



European Research Infrastructure supporting Smart Grid Systems Technology Development, Validation and Roll Out

Technical Report TA User Project **ECOSMIC**

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Abbreviations

<i>CapEx</i>	Capital Expenses
<i>COE</i>	Cost of Energy
<i>DER</i>	Distributed Energy Resource
<i>IRR</i>	Internal Rate of Return
<i>MG</i>	Microgrid
<i>MSP</i>	Minimum Selling Price
<i>NPC</i>	Net Present Cost
<i>NPV</i>	Net Present Value
<i>OpEx</i>	Operational Expenses
<i>PBP</i>	Payback Period
<i>PV</i>	Photovoltaic
<i>SoC</i>	State of Charge
<i>TA</i>	Trans-national Access
<i>TEA</i>	Techno-Economic Analysis

Executive Summary

The ECOSMIC User Group from University of Antwerp, Belgium submitted a research proposal during the 2nd call for applications for Transnational Access (TA) with ERIGrid, and the access to four research facilities was approved. The four visits have been carried out by the User Group representative Iolanda Saviuc between Oct 2017 and Feb 2018 at CRES (Greece), RSE (Italy), DTU (Denmark) and VTT (Finland).

The **objective of the project** was to carry out a techno-economic analysis (TEA) of the microgrid (MG) set-ups found on site. The motivation for the multiple visits was to enable comparison between set-ups, driven by questions such “how would a system optimized for Greek conditions perform (economically) in a different environment?”. The four facilities proposed for visiting were therefore selected so as to be different in both climate and economic/ policy conditions, e. g. to have different incentive schemes for photovoltaic panels.

Each visit was one week long and involved a series of experiments for a residential load profile typical for the location of the respective facility, served by renewable energy sources supported by storage as well as a connection to the main grid and/or a generator based on fossil fuels. The configurations of the MG components (Table 1) and the operation scenarios for each experiment set (Table 2) have been developed with the facility representatives before each visit; each scenario corresponded to one experiment (usually 24h long), and during each visit an experiment set was completed, consisting of 4-6 experiments, using the same equipment configuration.





				
Load	4,2 kW	9 kW	25 kW	2,33 kW
PV	4,2 kW	9 kW	10 kW	7,2 kW
Storage	Lead-acid 40,2 kWh	Li-Ion 12,5 kWh	Vd-redox/ Tesla W 27 kWh	Lead-acid 58 kWh
Wind	---	---	11 kW	5,5 kW
Grid	Yes	---	Yes	Yes
Diesel	Diesel generator 10 kW	CHP, natural gas 33 kW	---	---

Table 1: Overview of the