev}$  is the pool temperature in the previous time step.

### *Pool Hall Ventilation System*

The pool ventilation system maintains the required thermal and psychometric conditions in the pool hall:

- Renovation of indoor air in order to ensure the desired indoor air quality
- Heating of the space air to keep the comfort conditions
- Dehumidify the indoor air in order to remove the excess evaporation water coming from the pool surface

The model of the ventilation pool is built based on the characteristics of the AHU Astrapool Airpool 82 installed in the Barcelona pilot project. The equipment, includes the possibility to recover part of the condensation heat released in the dehumidifier to use it as a source in the pool heating. Although this feature is incorporated in the model, this has not yet been activated because the actual system does not have this feature currently activated.

The elements incorporated in the model are:

- Sensible air heat recovery device
- Mixing box of fresh and exhaust air
- Enthalpy controlled free cooling system
- Evaporator coil of the dehumidifier
- Condensing coil
- Heating coil

Furthermore, thermostats and humidistats connected to the building model, as well as several implemented equations determine the control status of the system elements (e.g. fans, compressors, etc.), which determine the power available at each thermal battery as well as the air flow circulating through each component. Those determine the conditions of the ventilation air which is fed to the building zone, and is used to compute the indoor conditions at each time step.

### *Swimming Pool Heating System*

The pool heating system has a hybrid water-air/water heat pump. If there is a cooling load to be met by the system, the heat pump operates as a water-water heat pump, and evaporator heat is used for the building central cooling system. Otherwise, it operates as a standard water-air heat pump and condensing is done by means of dry cooling incorporated in the equipment.

The heat pump model is a Climavenetta NECS-Q 512 and is included as a performance map based on correlations from performance data available from the manufacturer. The model control includes the control strategy of the real equipment (4 stages) and an estimation of the start-up losses derived from previous experience from monitoring data by Aiguasol. The flow rates of the system are set according to the specifications of the pumping equipment in the facilities. The system also incorporates two buffers (hot and cold) which are also in the real system due to the need of granting hydraulic stability in the heat pump heat exchangers.

In terms of calibration and validation, no validation of the components used in the model is performed since they are all sourced from already validated standard or commercial TRNSYS libraries.

The whole energy system model will be validated and calibrated using monitored data from the Barcelona pilot project.

### **Technical specifications and advances from the existing tools**

The model can compute the day ahead energy consumption of a building in 15-minutes time steps.

As input data, the model requires the configuration parameters, monitoring data to set up the initial conditions, and the weather forecast data in CSV format. Likewise, the outputs of the model are CSV file containing the technical performance data of the energy system.

In production mode, it is possible to source the model's outputs through a specially developed API REST. In this case, both the required parameters and the outputs are shared in JSON format.

Related to the development language, the new engine will be mainly implemented in C#, although some components developed in java will also be necessary. On the other hand, the swimming pool model will be implemented in TRNSYS' own development environment (Studio).

In order to calculate the performance of the modelled energy system it is necessary to provide a number of input files (e.g. 12 hours weather forecast) and characterize the system's components (e.g. size of the system, set point temperature, etc.).

The model is executed in Windows operating system, and does not require any additional hardware device.

The Swimming Pool Model has been built from scratch exclusively for the purpose of the inteGRIDy Barcelona pilot. As mentioned earlier, the model used already developed libraries available in TRNSYS to characterize energetically several components of the system. The configuration and setup of the wholistic model have been carried out under the inteGRIDy project.

### **Expected advantages compared to commercial products**

There are no known existing commercial products with the same characteristics. Although predictive control systems (MPC) based on models have been used in previous projects, none of them have considered using the pool as a virtual energy storage [PEA18]. As a result of the project, it is expected to develop a hardware-free tool able to optimize the control of existing HVAC systems in swimming pools and other similar equipment in a completely new way.

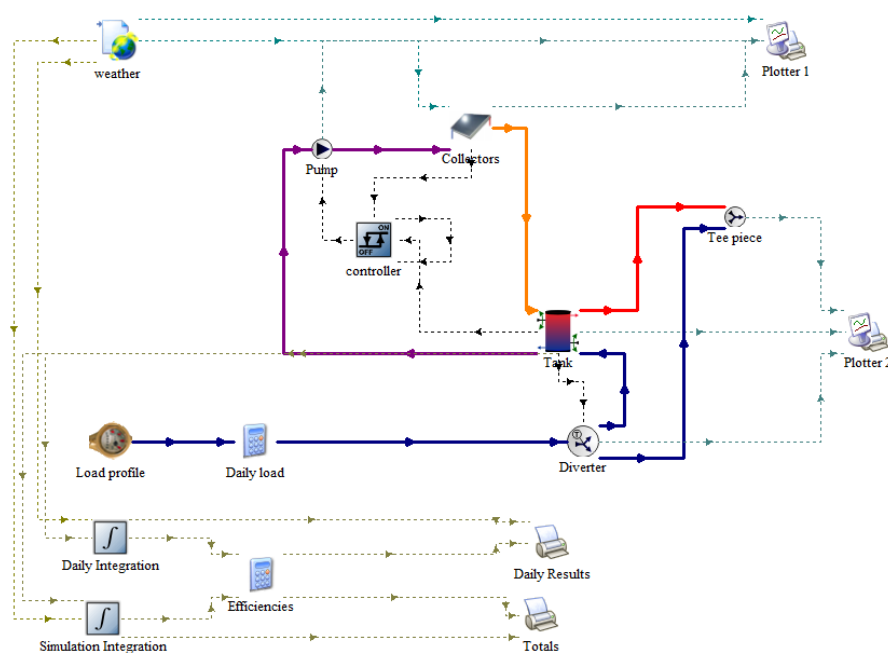
### **Implementation features and delivery**

The Swimming Pool model will be applied exclusively to the Barcelona pilot project. The model will perform the following tasks:

- Model the swimming pool systems, consisting of a swimming pool, heat pump, dehumidifier and boiler
- Evaluates the load and duration before the swimming pool reaches uncomfortable levels for the users in virtual storage mode

The Swimming Pool Model has been fully developed within the inteGRIDy project using components already available in the commercial software TRNSYS.

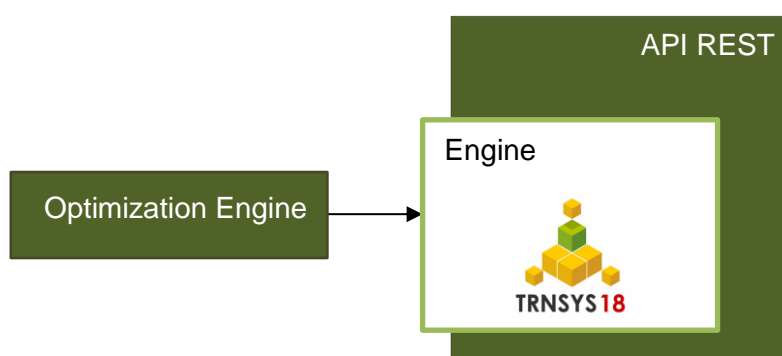
The energy systems are defined through the connection of a number of components using a GUI as shown in Figure 63 for a solar thermal system. Internally, the components have a set of equations that solve a determined physical phenomenon.



**Figure 63. Definition of connection between components of a solar thermal system in TRNSYS' GUI.**

TRNSYS is a standalone software designed to run on demand on desktop computers. The Barcelona pilot aims to implement a predictive control system based on models (MPC), application that is far from what was foreseen for this project. Therefore, in addition to the full development of the swimming pool model, it will be necessary to adapt it so that it can be executed remotely to predict and optimize the operation of a swimming-pool HVAC system. A new engine will be developed to run the kernel, as well as a new API REST to source the model's outputs.

As already mentioned, the TRNSYS model is a standalone application designed to run on desktop computers or cluster. However, thanks to the new engine can be containerized in Docker and run as a web service.



**Figure 64. Basic architecture of the new engine.**

Although it is common to perform co-simulations between TRNSYS and other simulation tools, such as MATLAB, it is probably the first time that TRNSYS will be used as a tool to model the behaviour of a system in a production environment. This has been possible mainly thanks to Docker's ability to modernize legacy apps. The TRNSYS kernel has been ported to a Docker container and new auxiliary services, such as databases or APIs, have been developed and integrated to have a fully functional web service. As already mentioned, TRNSYS has an





extensive library with components from vastly different areas, which can now be used in a new environment and a wide variety of projects.

An image of the Docker container will be made available in the inteGRIDy project repository. Currently there is no demo available.

For more information about the Swimming Pool model, please contact:

Oscar Cámara Moreno: [oscar.camara@aiguasol.coop](mailto:oscar.camara@aiguasol.coop)

#### 4.4.2 Supervisory Model Predictive Control for Energy Systems

##### General description of the inteGRIDy functionalities

The Supervisory Model Predictive Control (MPC) tool covers a broad variety of systems such as hydrogen generation, renewable energy and fuel cell systems. The tool enables the technical specification of the elements integrating the energy system. More specifically, the tool is based on the model-based control concept with the following capabilities and features:

- Model-based engineering that considers process dynamics and accelerates the development of accurate single variable or multi variable controllers.
- Handling of input and output system or process constraints based on specific variables.
- Consider the complex interactions between different subsystems of a system, process or network including various variables.
- Integration of powerful and robust optimization algorithms for the decision-making procedures related to the manipulated variables, able to set priorities and weights for every objective.
- Disturbance rejection due to the predictive nature of the controllers that compensate processes variations.
- User friendly environment that provides an interface to the tuning parameters of the MPC algorithm ensuring flexible behaviour.
- Provide control actions to low level or supervisory level systems, subsystems monitored by SCADA or other automation systems.

All four inteGRIDy pillars – Smartening the Distribution Grid, Demand Response, Energy storage technologies and EVs are addressed since the tool provides actions that can be related to the energy balance between the nodes of the microgrid, impacting the demand response mechanisms, smartening of the grid and energy storage including the EV scheduling.

##### Details of the modelling process

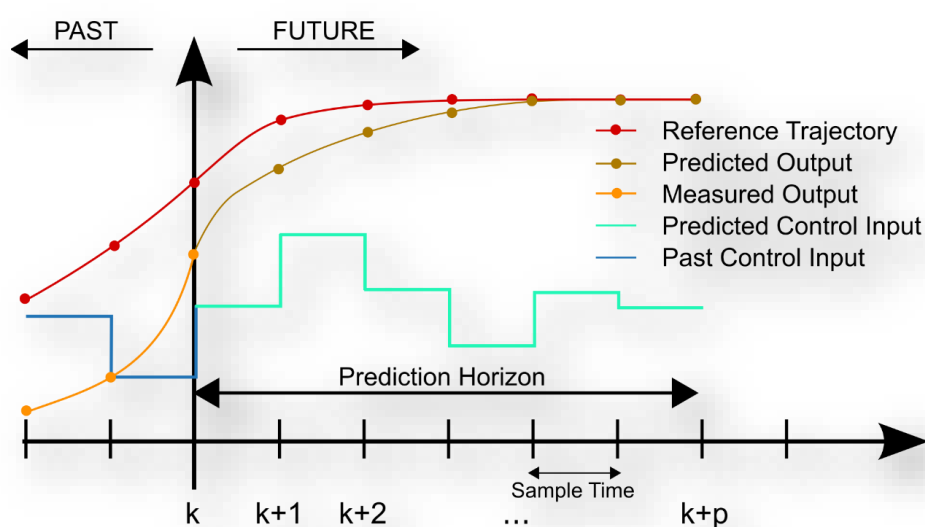
The Supervisory MPC, which is part of the online Advanced Process Control platform, runs on a computer-based system according to the needs and requests from the user/site. It can be integrated to a variety of industrial automation systems using OPC communication. Furthermore, it can share data with the process information systems of the site including data archiving servers or any OPC enabled system.

The tool includes mathematical models for renewable energy and energy storage systems from literature, and developed in MATLAB environment, including:

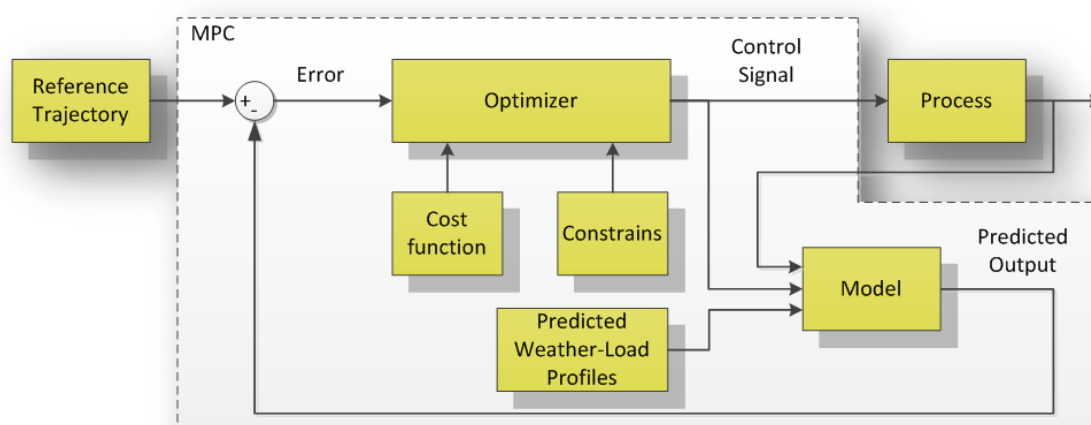
- Solar PV
- Wind generators
- Lead acid and lithium ion batteries
- Battery aging
- Polymer electrolyte membrane fuel cell
- Polymer electrolyte membrane electrolyser
- Compressor
- Buffer/final tank hydrogen storage
- Diesel generator

##### *Nonlinear Model Predictive Control (NMPC)*

The tool is developed based on the mathematical concept of Nonlinear Model predictive control (NMPC) (Figure 65 and Figure 66). It is part of a family of optimisation-based control methods, which perform on-line optimisation for the determination of the future control moves. NMPC is based on the assumption that past and present control actions affect the future response of the system. The main objective is to obtain a control action by minimising a cost function related to selected objectives or performance indices of the system. At each sampling time a finite horizon optimal control problem is solved over a prediction horizon  $T_p$ , using the current state of the process as the initial state. The optimisation yields an optimal control sequence  $\{u(k), u(k+1), \dots, u(k+N_c)\}$  over a control horizon  $T_c$  and only the first control action  $u(k)$  for the current time is applied to the system. At the next time instant the horizon is shifted by one sampling interval and the optimisation problem is resolved using the information of the new measurements acquired from the system



**Figure 65. Model Predictive control concept**



**Figure 66. Model Predictive Control Algorithm**

In the following, the models of all microgrid energy devices are presented.

### Solar PV model

The operational current  $I_{pv}$  (A) of a PV system is modelled as follows:

$$I_{pv} = I_L - I_o \cdot \left[ \exp\left(\frac{V_{pv} + I_{pv} \cdot R_s}{\alpha}\right) - 1 \right] - \frac{V_{pv} + I_{pv} \cdot R_s}{R_{sh}} \quad (102)$$

where  $I_L$  is the light current for the PV system, A;  $I_o$  is the diode reverse saturation current for the PV system, A;  $V_{pv}$  is the operation voltage of the PV-system, V;  $\alpha$  is the curve fitting parameter for the PV-system, V;  $R_s$  is the series resistance for the PV system,  $\Omega$ ; and  $R_{sh}$  is the shunt resistance for the PV system,  $\Omega$ .

The light current is obtained from the equation:

$$I_L = \frac{G_T}{G_{T,ref}} \cdot \left[ I_{L,ref} + \mu_{I,sc} \cdot (T_c - T_{c,ref}) \right] \quad (103)$$

where  $G_T$  is the solar radiation,  $W / m^2$ ;  $G_{T,ref}$  is the reference solar radiation,  $W / m^2$ ;  $I_{L,ref}$  is the reference light current for the PV system, A;  $T_1, T_2$  are the lower and higher temperature deviations from the *ref* temperature  $T_{c,ref}$  of the solar cell, K;  $T_c$  is the cell temperature K;  $T_{c,ref}$  is the reference cell temperature K and  $\mu_{I,sc}$  is expressed as:

$$\mu_{I,sc} = \frac{\Delta I_{sc}}{\Delta T} \cong \frac{I_{sc}(T_2) - I_{sc}(T_1)}{T_2 - T_1} \quad (104)$$

In short circuit current conditions:

$$I_{L,ref} = I_{sc,ref}$$

While in open circuit voltage conditions:

$$I_{o,ref} = I_{L,ref} \cdot \exp\left(\frac{-V_{oc,ref}}{\alpha_{ref}}\right) \quad (105)$$

$$I_o = I_{o,ref} \left( \frac{T_c}{T_{c,ref}} \right)^3 \cdot \exp\left[ \left( \frac{e_{gap} \cdot N_s}{a_{ref}} \right) \cdot \left( 1 - \frac{T_{c,ref}}{T_c} \right) \right] \quad (106)$$

where  $I_o$  is the reverse saturation current, A;  $I_{o,ref}$  is the reference reverse saturation current, A;  $T_c$  is the cell temperature, K;  $T_{c,ref}$  is the reference cell temperature, K;  $N_s$  is the number of cells in series; and  $e_{gap}$  is expressed as:

$$e_{gap} = 1.17 - 4.73 \cdot 10^{-4} \frac{T_c^2}{T_c + 636} \quad (107)$$

The curve fitting parameter  $\alpha$  is defined as:

$$\alpha = \alpha_{ref} \cdot \frac{T_c}{T_{c,ref}} \quad (108)$$

And  $\alpha_{ref}$  is computed as:

$$a_{ref} = \frac{\mu_{V,oc} \cdot T_{c,ref} - V_{oc,ref} + e_{gap} \cdot N_s}{\frac{\mu_{1,sc} \cdot T_{c,ref}}{I_{L,ref}} - 3} \quad (109)$$

where oc and sc refer to open and short circuit respectively.  $\mu_{V,oc}$  is expressed as:

$$\mu_{V,oc} = \frac{\Delta V_{oc}}{\Delta T} \cong \frac{V_{oc}(T_2) - V_{oc}(T_1)}{T_2 - T_1} \quad (110)$$

$R_{s,ref}$  is computed as:

$$R_{s,ref} = \frac{a_{ref} \cdot \ln \left( 1 - \frac{I_{mp,ref}}{I_{L,ref}} \right) - V_{mp,ref} + V_{oc,ref}}{I_{mp,ref}} \quad (111)$$

where  $I_{mp}$  and  $V_{mp}$  correspond to  $I_{pv}$  and  $V_{pv}$  at conditions of maximum power point (MPP).

The output power from the PV array is computed taking the maximum pair of current-voltage measurements as:

$$P_{pv} = V_{pv} \cdot I_{pv} \cdot \eta_{pv} \quad (112)$$

where  $\eta_{pv}$  : efficiency as a lumped parameter that combines all electrical parasitic losses (usually  $\approx 90-95\%$  )

#### Lead acid accumulator model (KiBam)

The available charge in Ah of a lead acid battery is modelled as:

$$q_1 = q_{1,0} \cdot e^{-k \cdot t} + \frac{(q_0 \cdot k \cdot c - I_{ac}) \cdot (1 - e^{-k \cdot t})}{k} - \frac{I_{ac} \cdot c \cdot (k \cdot t - 1 + e^{-k \cdot t})}{k} \quad (113)$$

The bound charge in Ah is computed as:

$$q_2 = q_{2,0} \cdot e^{-k \cdot t} + q_0 \cdot (1 - c) \cdot (1 - e^{-k \cdot t}) - \frac{I_{ac} \cdot (1 - c) \cdot (k \cdot t - 1 + e^{-k \cdot t})}{k} \quad (114)$$

$q_0$  results from:

$$q_0 = q_{1,0} + q_{2,0} \quad (115)$$

where  $q_{1,0}$  is the initial available charge, Ah ; and  $q_{2,0}$  is the initial bound charge, Ah .

Maximum discharging (for  $q_1 = 0$  ) and charging (for  $q_1 = c \cdot q_{max}$  ) current are respectively:

$$I_{d,\max} = \frac{k \cdot q_{1,0} \cdot e^{-k \cdot t} + q_0 \cdot k \cdot c \cdot (1 - e^{-k \cdot t})}{1 - e^{-k \cdot t} + c \cdot (k \cdot t - 1 + e^{-k \cdot t})} \quad (116)$$

$$I_{c,\max} = \frac{-k \cdot c \cdot q_{\max} + k \cdot q_{1,0} \cdot e^{-k \cdot t} + q_0 \cdot k \cdot c \cdot (1 - e^{-k \cdot t})}{1 - e^{-k \cdot t} + c \cdot (k \cdot t - 1 + e^{-k \cdot t})} \quad (117)$$

And  $q_{\max}$  is computed as:

$$q_{\max} = \frac{q_t \cdot [(1 - e^{-k \cdot t})(1 - c) + k \cdot c \cdot t]}{k \cdot c \cdot t} \quad (118)$$

where  $k, c$  are manufacturer parameters;  $t$  is time,  $h$ ;  $I_{ac}$  is the charging or discharging current,  $A$ ;  $E_{ac}$  is the source voltage,  $V$ ;  $R_o$  is the Internal resistance,  $\Omega$ ;  $I_{d,\max}$  is the maximum discharging current for time  $t$ ,  $A$ ;  $I_{c,\max}$  is the maximum charging current for time  $t$ ,  $A$ ;  $q_{\max}$  is a model parameter; and  $q_t$  is the capacity that corresponds to current  $I_t = q_t / t$  in  $Ah$  at time  $t$ .

The voltage-current relation is expressed as:

$$V_{ac} = E_{ac} - I_{ac} \cdot R_o \quad (119)$$

where in the discharge case is:

$$E_{ac} = E_{\min} + (E_{od} - E_{\min}) \frac{q_1}{q_{1\max}} \quad (120)$$

And in the charge case is:

$$E_{ac} = E_{oc} + (E_{\max} - E_{oc}) \frac{q_1}{q_{1\max}} \quad (121)$$

Finally, the state of charge is computed as:

$$SOC(t+1) = SOC(t) \cdot (1 - \sigma_{ac}) + I_{ac} \cdot \eta_{ac} \cdot (\Delta t) \quad (122)$$

where  $\eta_{ac}$  is the efficiency factor ( $\approx 95\%$ );  $I_{ac}$  is the charge-discharge current,  $A$ ; and  $\sigma_{ac}$  is the discharging rate of accumulator ( $\approx 2.5\%$ ).

#### Proton Exchange Membrane (PEM) Electrolyzer model

The operating cell voltage (V) of the PEM electrolyzer is computed as:

$$V_{elec} = V_{rev,elec} + \frac{r_1 + r_2 \cdot T_{elec}}{A_{elec}} \cdot I_{elec} + (s_1 + s_2 \cdot T_{elec} + s_3 \cdot T_{elec}^2) \cdot \log \left( \frac{t_1 + t_2 / T_{elec} + t_3 / T_{elec}^2}{A_{elec}} \cdot I_{elec} + 1 \right) \quad (123)$$



where  $V_{rev,elec}$  is the reversible cell voltage,  $V$  ( maximum voltage that can be applied across the electrodes of the electrolyzer);  $r_i$  are the parameters for ohmic resistance of the electrolyte;  $s_i, t_i$  are the parameters for the overvoltage that occurs in the electrodes;  $A_{elec}$  is the electrode area,  $m^2$ ;  $T_{elec}$  is the temperature of electrolyte,  $^{\circ}C$ ; and  $I_{elec}$  is the current through the cell,  $A$ .

The hydrogen production rate in an electrolyzer (mol/s) is computed as:

$$\dot{n}_{H_2} = \eta_F \cdot \frac{n_c \cdot I_{elec}}{n_e \cdot F} \quad (124)$$

where  $\eta_F$  is the Faraday efficiency  $\left( \frac{\text{actual amount of hydrogen produced}}{\text{theoretical amount of hydrogen produced}} \right)$ ;  $n_c$  is the number of cells;  $I_{elec}$  is the electrical current in the external circuit;  $n_e$  is the number of moles of electrons per moles of water,  $n_e = 2$ ; and  $F$  is the Faraday constant ( $F = 96,485 A \cdot s / mol$ ).

#### Hydrogen storage tank model

The tank pressure (bar) is computed as:

$$P_T = \frac{n \cdot R \cdot T_{stor}}{V_T - n \cdot b} - \alpha \cdot \frac{n^2}{V_T^2} \quad (125)$$

where  $n$  is the number of stored moles of hydrogen;  $R$  is the universal gas constant,  $8,3144598 \times 10^{-5} bar \cdot m^3 / mol \cdot K$ ;  $T_{stor}$  is the storage temperature,  $K$ ;  $V_T$  is the tank volume,  $m^3$ ;  $T_{cr}$  is the hydrogen critical temperature  $33,15 K$  and  $p_{cr}$  : hydrogen critical pressure  $13 bar$ . The parameters  $a$  and  $b$  are computed as follows:

$$a = \frac{27 \cdot R^2 \cdot T_{cr}^2}{64 \cdot p_{cr}} \quad (126)$$

$$b = \frac{R \cdot T_{cr}}{8 \cdot p_{cr}} \quad (127)$$

#### Hydrogen compressor model

The compressor power (W) is computed as:

$$\Delta W_{pol} = \frac{\kappa}{\kappa - 1} \cdot n_{H_2, comp} \cdot R \cdot T_I \cdot \left[ \left( \frac{P_2}{P_1} \right)^{\frac{\kappa - 1}{\kappa}} - 1 \right] / \eta_{comp} \quad (128)$$

where  $n_{H_2,comp}$  is the hydrogen flow at the compressor,  $mol / s$ ;  $T_i$  is the inlet hydrogen temperature,  $K$ ;  $P_1, P_2$  are the inlet, outlet hydrogen pressure,  $Pa$ ;  $\kappa$  is the polytropic coefficient for hydrogen (1.609); and  $\eta_{comp}$  is the compressor efficiency.

#### Wind generator model

The output power of the wind generator (W) at steady state is computed as:

$$P_w = c_p(\lambda, \beta) \cdot \frac{\rho A_w}{2} \cdot v_{wind}^3 \cdot \eta_{conv} \quad (129)$$

where the coefficient of performance of the generator  $c_p$  is calculated as:

$$c_p(\lambda, \beta) = c_1 \cdot \left( \frac{c_2}{\lambda_i} - c_3 \cdot \beta - c_4 \right) \cdot e^{-\frac{c_5}{\lambda_i}} + c_6 \cdot \lambda \quad (130)$$

where  $\lambda$  is the tip speed ratio;  $\beta$  is the blade pitch angle, deg;  $\rho$  is the air density,  $kg / m^3$ ;  $A_w$  is the generator swept area,  $m^2$ ;  $v_{wind}$  is the wind speed,  $m / s$ ; and  $\eta_{conv}$  : efficiency of the AC/DC converter ( $\square 90-95\%$ ).

The tip speed ratio and blade pitch angle are related as follows:

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08 \cdot \beta} - \frac{0.035}{\beta^3 + 1} \quad (131)$$

Finally, the tip speed ratio can be also computed as:

$$\lambda = R \cdot \frac{\omega}{v_{wind}} = \frac{TipSpeed}{v_{wind}} = \frac{\frac{v_{wind}^2}{R}}{v_{wind}} = \frac{v_{wind}}{R} \quad (132)$$

where  $R$  is the radius of wind generator blades  $m$  and  $\omega$  is the angular speed of wind turbine  $rad / s$ .

#### Proton exchange membrane (PEM) fuel cell model

The voltage per cell (V) in a PEM fuel cell is computed as:

$$V_{fc} = E - \eta_{act} - \eta_{ohmic} \quad (133)$$

where  $E$  is computed as:

$$E = 1.229 - 0.85 \cdot 10^{-3} \cdot (T - 298.15) + 4.3085 \cdot 10^{-5} \cdot T \cdot (\ln P_{H_2} + 0.5 \ln P_{O_2}) \quad (134)$$

and

$$\eta_{act} = \xi_1 + \xi_2 \cdot T + \xi_3 \cdot T \cdot \ln C_{O_2} + \xi_4 \cdot T \cdot \ln i \quad (135)$$

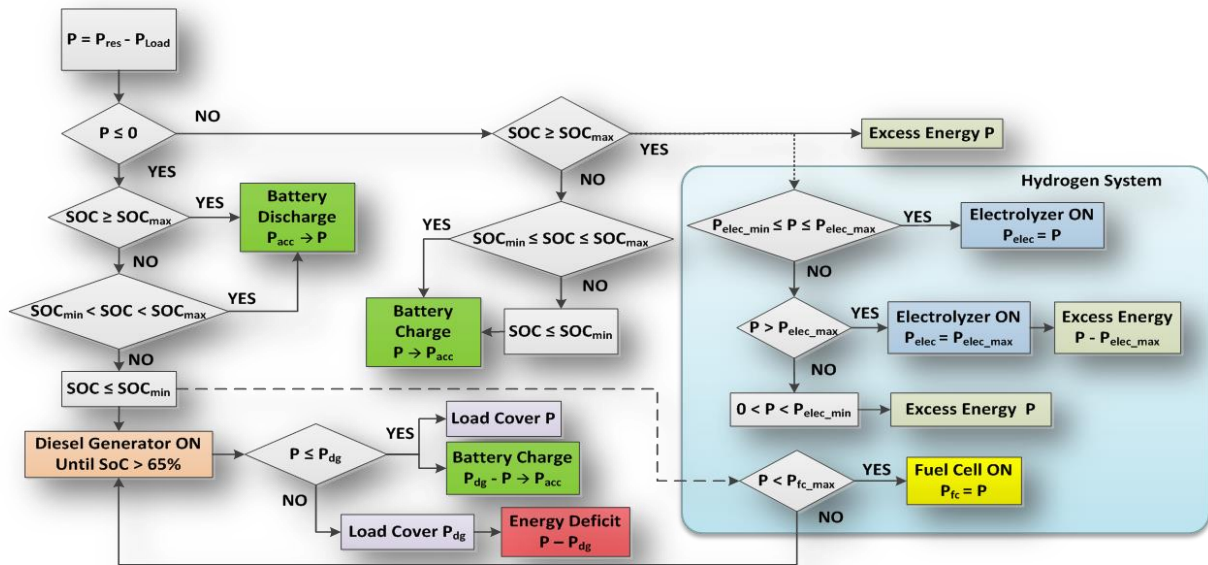
$$\eta_{ohmic} = i \cdot (\xi_5 + \xi_6 \cdot T + \xi_7 \cdot i) \quad (136)$$

where  $V_o$  is the open circuit voltage per cell,  $V$ ;  $i$  is the current density,  $\left(i = \frac{I}{A}, A/cm^2\right)$ ;  $T$  is the fc temperature,  $K$ ;  $P_{H_2}$  is the Hydrogen partial pressure, bar;  $P_{O_2}$  is the Oxygen partial pressure, bar;  $C_{O_2}$  is the Oxygen concentration;  $n$  is the number of cells;  $F$  is the Faraday constant ( $F = 96.485 A \cdot s / mol$ ); and  $\eta_F$  is the Faraday efficiency.

Finally, the hydrogen consumption rate (mol/sec) is computed as:

$$H_2 = \frac{n \cdot I}{2F \cdot \eta_F} \quad (137)$$

A topology model of Xanthi Pilot is developed according to the existing subsystems based on [PAA07] and [YIN15]. Each node implements an internal energy management strategy, based on the available infrastructure, and a model of each of them has been developed. The goals of having the device and the node models of the microgrid, is to be able to simulate and predict the power flow and operation of the microgrid. The next figure shows the internal energy management strategy applied at each node, showing also the models' interaction.

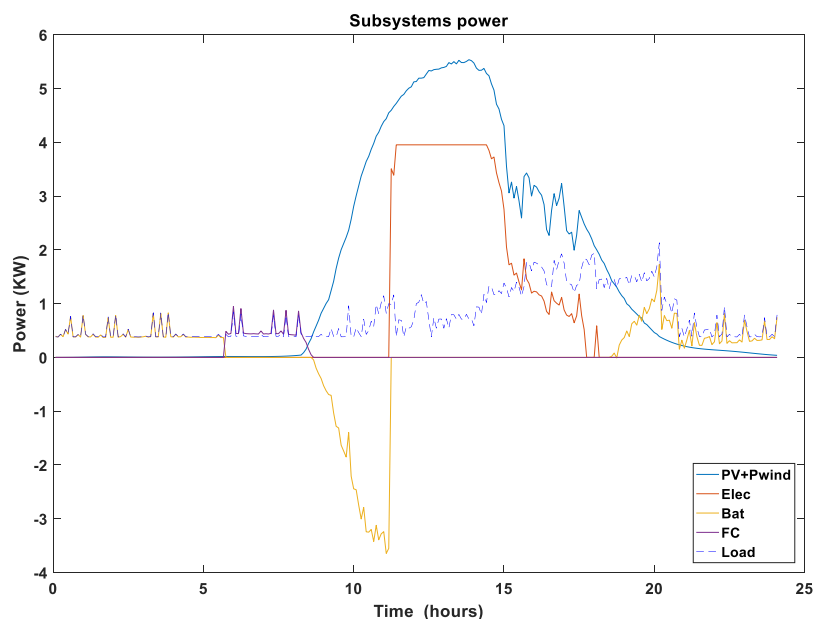


**Figure 67. Energy Management strategy of the nodes**

In case the subsystems are modified, the parameters of the models will have to be updated according to the new specifications or topology.

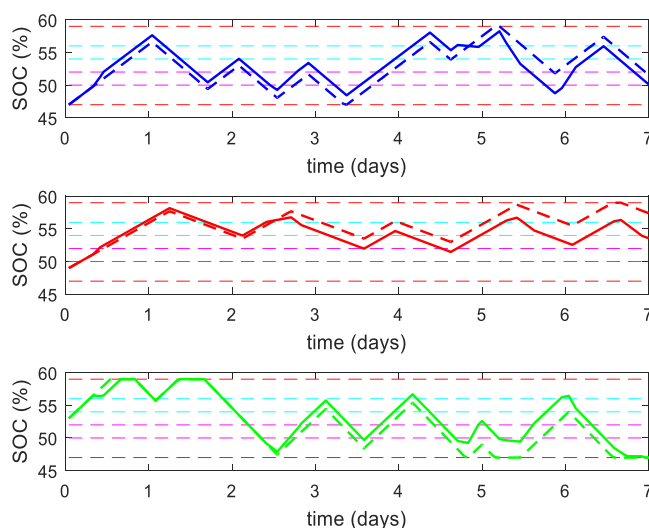
A preliminary evaluation and operation analysis of the developed models has been performed. In the following, some of the results of the preliminary evaluation are provided. Figure 68 plots

the power operation profiles of a system including solar PV and wind generation, battery storage and load for a 24 hours period at Xanthi pilot.



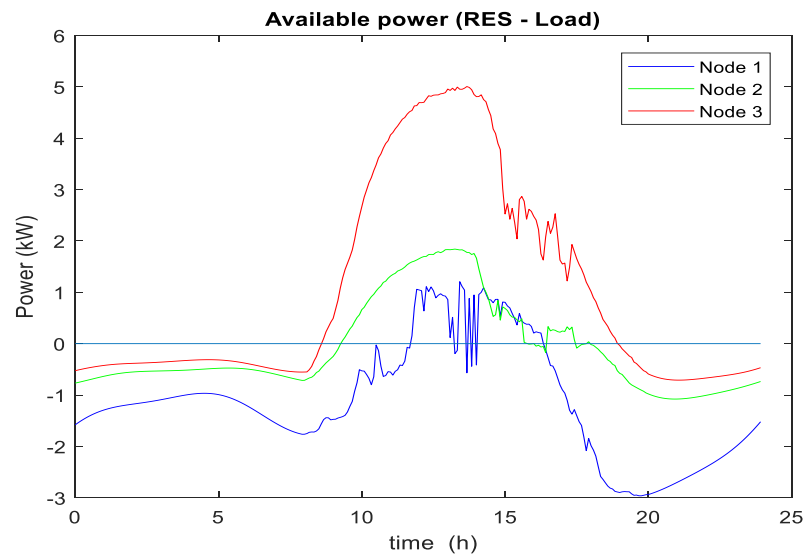
**Figure 68. Modelled operation profiles of a system including renewable generation, battery storage and load for a 24 hours period at Xanthi pilot.**

Figure 69 plots seven-day modelled operation profiles of three battery storage systems and analyses how these are affected with an energy exchange scenario enabled or disabled.

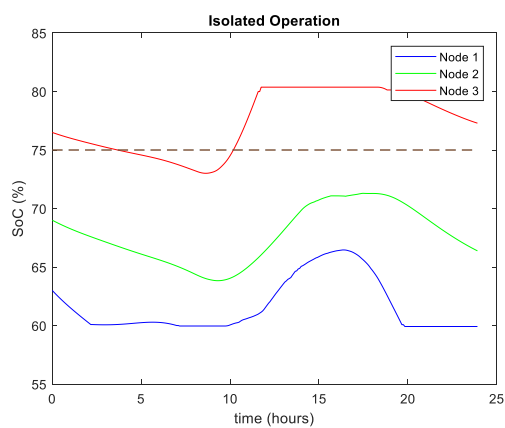


**Figure 69. Seven-day modelled operation profiles of the SOC of three battery storage systems operating independently (solid line) or interconnected (dashed line).**

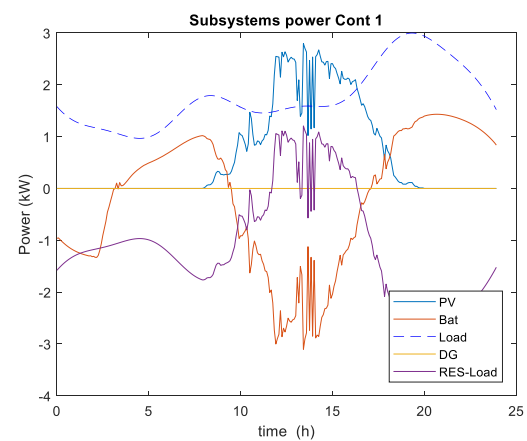
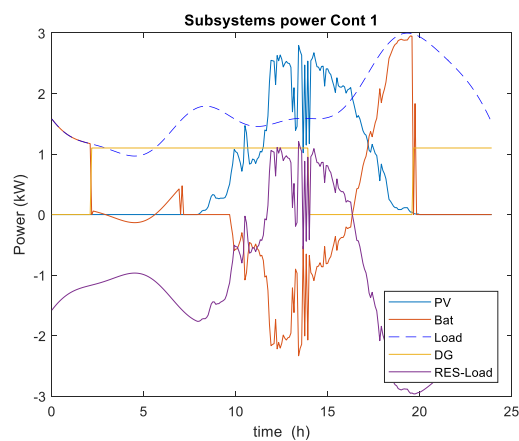
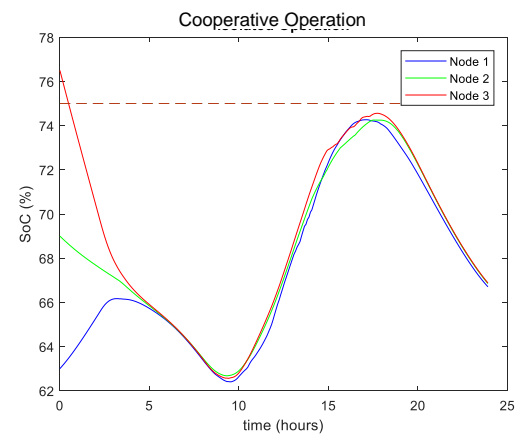
Furthermore, Figure 70 presents the results from the model of the microgrid with the NMPC disabled and enabled.

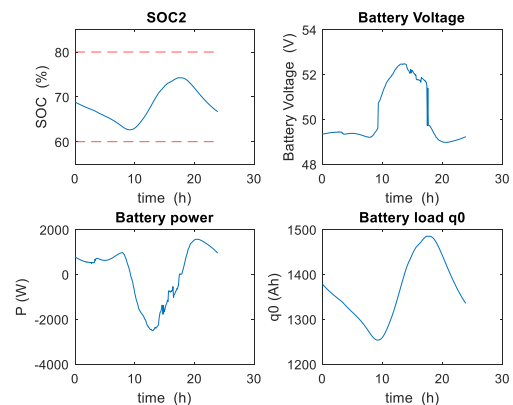
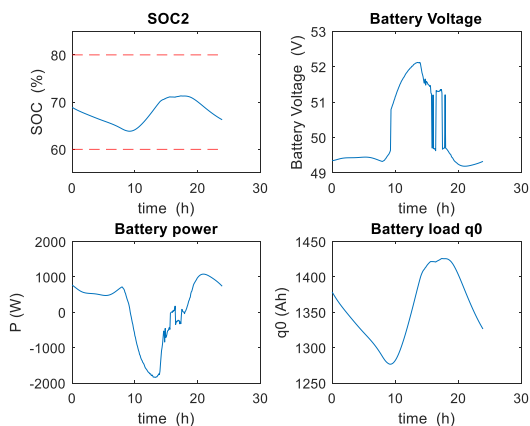
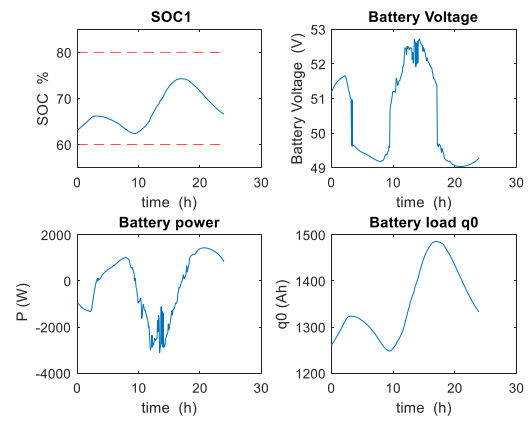
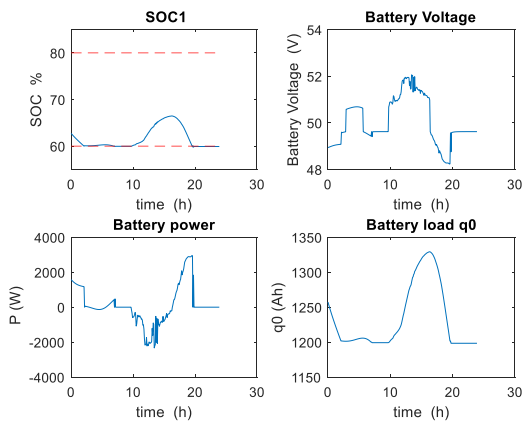
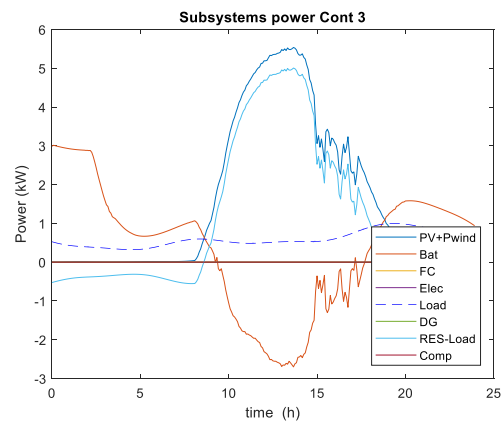
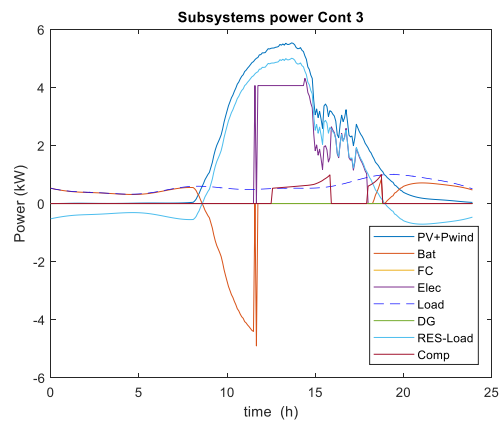
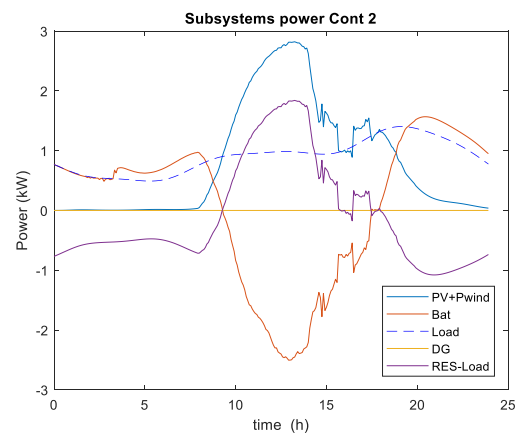
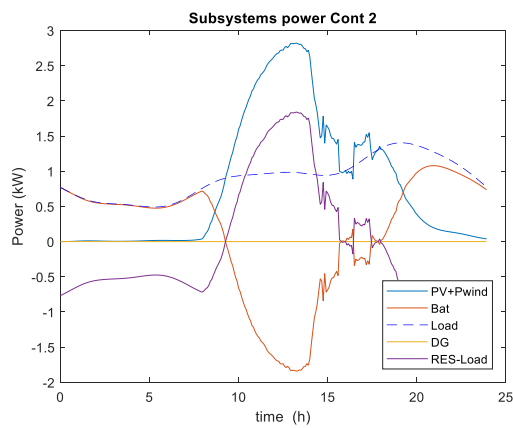


**Simulation and prediction with NMPC  
dissabled**

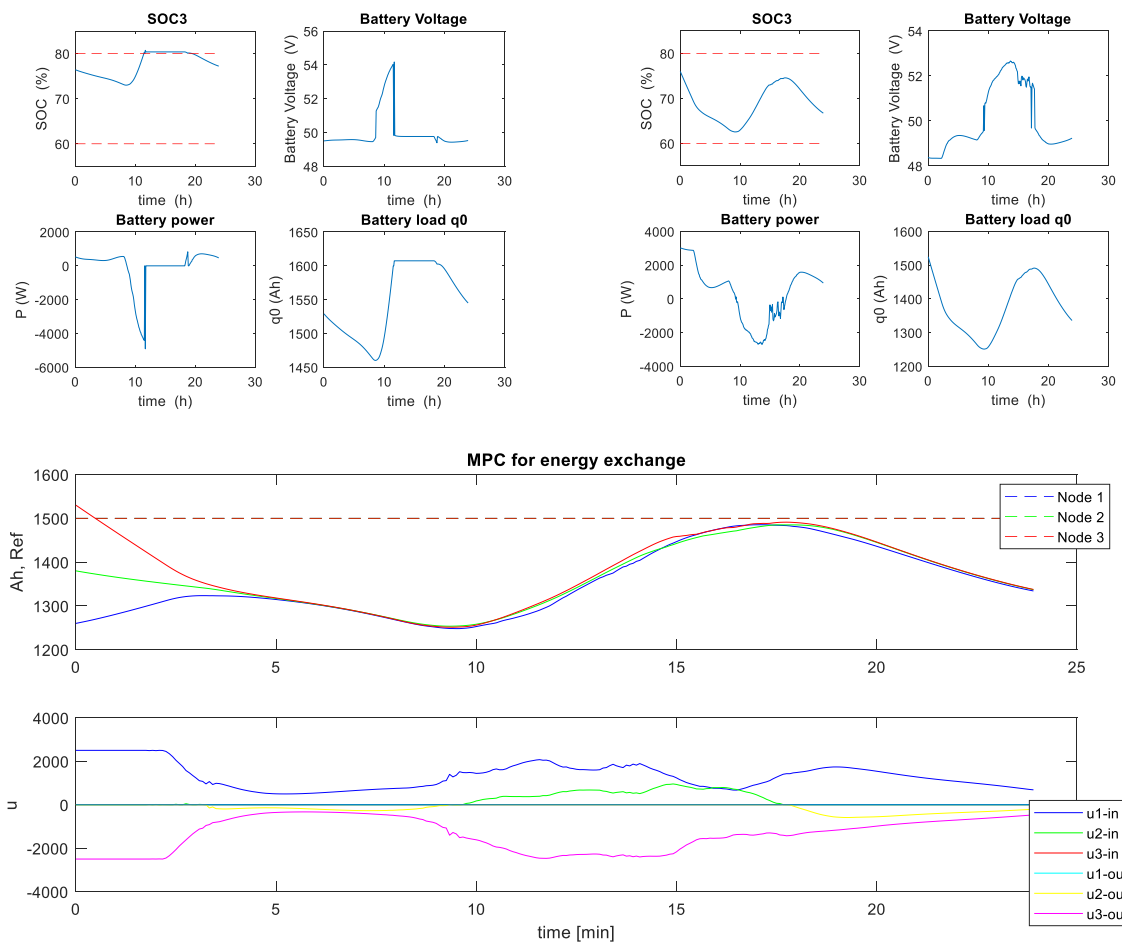


**Simulation and prediction with NMPC  
enabled**

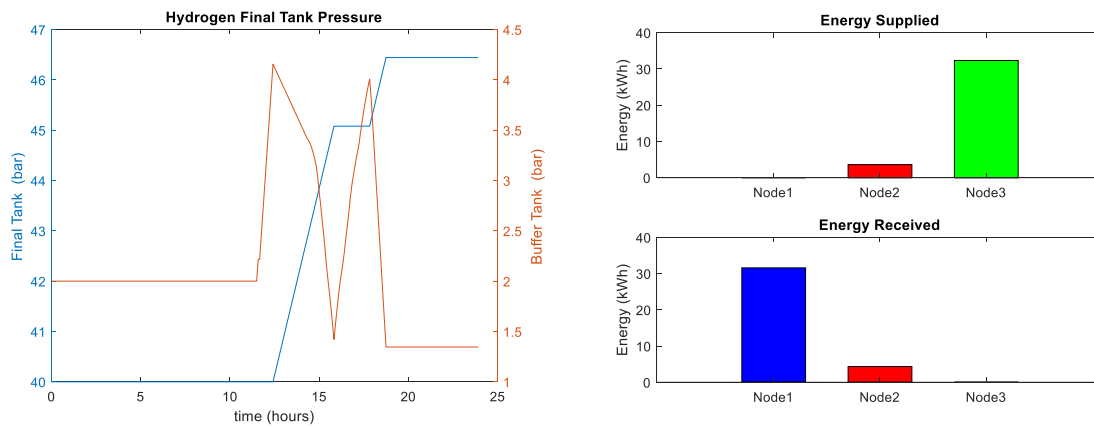


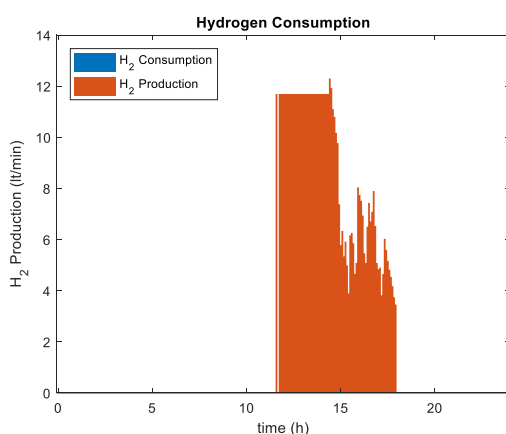






a) Battery capacity, b) Control actions for energy exchange (grid DC/DC converters operational power)

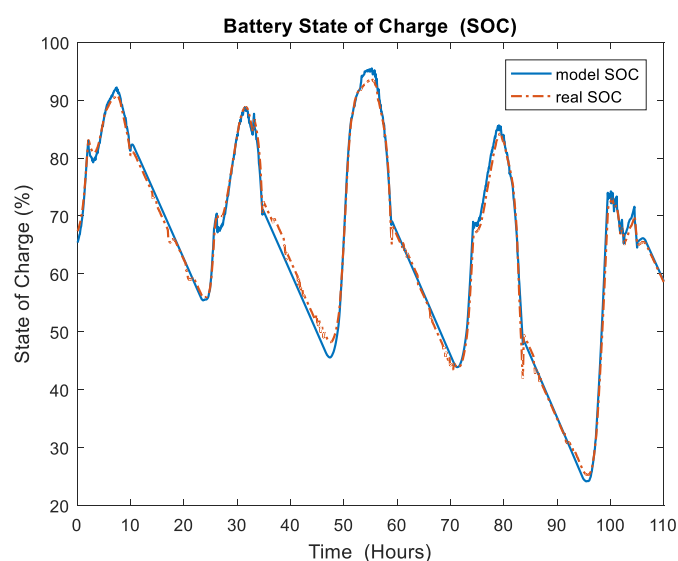




**Figure 70. Simulated operation of the microgrid with the NMPC disabled and enabled.**

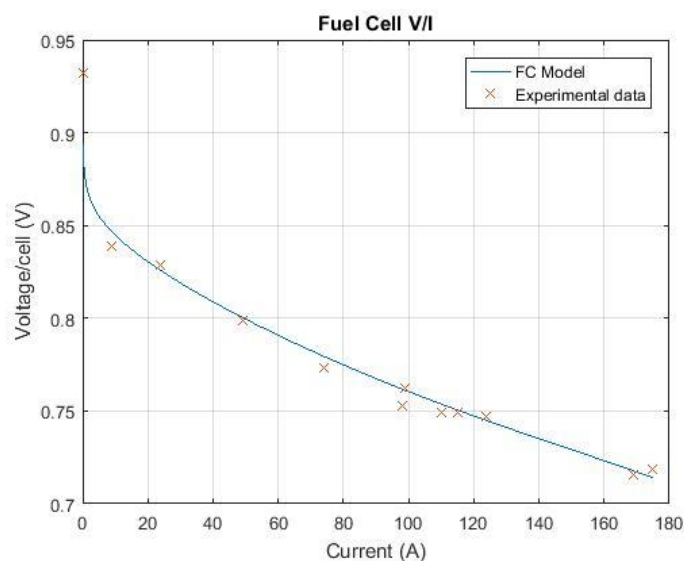
Regarding the calibration and validation, in the following are presented the validation results of a number of energy component models included in the Supervisory MPC tool.

The validation of the modelled SOC of battery storage system for a time period of 110 hours is depicted in Figure 71. The results show that the model correctly captures the dynamic changes in the battery SOC.

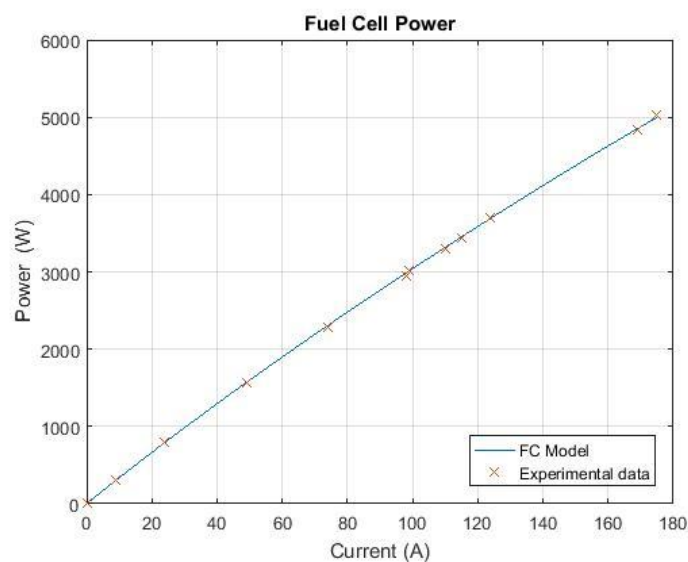


**Figure 71. Validation of the modelled SOC of battery storage systems.**

For a fuel cell, 180 hours of modelled and experimental data for voltage/current and power/current are compared in Figure 72 and Figure 73, respectively. For both sets of parameters, it is observed that the model approximates reasonably well the operation of a fuel cell.

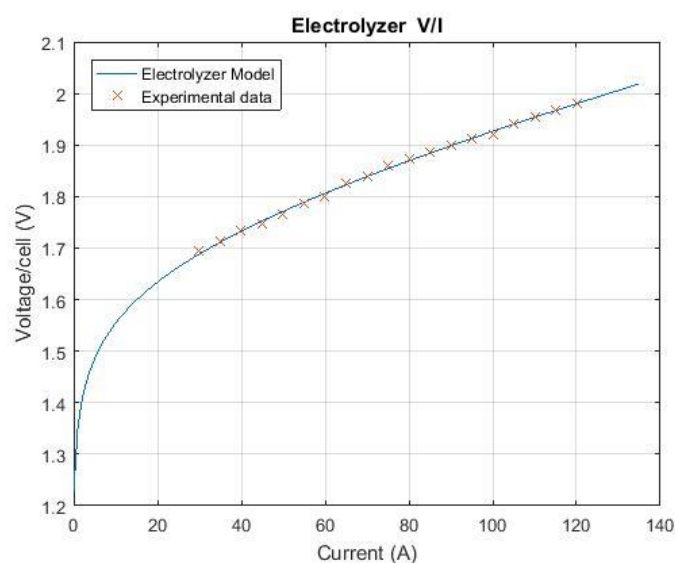


**Figure 72. Modelled versus experimental voltage/current data of a fuel cell.**

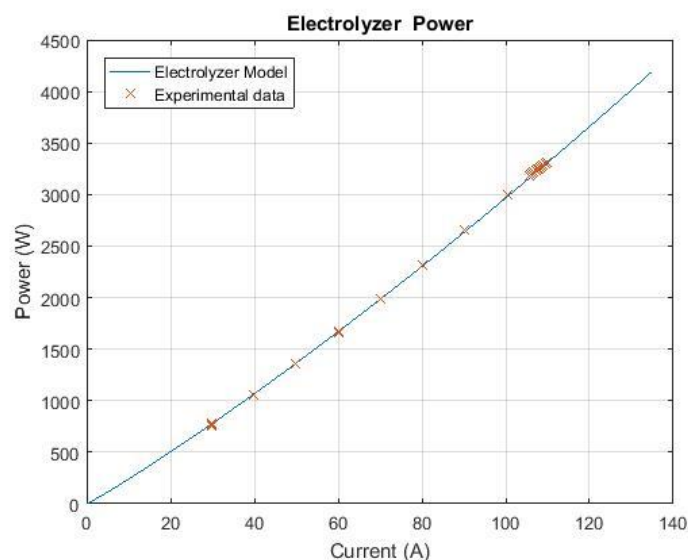


**Figure 73. Modelled versus experimental power/current data of a fuel cell.**

Figure 74 and Figure 75 depict respectively the voltage/current and power/current modelled and experimental data for a 140 hours period of an electrolyser. As in the previous cases, it can be observed good agreement between modelled and experimental data.



**Figure 74. Modelled versus experimental voltage/current data of an electrolyser.**



**Figure 75. Modelled versus experimental power/current data of an electrolyser.**

### Technical specifications and advances from the existing tools

The tool can compute the day ahead energy consumption, energy distribution and storage and systems operation. The tool can update the proposed solution for energy consumption, distribution and storage on hourly basis. During the development of the tool, the simulations are being performed at 5-minute basis.

Time horizon can be extended further than 1 day and time step can be reduced below 1 hour.

The input and output data depend on the characteristics of the project, and most of these data are provided by the Data Exchange Tool. For instance, input/output data include solar irradiation, wind speed, load profiles, power profiles, systems devices limitations, batteries state, hydrogen storage and power flows, control actions for the bidirectional DC/DC converters for implementing energy exchange between the nodes.

The Supervisory MPC component depends on the data received from the pilot project via the SCADA system. In order to ensure the correct operation of the Supervisory MPC, measurements and values of variables need to be formatted based on standards (json,csv) and use one of the following communications protocols: OPC, RESTFul, IoT, IEC61850 (TCP/IP)

More specifically the DET tool retrieves data from the SCADA via OPC communication protocol and sends the data in json string format by using the MQTT protocol.

The tool requires data from CERTH/CPERI's Data Exchange Tool, power demand and data from the models. Real and forecasted weather data is under consideration. In the battery control case, the MPC component depends both on Data Exchange Tool and the respective battery management system.

In addition, the tool also will provide data to the Data Exchange tool.

The models incorporated in the tool, along with the model predictive control algorithm, are developed in MATLAB environment. [Windows and Linux operating systems that support MATLAB Platform](#). In addition, the tool requires the contribution and communication with the DET tool, in order to receive the required data, such as the power state from each node, loads, etc.

Finally, the tool does not require any additional hardware device.

The tool is based on different modules-functions. One of the modules comprising the tool and is related to T4.2, are the mathematical models of all the integrated energy systems. In order for the Model Predictive Algorithm to work, a mathematical model of each node of the microgrid had to be developed, which is comprised from the synergies of the single models, adopting the energy management strategy applied in each node.

### Expected advantages compared to commercial products

There are no known existing commercial products with the same characteristics. Although model predictive control methodology (MPC) has been used in other projects, mainly to control and optimize the operation of dedicated devices (FCs, Batteries), none of them have considered using the entire topology of a microgrid to provide an aggregated hybrid energy storage (hydrogen, batteries) and to achieve a virtual energy storage for balancing the grid. This will lead to the delivery of a tool that will provide optimal control of energy systems in terms of energy exchange and balancing.

### Implementation features and delivery

The Supervisory MPC tool is used in the inteGRIDy pilot projects of Thessaloniki, Xanthi and IoW.

In the Xanthi pilot the Supervisory MPC tool's objective is to maintain the maximum possible energy in each microgrid's storage means, fulfil the load and avoid the usage of the diesel generator (acts as an economical and environmental criterion). A periodical connection of the EVs to the grid is an additional term in the objective function. The terms in the objective function are properly weighted either from the grid manager or from the ID&SSS tool along with additional parameters calibration. The objective function is given by:

$$J = \sum_{j=1}^m \sum_{i=1}^n (w_{Pij} P_{ij}^2 + w_{Uij} U_{ij}^2) + \sum_{j=1}^k \sum_{i=1}^n (w_{Eij} E_{ij}^2 + w_{ECij} EC_{ij}^2) \quad (61)$$

where:

$w_P, w_U, w_E, w_{EC}$  : weight coefficients

$P$  : the deviation of the node's energy state from the reference trajectory

$E$  : the deviation of the EV's energy state from the reference trajectory

$U, EC$  : the control outputs in every step

$m$  : the number of the nodes

$n$  : the prediction horizon

$k$  : the number of the EVs

In addition, in the Thessaloniki's pilot the Supervisory MPC tool aims to minimize the deviation between energy demand and supplied energy. Considering that the Supervisory MPC alongside with the BESS are operating on a dynamic pricing environment, it targets to achieve a high economic profit for the end user. Last but not least, Supervisory MPC tool aims to prevent premature ageing of the BESS. All terms in the cost function are properly weighted. The end user has the ability to adjust all the weight coefficients.

The objective of the MPC is stated as:

$$J = \sum_{i=1}^n (w_{E_i} E_i^2 + w_{U_i} U_i^2) + \sum_{i=1}^n (w_{F_i} F_i^2 + w_{U_{F_i}} U_{F_i}^2) + \sum_{i=1}^n (w_{A_i} A_i^2 + w_{U_{A_i}} U_{A_i}^2) \quad (62)$$

where

$w_{E_i}, w_{U_i}, w_{F_i}, w_{U_{F_i}}, w_{A_i}, w_{U_{A_i}}$  : represent weight coefficients

$E$  : symbolizes the deviation between energy demand (Reference trajectory) of the building and supplied energy

$F$  : symbolizes the deviation between financial profit set point (Reference trajectory) and the actual financial profit

$A$  : symbolizes the deviation between BESS's ageing set point (Reference trajectory) and the actual ageing

$U, U_F, U_A$  : the control outputs in every step

$n$  : the prediction horizon

In the IoW pilot the objective of the Supervisory MPC tool is twofold. First and foremost, it aims to cover the maximum possible energy demand. Moreover, Supervisory MPC targets to maintain the desirable lifetime expectancy of the fuel cell (which is defined by the end user). All terms in the cost function are properly weighted. The end user has the ability to adjust all the weight coefficients.

$$J = \sum_{i=1}^n (w_{E_i} E_i^2 + w_{U_i} U_i^2) + \sum_{i=1}^n (w_{A_i} A_i^2 + w_{U_{A_i}} U_{A_i}^2) \quad (63)$$

where

$w_{E_i}, w_{U_i}, w_{A_i}, w_{U_{A_i}}$  : represent weight coefficients

$E$  : symbolizes the deviation between energy demand (Reference trajectory) and supplied energy

$A$  : symbolizes the deviation between fuel cell's lifetime set point (Reference trajectory) and the actual lifetime

$U, U_A$  : the control outputs in every step

$n$  : the prediction horizon



The initial Supervisory MPC tool was a standalone application with GUI that run in a laptop or a PC. The tool required data from the system (e.g. fuel cell), the current status (e.g. voltage, air flow, etc.) and the desired set-points (e.g. power, oxygen excess ratio, etc.). The extensions made to the tool, include the models of all the above-mentioned devices, and the aspects that the tool is called to solve, like optimum energy management and exchange.

The tool consists of six main modules. More specifically comprises two main modules for each one of the pilots that it is going to be applied (Xanthi, Thessaloniki, Isle of Wight). Three of those modules contain the corresponding models of the three pilots. e.g. battery, Fuel Cell, electrolyser, compressor and all the above-mentioned models for the Xanthi's pilot, battery model for the Thessaloniki's pilot, Fuel cell and electrolyser models for the IoW pilot. At the same time, they are providing the power topology of the systems and simulate the whole operation of the systems. The other three modules contain the dynamic optimization methodologies and perform the optimization tasks (for each pilot) in which the set points and control actions for the controllable devices will be delivered.

The source code is stored in a dedicated PC in CERTH/CPERI's premises and it will be released in a virtual machine.

Furthermore, a demo of the tool is not currently available as this is currently being updated and upgraded. Nevertheless, Figure 76 presents a screenshot of an earlier version of the Supervisory MPC/s GUI.

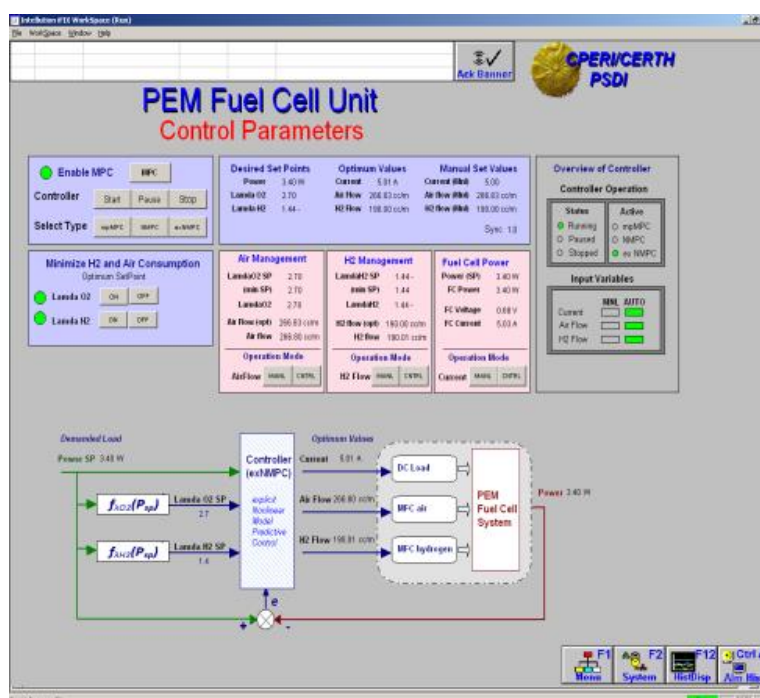


Figure 76. Screenshot of the Supervisory MPC's GUI.

For more information about the Supervisory MPC, please contact:

Simira Papadopoulou: [shmira@cperi.certh.gr](mailto:shmira@cperi.certh.gr)

## 4.5 Final Considerations

This section has presented a comprehensive review of the different energy models available in the inteGRIDy project. Energy models have been arranged into three macro-functionality categories: Network Modelling, Demand Response and Demand Side Management, and Storage Systems.

The review of energy models has covered the following items:

- Technical description of the tool, including in some cases the mathematics & physics behind the model. When possible, results from the calibration and validation of the energy models have been presented.
- [inteGRIDy pillars addressed by the tool.](#)
- Dependencies that the energy model may have with other tools or data.
- Format and time period of input and output data, as well as time horizon of models.
- Energy model programming language, supported operating system and architecture.
- Requirements for hardware devices.
- [Advances in the energy model made through the inteGRIDy project](#)
- [Advantages compared to similar commercial tools available in the market.](#)
- Whether a demo of the energy model is available.
- Description of the implementation of the energy model in inteGRIDy pilot project/s.

The review has revealed that the energy models available in inteGRIDy cover a wide range of energy applications, with the main areas covered being energy system characterization, grid modelling, load assessment, and DR and DSM. In addition, the review has depicted the complexity behind some of the energy models and how well they approximate the actual behaviour of energy systems, grid network and demand assessment.

Containerization of energy models in Docker has been assessed. Eight out of thirteen energy models could potentially be containerized in Docker. In some cases, it may be the case that the whole tool cannot be containerized, but rather only a limited number of their functionalities. In addition, energy tools that run on software platforms may present higher complexity to be containerized. Finally, proprietary software may not be containerized.

## 5.Impacts and Advantages of the Proposed Solutions

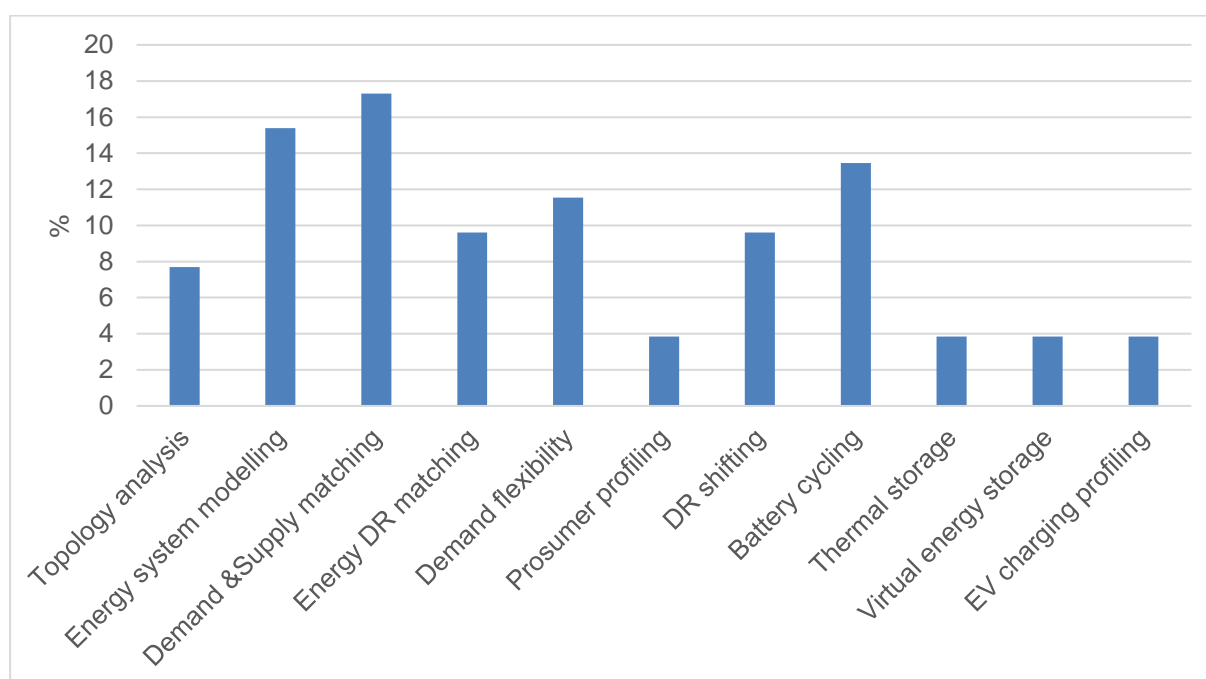
### 5.1 Key Technical Features of the Project Toolset

The present section presents the main trends resulted from the review and analysis of the energy models included under the Modelling Mechanisms for Topology Analysis, DR Flexibility and Storage layer.

For that purpose, a distribution of the functionalities addressed by the energy models is first presented. This is followed by a summary of review of the calibration and validation approaches followed by the technology providers. Finally, a review of the technical specifications is provided, including input/output data, dependencies, data formats, time steps and horizons, programming language and supported operating systems.

#### *Addressed functionalities of the Modelling Mechanisms layer*

The data included in Table 1 related to the addressed functionalities by the energy models is presented in Figure 77. It is clear that both Demand & Supply Matching and Energy System Modelling represent the functionalities that are more present in the energy models, which is in line with the scope of the majority of the inteGRIDy pilots. Functionalities such as thermal and virtual energy storage do not have a high present among the energy models, but this is coherent with the fact that these are not widely used in the inteGRIDy pilots. For instance, virtual energy storage is only used in the swimming pool at the Barcelona pilot and the domestic electric fixtures at the St. Jean pilot.



**Figure 77. Percentage of energy models for Task 4.2 functionalities.**

#### *Calibration and validation*

Modelling physical phenomena, as can be solar photovoltaic conversion or power flow in a grid network, may require a process of calibration where values are assigned to parameters such

that the modelling formulation provides an adequate representation of the system. The process of validation ensures the accuracy of the model's computed values for the specific application.

There are several energy models, that due to their scope, cannot undergone a process of calibration and validation, as can be SimaPro (LCA and LCC) or DEMS (DR services).

Calibration and validation of energy models are or will be performed using actual data from the pilots. This is the case for the tools Medium Voltage Distribution Networks Management for the grid network and solar PV plants in the San Severino Marche pilot and TRNSYS Swimming Pool Model for the whole energy system using monitored data from the Barcelona pilot project.

Alternatively, other technology providers are calibrating and validating their energy models against experimental data. For the Medium Voltage Distribution Networks Management, POLIMI has validated the energy storage scheduler in their laboratories. For the Multi-Carrier Hub Optimization Engine, calibration of the battery model will be performed against experimental data. Calibration and validation against experimental data is performed for battery systems, fuel cells and electrolyser under the Supervisory Model Predictive Control for Energy Systems.

In addition, APROS Dynamic Process Simulation uses the technical specifications from the system component manufacturing to calibrate and validate their energy model. Other energy models such as Energy Integrated Information System, Building Occupancy & Energy Consumption Simulation, and Demand Side Energy Profiling analyse large sets of data to calibrate some parameters that can characterize user's energy consumption and their flexibility.

Finally, when data are not available to perform a calibration and validation, benchmarking against other commercial energy models is an alternative to reduce the uncertainties in the results. This is the case of Integrated Test Environment for the distribution grid in the Isle of Wight.

### *Technical specifications*

Part of the information presented for every energy model in Section 4 related to technical specifications is analysed in Section 6 to perform a synergy assessment.

In terms of data, the inteGRIDy energy models require the following input:

- Physical parameters characterizing the generators, loads, components or grid.
- Data measurements collected in real-time with local/remote sensors to understand the status of the assets.
- Status of actuators controlling the assets.
- Users' data, including status, usage profile (e.g. occupancy) and preferences.
- Historical data on system's (e.g. building, generator, grid) performance/consumption and user's behavior.
- RES and load profile forecast.
- Energy storage availability, efficiency and rating.
- Requests from DSO (e.g. DR event).
- Current and forecasted weather data.
- Electricity pricing and tariff structures.
- CO<sub>2</sub> emissions data.

Likewise, the output data required are as follows:

- Forecast of energy demand/generation profiles.
- Setpoints for generators, loads or grid equipment.

- Control signal of assets.
- Energy consumption flexibility by assets/consumers.
- Load flow results in grid.
- Energy storage SOC change.
- Costs and profits derived from operation of assets and provision of ancillary services to DSO.
- Emitted and saved CO<sub>2</sub> data.

In addition, in terms of dependencies, the inteGRIDy energy models require connection with external services to retrieve weather data, SCADA, environmental sensors (e.g. temperature, humidity), energy meters and control devices.

Furthermore, in terms of technical specifications, it is interesting to highlight the following outcomes from the analysis performed in Section 6:

- There are multiple data formats used by inteGRIDy energy tools, including Json, CSV, \*.txt, \*.xls and XML.
- Time steps of inteGRIDy energy models range between 5 and 60 minutes.
- Time horizons are generally in line except for SimaPro that requires at least 20 years to compute the LCA & LCC.
- InteGRIDy energy models are developed in a number of languages: MATLAB, Java, C++, C#, Python, Symantics Constraint Language, JRE 8, JEE, RS and Visual Basic.
- Most of inteGRIDy energy models are supported by both Windows and Linux operating systems.

## 5.2 Progress beyond the SoTA

The Modelling Mechanisms for Topology Analysis, DR Flexibility and Storage layer covers a wide range of energy-related models, where these may belong to completely different research fields. It is out of the scope for this report to analyse the current status in the research in all energy modelling fields, but rather discuss some of the innovation examples given in Section 4.

Addressing grid topology, the Medium Voltage Distribution Networks Management tool enables the integration of DERs in the market at local and country level, as well as the provision of ancillary services by DERs to the grid. The solution presents the advantage that is highly scalable and can be applied from tens of KW to a MW size range.

Continuing with grid topology, the Integrated Test Environment by UNEW assesses the impact of control algorithms in the grid network, which is currently not considered by other power software in the market.

A different approach to innovation at the LCA level is taken by CERTH with SIMAPRO tool, where they monitor the environmental impact in different implementation scenarios, leading to a dynamic impact assessment which is far beyond the literature static studies. Hence, this will yield to an estimate of the reduction in emissions from both manufacturing and operation stages.

The Energy Integrated Information System by SIVECO helps system operators' decisions through cross domain big data analytics. The tool also presents cutting-edge forecasting and optimization algorithms detailed in D4.3 and D4.4, respectively.

Furthermore, inteGRIDy project includes tools with functionalities that have not yet been addressed commercially, but represent a niche market. For instance, the Swimming Pool

Model optimizes the operation of the swimming pool, but also characterizes the energy consumption and flexibility. The characterization of these two terms enables the use of the swimming pool as a virtual energy storage, which has not been performed to date.

Finally, the Supervisory Model Predictive Control for Energy Systems uses the model predictive control methodology to integrate hybrid energy storage into a microgrid topology and optimize the balance of the grid through virtual energy storage.

### 5.3 Potential Impacts and Advantages

The Modelling Mechanisms for Topology Analysis, DR Flexibility and Storage layer addresses the expected impacts from the EU and included in the work programme. To be more specific, the reviewed energy models in Section 4 are linked to the four inteGRIDy pillars Demand Response, Smartening the Distribution Grid, Energy storage Technologies and Smart Transport Integration, as summarized in Table 1 in Section 3.3. Furthermore, while there are few energy models that only provide one or two functionalities, the majority of the energy models provide more than two functionalities under the inteGRIDy 4.2 layer.

In terms of scale of application, the majority of the energy models are linked to mid to large stakeholders, comprising DSOs, independent power producers or building managers. For instance, tools targeting microgrid or distribution system operators include the Medium Voltage Distribution Networks Management, Integrated Test Environment and even Supervisory Model Predictive Control for Energy Systems. In terms of independent power producers, the energy generation of their renewable energy and energy storage units are covered by APROS Transient Process and Multi-Carrier Hub Optimisation Engine among others. Energy models addressed to building managers include for example NEMO Tool, Distributed Energy Management System and Swimming Pool Model (i.e. if the facility includes a swimming pool).

Moreover, there are other energy models that rather focus on small consumers and to characterize their energy consumption profile and the flexibility that they can provide. The tools Energy Integrated Information System and Building Occupancy & Energy Consumption Simulation both address the energy consumption profiles, while the Demand Side Energy Profiling characterizes the flexibility provided by small users on their use of a number of house electric fixtures. Finally, Kisense Energy Management System combines generation and consumption profiles to optimize the charge and discharge of electric vehicles.

### 5.4 Integration of Modelling Mechanisms for Topology Analysis, DR Flexibility and Storage Layer Tools

As was depicted in Table 1 in Section 3.3, there is a large number of functionalities available in the inteGRIDy energy models. Furthermore, there is the possibility to share functionalities between energy models, which can lead to an increase of their individual scope.

The reader is referred to Section 6, which includes a comprehensive analysis of the possible synergies and integration between inteGRIDy energy models.



## 6. Assessment of Synergies of InteGRIDy Modelling Mechanisms

### 6.1 Context

The inteGRIDy project includes the use of a number of energy models in different pilot projects. There are already several interactions and synergies happening within the pilots between models, and these were identified before the start or in earlier stages of the project inteGRIDy. However, it is interesting to assess whether additional synergies may be possible between the energy models available in the pool of inteGRIDy. The identification of these synergies can benefit the owners of these tools as they might be able to exploit them in future projects.

It is important to clarify that synergy in this context does not imply a replacement of one tool by another, but rather that one tool could potentially provide functionality to another tool which will enhance its scope and capability.

This chapter assesses the potential synergies between inteGRIDy energy models. Section 6.2 presents the identified synergies between the inteGRIDy energy models. Section 6.3 provides an overview of the technical constraints for the integration of energy models. Section 6.4 draws the final considerations of the chapter.

### 6.2 Identified Synergies between Tools

This section presents the identified synergies for each of the energy models included in the inteGRIDy project.

#### 6.2.1 Medium Voltage Distribution Network Management

As presented in Section 4.2.1, the tool Medium Voltage Distribution Network Management characterizes the medium voltage grid network, taking into account consumption and generation profiles across the network. Based on the characteristics listed in Section 4.2.1, Table 16 lists the identified inteGRIDy energy models that present synergies with the tool Medium Voltage Distribution Network Management. In addition, Table 16 includes the respective functionality to be provided by each of the identified tools. As revealed by Table 16 there are four inteGRIDy energy models that present synergies with the tool Medium Voltage Distribution Network Management. The main functionalities that the identified tools can contribute are related to energy system generation models, consumption profiles, DR strategies and LCA & LCC.

**Table 16. Identified inteGRIDy energy models that present synergies with the tool Medium Voltage Distribution Network Management and respective functionalities.**

Energy model	Functionality for Medium Voltage Distribution Network Management
Integrated Test Environment	Crossover as it also provides grid power flow management. The tool can provide models of solar PV system, user's behaviour or DR strategies
Energy Integrated Information System	Provide residential and commercial consumption profiles
Distributed Energy Management System	Flexibility forecast of assets based on power production limits and forecast calculation
Building Occupancy & Energy Consumption Simulation	Provide residential and commercial consumption profiles

### 6.2.2 APROS Dynamic Process Simulation

As described in Section 4.2.2, APROS models steady state and dynamic thermal and electric systems. Table 17 lists the identified inteGRIDy energy models that present synergies with APROS, as well as the respective functionality that they could provide.

Table 17 exhibits the seven inteGRIDy energy models that can add functionalities to APROS related to: energy system generation models, consumption profiles and LCA & LCC.

**Table 17. Identified inteGRIDy energy models that present synergies with APROS Dynamic Process Simulation and their respective functionalities.**

Energy model	Functionality for APROS Dynamic Process Simulation
NEMO	Generation models of multiple systems, e.g. CHP, solar PV or electric batteries
TRNSYS Swimming Pool Model	Energy model developed of sport centre and swimming pool
Energy Integrated Information System	Residential and commercial consumption profiles
Multi Carrier Hub Optimisation Engine	Models of battery and CHP systems that can provide flexibility in energy generation
Supervisory Model Predictive Control	Models of solar PV, wind turbines, batteries, fuel cells, electrolyser, compressor and diesel generator
SimaPro	Can be used to perform LCA & LCC of energy systems
Building Occupancy & Energy Consumption Simulation	Residential and commercial consumption profiles

### 6.2.3 SimaPro

Section 4.2.3 described that SimaPro is used to perform LCA and LCC over the lifespan of a project. Due to the specific scope of the tool, the analysis of the energy models available in the inteGRIDy pool has not identified any possible candidate that could provide any functionality to SimaPro.

### 6.2.4 Energy Integrated Information System

As described in Section 4.2.4, Energy Integrated Information System generates consumption profiles. Among the inteGRIDy energy model pool, Table 18 identifies Demand Side Profiling as the only energy model that could have some synergies with Energy Integrated Information System. The identified synergies are related to comfort and device profiles.

**Table 18. Identified inteGRIDy energy model that presents synergies with Energy Integrated Information System and respective functionalities.**

Energy model	Functionality for Energy Integrated Information System
Demand Side Profiling	Comfort and device profiles can complement consumption profiles

### 6.2.5 NEMO

As depicted in Section 4.2.5, NEMO provides energy demand prediction, allocates generation resources and optimizes generation dispatch. Table 19 identifies nine inteGRIDy energy models that present synergies with NEMO and includes the functionalities that these tools

could provide to NEMO. These functionalities are related to consumption and generation profiles, energy loads of systems/buildings, energy system models, DR/flexibility and LCA/LCC.

**Table 19. Identified inteGRIDy energy models that present synergies with NEMO and respective functionalities.**

Energy model	Functionality for NEMO
Demand Side Profiling	Developed comfort and device profiles of HVAC, hot water boiler and lighting to provide load information
TRNSYS Swimming Pool Model	Electricity and heat demand of swimming pool and building to provide load information
Integrated Test Environment	Demand side response
MV Distribution Network Management	Solar PV generation and load profiles, as well as ancillary services
APROS	Energy loads for buildings and energy system generation models (solar PV and battery)
Multi Carrier Hub Optimisation Engine	Assesses flexibility and modifies energy behaviour of batteries and CHP
Supervisory Model Predictive Control for Energy Systems	Mathematical models of energy systems solar PV, wind energy, batteries, fuel cells, electrolyzers, compressor and diesel generator
Distributed Energy Management System	Can validate DR baselines and provide price signal support and intraday market forecasting
SimaPro	Can be used to perform LCA & LCC of energy systems

### 6.2.6 Building Occupancy & Energy Consumption Simulation

Section 4.2.6 presented that Building Occupancy & Energy Consumption Simulation provides consumption profiling and load flexibility. Table 20 identifies Demand Side Profiling as the sole energy model that presents synergies with Building Occupancy & Energy Consumption Simulation, contributing with comfort and device profiles that could complement the consumption profiling.

**Table 20. Identified inteGRIDy energy model that present synergies with Building Occupancy & Energy Consumption Simulation and respective functionalities.**

Energy model	Functionality for Building Occupancy & Energy Consumption Simulation
Demand Side Profiling	Comfort and device profiles to complement consumption profiles

### 6.2.7 Demand Side Energy Profiling

Section 4.3.1 depicted that Demand Side Energy Profiling provides user comfort and device (HVAC, water heater and lighting) profiles. Based on these capabilities, Table 21 presents the six identified energy models that present synergies with Demand Side Energy Profiling. For each identified energy model, Table 21 also includes the respective functionalities which can be categorized into energy system modelling, user/building consumption profiles, DR/flexibility and LCA & LCC.

**Table 21. Identified inteGRIDy energy models that present synergies with Demand Side Energy Profiling and respective functionalities.**

Energy model	Functionality for Demand Side Energy Profiling
--------------	--

NEMO	Can provide models of PV, wind, battery, CHP, heat and load demand (and economic analysis)
TRNSYS Swimming Pool Model	Characterize the flexibility that a swimming pool can provide for DR
Integrated Test Environment	Demand side response in residential and commercial scale
Energy Integrated Information System	Residential and commercial consumption profiles
MV Distribution Network Management	Models of battery and CHP flexibility
SimaPro	Can be used to perform LCA & LCC of energy systems
Building Occupancy & Energy Consumption Simulation	Residential and commercial consumption profiles

### 6.2.8 Multi Carrier Hub Optimization Engine

Section 4.3.2 showed that Multi Carrier Hub Optimization Engine models microgrid equipment that can modify their energy performance, focusing on electric batteries and CHP. Table 22 shows the eight identified energy models that present synergies with Multi Carrier Hub Optimization Engine and respective functionalities that they could provide. These functionalities fall under the categories of energy system models, generation and consumption profiles, DR and LCA & LCC.

**Table 22. Identified inteGRIDy energy models that present synergies with Multi Carrier Hub Optimization Engine and respective functionalities.**

Energy model	Functionality for Multi Carrier Hub Optimization Engine
NEMO	Can improve generation and load models and match forecast between load and generation
Integrated Test Environment	Input on demand response from other systems
APROS	Can provide energy loads for buildings and systems, and energy system generation models
Energy Integrated Information System	Provide residential and commercial consumption profiles
MV Distribution Network Management	PV generation model & forecast, user's behaviour and DR strategies
Supervisory Model Predictive Control for Energy Systems	Mathematical models of solar PV, wind turbines, batteries, fuel cells, electrolyser, compressor and diesel generator
SimaPro	Can be used to perform LCA & LCC of energy systems
Building Occupancy & Energy Consumption Simulation	Residential and commercial consumption profiles

### 6.2.9 Kisense Energy Management System

As described in Section 4.3.3, Kisense Energy Management System generates consumption profiles during the time periods that there is a communication fault which leads to a peak in the registered consumption. The analysis of the energy models available in the inteGRIDy pool has revealed that no energy model presents any synergy with Kisense Energy Management System.

### 6.2.10 Integrated Test Environment

The Integrated Test Environment tool can model energy storage systems as well as residential-industrial-commercial DR, as depicted in Section 4.3.4. Eleven energy models have been identified to present some synergies with Integrated Test Environment, as exhibited in Table 23. The functionalities provided by these tools focus on energy system models, consumption profiles, DR/flexibility and LCA & LCC.

**Table 23. Identified inteGRIDy energy models that present synergies with Integrated Test Environment and respective functionalities.**

Energy model	Functionality for Integrated Test Environment
Demand Side Profiling	Comfort and device profiles
NEMO	Generation models and match forecast between load and generation
TRNSYS Swimming Pool Model	Sport centre model that can act as a virtual energy storage (or DR) tool
APROS	Energy loads of buildings and systems, and energy system generation models
Energy Integrated Information System	Residential and commercial consumption profiles
MV Distribution Network Management	PV generation, user's behaviour or DR strategies
Multi Carrier Hub Optimisation Engine	Models of battery and CHP systems that can provide flexibility in energy generation
Supervisory Model Predictive Control for Energy Systems	Mathematical models of solar PV, wind turbines, batteries, fuel cells, electrolyser, compressor and diesel generator
Distributed Energy Management System	Flexibility forecast of assets based on power production limits and forecast calculation
SimaPro	Can be used to perform LCA & LCC of energy systems
Building Occupancy & Energy Consumption Simulation	Residential and commercial consumption profiles

#### **6.2.11 Distributed Energy Management System**

Section 4.3.5 describes the capabilities of Distributed Energy Management System, which include load shifting or DR and asset flexibility or VPP capabilities. Table 24 presents the eleven inteGRIDy energy models that present synergies with Distributed Energy Management System, as well as their functionalities. These functionalities fall into energy system modelling, generation and consumption profiles, DR/flexibility and LCA & LCC.

**Table 24. Identified inteGRIDy energy models that present synergies with Distributed Energy Management System and respective functionalities.**

Energy model	Functionality for Distributed Energy Management System
Demand Side Profiling	Comfort and device profiles can feed the calculation of flexibility by assets
NEMO	Models of PV, wind, battery, CHP, heat and load demand to characterize assets
TRNSYS Swimming Pool Model	Flexibility that a swimming can provide as virtual power storage and DR
Integrated Test Environment	Power system model, energy storage and flexibility of assets, demand response
APROS	Energy loads for buildings and systems, and energy system generation models
Energy Integrated Information System	Residential and commercial consumption profiles to feed calculation of asset flexibility
MV Distribution Network Management	Power system model, energy storage and flexibility of assets, demand response, PV model and users' profiles
Multi Carrier Hub Optimisation Engine	Models of battery and CHP systems that can provide flexibility in energy generation
Supervisory Model Predictive Control for Energy Systems	Mathematical models of solar PV, wind turbines, batteries, fuel cells, electrolyser, compressor and diesel generator
SimaPro	Can be used to perform LCA & LCC of energy systems
Building Occupancy & Energy Consumption Simulation	Residential and commercial consumption profiles (to feed calculation of asset flexibility and DR strategies)

#### 6.2.12 TRNSYS Swimming Pool Model

Section 4.4.1 presented that the TRNSYS Swimming Pool Model assesses the thermal behaviour and energy system of a building and a swimming pool. Table 25 presents six inteGRIDy energy models that present synergies with TRNSYS Swimming Pool Model, providing functionalities focusing on energy system models, load and consumption calculation, DR/flexibility and LCA & LCC.

**Table 25. Identified inteGRIDy energy models that present synergies with TRNSYS Swimming Pool Model and respective functionalities.**

Energy model	Functionality for TRNSYS Swimming Pool Model
Demand Side Profiling	Developed comfort and device profiles used for HVAC, hot water boiler and lighting. These profiles together with the flexibility estimation could be applied to swimming pool model
NEMO	Calculate heat and electricity generation based on swimming pool load
Integrated Test Environment	Contribute with DR strategies
APROS	Energy models can be integrated with Swimming pool model
Distributed Energy Management System	Load forecast and assessment of asset flexibility
SimaPro	Can be used to perform LCA & LCC of energy systems



### 6.2.13 Supervisory Model Predictive Control for Energy Systems

As presented in Section 4.4.2, Supervisory Model Predictive Control for Energy Systems models energy systems such as solar PV, wind generators, electric batteries, etc. Table 26 identifies eight inteGRIDy energy models that present synergies with Supervisory Model Predictive Control for Energy Systems and can provide functionalities focusing on energy system models, consumption profiles, DR/flexibility and LCA & LCC.

Table 26. Identified inteGRIDy energy models that present synergies with Supervisory Model Predictive Control for Energy Systems and respective functionalities.

Energy model	Functionality for Supervisory Model Predictive Control for Energy Systems
NEMO	CHP, solar PV, wind turbine or battery models
TRNSYS Swimming Pool Model	Model developed of a sport centre and swimming pool
Integrated Test Environment	Input on demand response from other systems
Energy Integrated Information System	Residential and commercial consumption profiles
Multi Carrier Hub Optimisation Engine	Models of battery and CHP systems that can provide flexibility in energy generation
MV Distribution Network Management	PV generation model & forecast, user's behaviour or DR strategies can be shared.
SimaPro	Can be used to perform LCA & LCC of energy systems
Building Occupancy & Energy Consumption Simulation	Residential and commercial consumption profiles

### 6.2.14 Summary of synergies

The analysis presented in earlier sections has revealed that there is a number of potential synergies between energy models available in inteGRIDy. Table 27 presents a summary of the identified synergies, highlighting those energy models that can provide one or more functionalities to the identified tool. In total, 69 different synergies have been identified among the energy models available in inteGRIDy.

As indicated in Sections 4.2.3 and 6.2.9, it is worth mentioning that no inteGRIDy energy model has been identified that could provide any functionality to the tools SimaPro and Kisense Energy Management System. The main reason for this is that both tools present very specific and restricted scope, which limits possible connections with other tools and their associated functionalities.

In addition, it has been identified that the tool SimaPro could provide functionalities related to the performance of LCA & LCC of energy systems to more than half of the inteGRIDy energy models. It is expected to experience some compatibility issues and analysed energy systems will have to be built from scratch in SimaPro.

Table 27. Summary of identified synergies between energy models available in the inteGRIDy project.

Identified model	Can provide at least one or more functionalities to identified model												
	Demand Side Profiling	NEMO	TRNSYS Swimming Pool Model	Integrated Test Environment	APROS Transient Process	Energy Integrated Information System	Kisense Energy Management System	MV Distribution Network Management	Multi Carrier Hub Optimisation Engine	SimaPro	Supervisory Model Predictive Control for Energy Systems	Distributed Energy Management System	Building Occupancy & Energy Consumption Simulation
Demand Side Profiling													
NEMO													
TRNSYS Swimming Pool Model													
Integrated Test Environment													
APROS Transient Process													
Energy Integrated Information System													
Kisense Energy Management System													
MV Distribution Network Management													
Multi Carrier Hub Optimisation Engine													
SimaPro													
Supervisory Model Predictive Control for Energy Systems													
DEMS													
Building Occupancy & Energy Consumption Simulation													

### 6.3 Integration Technical Constraints

Section 6.2 presented the identified synergies between the reviewed inteGRIDy energy models. Based on the information collected in Section 4, this section summarizes general technical constraints faced when evaluating the integration of inteGRIDy energy models. The following sections present the identified integration constraints classified in multiple categories.

#### 6.3.1 Dependencies

A number of functionalities that energy models can provide to identified tools depend on the access and availability of external resources, such as:

- Proprietary (e.g. MATLAB) or open source software performing one or more calculations of the functionality.
- Data measured (e.g. electric readings provided by DSO) or generated by a third party (e.g. meteorological or electric market price data).
- Hardware devices used to collect data onsite through meters (e.g. electricity) and sensors (e.g. temperature, humidity and luminance levels).

#### 6.3.2 Data format

There are multiple data formats used by the energy tools in the inteGRIDy pool including: Json, CSV, \*.txt, \*.xls and XML. In order to integrate energy models, it is required to homogenize the input/output data of the integrated models.

#### 6.3.3 Time horizon and time step

In order to couple energy models, it is required that these operate in the same time scale. The majority of InteGRIDy energy models present minimum time steps that range between 5 to 60 minutes. When coupling energy models with different minimum time steps, it is advised to increase the time step of that with a lower value to match the high sampling period. This ensures that the physics are properly computed and captured at each time step, and these are not generated synthetically during data post-processing.

For instance, there are two models that have a minimum sampling period of 5 and 15 minutes respectively. The computed values every 15 minutes of the 5-minute sampling period data will be used to ensure the validity of the physics behind the computed results. If otherwise 5-minute period data will be generated from the 15-minutes data, this could yield errors that may be significant when looking at short time scales.

Differences in time horizons are not in general as critical as the time step might be. Time horizon can expand from a couple of hours to a year, with the exception of SimaPro where 20 years horizon is required to compute the LCA & LCC. In general, when energy tools have different time horizons, the largest time horizon is reduced to match the shortest time horizon.

#### 6.3.4 Development language

InteGRIDy energy models have been developed in a number of languages: MATLAB, Java, C++, C#, Python, Symantics Constraint Language, JRE 8, JEE, RS and Visual Basic. Full integration between energy models will require adapting the programming language. If energy models are not fully integrated and only inputs/outputs of each model are employed, there might not be any need to adapt their programming language.

#### 6.3.5 Supported operating system and architecture

In general, most of the energy models are supported by Windows and Linux. All tools that can operate in Windows environment will require version 7 or above.

Several of the energy models can operate as stand-alone applications running on web applications or on proprietary software platforms (e.g. MATLAB, TRNSYS and APROS).

Containerization in Docker could act as a driver for the energy model integration. However, containerization of energy models that rely on proprietary software platforms for their operation may present additional difficulties.

## 6.4 Final Considerations

This section has assessed the potential synergies between existing inteGRIDy energy models. A table for each model is presented listing the energy models that could be integrated with and the functionalities that they could provide to the analysed tool. A summary table including all identified synergies is provided, revealing that there are 69 potential synergies among inteGRIDy energy models.

Due to their narrow application scope, no inteGRIDy energy models have been identified that could provide any functionality to the tools SimaPro and Kisense Energy Management System. However, the analysis revealed that the tool SimaPro could provide LCA & LCC functionalities to at least more than half of the inteGRIDy energy models, provided that the energy systems analysed are built from scratch in SimaPro.

The analysis of the integration technical constraints has revealed that some of the energy models rely on proprietary software which may difficult their integration with other tools. In addition, full integration of energy models may require adapting their programming language. However, if energy models do not require to be fully integrated, these may only lead to updates on the data format and time step.



## 7. Conclusions

This report has presented a comprehensive review of the energy models available in the inteGRIDy project and has provided an assessment of possible synergies between the reported energy models.

A review of the inteGRIDy energy models have been structured based on the three macro-functionality categories: Network Modelling, Demand Response and Demand Side Management, and Storage Systems. For each model the methodology employed is depicted, and when available validation results are shown. Some other important aspects of the tools have also been reviewed, such as dependencies, data format and time period, programming language, need for hardware devices and whether a demo of the tool is available. In addition, the implementation of each energy model in the inteGRIDy pilot projects has been described.

The energy models available in the inteGRIDy project cover a wide range of energy related fields, and these have demonstrated to approximate well the actual behaviour of energy systems, grid network and demand assessment.

The evaluation of containerization of energy models in Docker has revealed that eight out of twelve energy models could potentially be containerized. However, the following constraints have been identified: restricted number of functionalities of an energy model can be containerized; and complexity to containerize energy models that run on software platforms. Finally, for those energy models running on proprietary software, containerization might not be possible.

Addressing the EC feedback, this document has highlighted how the inteGRIDy energy models address the four pillars, covering the majority of the expected impacts from the EU included in the work programme. In addition, the report has presented the developments made in the energy models through the inteGRIDy project, as well as emphasized the innovations beyond the state of the art achieved by inteGRIDy technology developers. In some cases, it has been demonstrated that there is currently no similar tool in the market to the inteGRIDy energy models. In other cases, the advantages of the inteGRIDy solutions against available commercial tools have been provided. Furthermore, it has been shown that the inteGRIDy energy models can apply to different scales, from DSOs to residential consumers. The integration of functionalities brought by the different inteGRIDy energy models is addressed through a comprehensive identification and analysis of their synergies.

A synergy assessment has been performed among the 13 energy models available in inteGRIDy. For each energy model, a table has listed the energy models that could be integrated with and the functionalities that they could provide to the analysed tool. In total, 69 synergies have been identified among the inteGRIDy energy models. It has been concluded that none of the energy models could provide any functionality to the tools SimaPro and Kisense Energy Management System. Nevertheless, it is found that SimaPro could provide LCA & LCC functionalities to more than half of the inteGRIDy energy models, provided that the energy systems analysed are built from scratch in SimaPro.

A second part of the synergy assessment has looked into the integration technical constraints. Apart from highlighting the difficulty to integrate proprietary energy models, the constraint analysis has revealed that it is necessary to separate into two types of integration: full integration of energy models may require them to have the same programming language; while if full integration is not required, it might be sufficient to update their data format and time step.



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## Appendix A. Power flow in distribution network of IoW with IPSA and Integration Test Environment

P_ITE	P_IPSA	Q_ITE	Q_IPSA	P_Error	Q_Error	P_Error(%)	Q_Error (%)
14.49548501	14.49639721	2.766283963	2.759252738	-0.00091	0.007031225	-6.293E-05	0.002541758
14.49548501	14.49639721	2.766283963	2.759252738	-0.00091	0.007031225	-6.293E-05	0.002541758
8.87719616	8.879041478	-0.463808608	-0.47754067	-0.00185	-0.013732065	-0.000207872	-0.02960718
8.801668371	8.803482602	-0.538654684	-0.55244177	-0.00181	-0.013787089	-0.000206124	-0.02559541
6.995992417	6.994780284	-8.786123639	-8.83845069	0.001212	-0.052327046	0.000173261	-0.00595565
7.241681944	7.240424064	-9.095095217	-9.14926162	0.001258	-0.054166407	0.0001737	-0.00595556
1.941655879	1.943278886	-7.012348657	-7.02727405	-0.00162	-0.014925395	-0.000835888	-0.00212844
11.72319769	11.72248299	5.057782818	5.063963198	0.000715	-0.00618038	6.09644E-05	-0.00122195
12.56481906	12.5639099	5.650264401	5.656896338	0.000909	-0.006631937	7.23576E-05	-0.00117374
2.300221356	2.300057341	-3.418122514	-3.41926697	0.000164	-0.001144456	7.1304E-05	-0.00033482
3.13E-10	3.3968E-10	-0.010255727	-0.01025833	-2.7E-11	-2.5987E-06		-0.00025339
-3.364116445	-3.362327223	-4.414459146	-4.42821245	0.001789	-0.0137533	0.000531855	-0.00311551
15.82457234	15.82433604	4.551479273	4.551311885	0.000236	0.000167388	1.49323E-05	3.67767E-05
6.327354686	6.327171315	1.703959059	1.704225606	0.000183	-0.000266547	2.89807E-05	-0.00015643
6.319161269	6.318980954	1.720076559	1.720359442	0.00018	-0.000282882	2.85346E-05	-0.00016446
-2.020757228	-2.019768398	-1.815470742	-1.82249847	0.000989	-0.007027728	0.000489337	-0.00387102
11.49380352	11.49376629	4.270284574	4.27003469	3.72E-05	0.000249885	3.23832E-06	5.85171E-05
1.14E-09	1.14241E-09	-0.020808061	-0.0208152	1.04E-12	-7.14002E-06	0.000910577	-0.00034314
-6.009148319	-6.009143091	-2.361625074	-2.36146313	5.23E-06	0.000161943	8.70117E-07	6.85726E-05
-0.480103378	-0.480108808	-0.679102283	-0.67906021	-5.4E-06	4.20716E-05	-1.13094E-05	6.19518E-05
11.52209227	11.52199481	3.353825398	3.353426115	9.75E-05	0.000399282	8.45879E-06	0.000119053
6.298791111	6.298773365	2.026007342	2.025863114	1.77E-05	0.000144228	2.81739E-06	7.11884E-05
5.066486578	5.066464114	0.986113695	0.986005631	2.25E-05	0.000108063	4.43383E-06	0.000109585
11.5845096	11.5844394	4.521757259	4.521379056	7.02E-05	0.000378203	6.05948E-06	8.36408E-05
9.375677838	9.375669193	2.461373615	2.461095166	8.65E-06	0.000278449	9.22114E-07	0.000113128
12.80283669	12.80295907	8.493366036	8.494328268	-0.00012	-0.000962232	-9.5589E-06	-0.00011329
11.5351528	11.53494623	0.239115229	0.237329519	0.000207	0.001785711	1.79077E-05	0.007467992
8.438891121	8.438712356	-1.802320454	-1.80435373	0.000179	-0.002033279	2.11834E-05	-0.00112815
9.749050282	9.749188704	8.448420868	8.449852166	-0.00014	-0.001431298	-1.41985E-05	-0.00016942
3.048018674	3.048008897	1.901338469	1.901653533	9.78E-06	-0.000315064	3.20767E-06	-0.00016571
2.966195944	2.966201659	-0.227273019	-0.22766214	-5.7E-06	-0.000389125	-1.92662E-06	-0.00171215
9.685354938	9.68550463	8.265718631	8.267198175	-0.00015	-0.001479544	-1.54555E-05	-0.000179
8.41682803	8.416655448	-1.660221786	-1.6621603	0.000173	-0.00193851	2.05045E-05	-0.00116762
-5.745364401	-5.745365734	-1.777841843	-1.77768483	-1.3E-06	0.000157011	-2.31982E-07	8.83155E-05
-3.789090251	-3.789261892	-5.516533843	-5.51765536	-0.00017	-0.001121515	-4.52989E-05	-0.0002033
2.81E-06	2.8134E-06	-0.214684477	-0.21475561	-9.3E-10	-7.11354E-05	-0.000331587	-0.00033135
8.02E-08	8.02122E-08	-0.06440467	-0.06442601	-3E-11	-2.13404E-05	-0.000370145	-0.00033135
2.82E-10	2.92276E-10	-0.010161933	-0.01016452	-1.1E-11	-2.58327E-06	-0.037454728	-0.00025421
10.27440724	10.27447975	1.748740977	1.748222109	-7.3E-05	0.000518868	-7.05716E-06	0.000296709
16.72598132	16.72590677	4.951647581	4.952165738	7.45E-05	-0.000518156	4.45706E-06	-0.00010464



6.82E-10	6.94546E-10	-0.010109712	-0.0101132	-1.3E-11	-3.48825E-06	-0.018896559	-0.00034504
0	0	0	0	0	0		
3.78909025	3.789261892	5.526695776	5.527819875	-0.00017	-0.001124099	-4.52989E-05	-0.00020339
2.286326137	2.286159867	-3.424815935	-3.42595958	0.000166	-0.001143647	7.27238E-05	-0.00033393
2.40E-05	2.40196E-05	-0.205209205	-0.20527964	-8.3E-09	-7.04309E-05	-0.00034516	-0.00034322
6.69E-10	6.69644E-10	-0.003294795	-0.00329593	-3.9E-13	-1.13084E-06	-0.000581795	-0.00034322
2.05E-06	2.04978E-06	-0.191312457	-0.19137812	-7.7E-10	-6.56614E-05	-0.000373419	-0.00034322
21.85237957	21.82836295	-4.794284997	-4.94500087	0.024017	-0.150715876	0.001099039	-0.03143657
21.48659542	21.5101094	-4.876372166	-4.84275127	-0.02351	0.033620896	-0.001094356	0.006894653
36.75689232	36.75770181	29.42193908	29.48638766	-0.00081	-0.064448578	-2.2023E-05	-0.00219049
37.05534317	37.05682999	29.62118883	29.68861994	-0.00149	-0.067431105	-4.01244E-05	-0.00227645
10.05356014	10.02423135	3.015899228	3.007105815	0.029329	0.008793414	0.002917255	0.002915685
10.02423883	10.02423135	3.007266287	3.007105815	7.48E-06	0.000160472	7.46211E-07	5.33615E-05
0	8.47397E-15	0	0	-8.5E-15	0		
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0	9.34756E-15	0	0	-9.3E-15	0		
-1.40E-15	-4.07733E-12	1.53E-16	-3.5008E-12	-4.1E-12	-3.50067E-12		
-2.10E-15	-4.01956E-12	2.15E-16	-5.4732E-12	-4E-12	-5.47298E-12		
3.005499415	3.005497017	0.840692853	0.840670214	2.4E-06	2.26393E-05	7.9789E-07	2.69293E-05
3.00637863	3.006377825	0.840123478	0.840099366	8.05E-07	2.41124E-05	2.67812E-07	2.8701E-05
6.294698689	6.294527323	1.977429405	1.977831084	0.000171	-0.000401679	2.72239E-05	-0.00020313
10.47305923	10.47314193	4.095772806	4.09550871	-8.3E-05	0.000264096	-7.89638E-06	6.44801E-05
10.30384648	10.30390864	2.485744307	2.484966217	-6.2E-05	0.00077809	-6.03221E-06	0.000313021
2.966127967	2.966133703	-0.20655595	-0.20693799	-5.7E-06	-0.000382037	-1.93391E-06	-0.00184956
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0	8.49468E-15	0	0	-8.5E-15	0		
9.670440641	9.670592963	8.216004311	8.21749262	-0.00015	-0.001488309	-1.57512E-05	-0.00018115
8.41038635	8.410215669	-1.681694053	-1.68362622	0.000171	-0.001932171	2.02941E-05	-0.00114894
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6.286957532	6.286944114	2.008087036	2.007956689	1.34E-05	0.000130347	2.13419E-06	6.49111E-05
0	0	0	0	0	0		
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5.450933584	5.450914121	1.858137805	1.858119969	1.95E-05	1.78364E-05		9.59905E-06



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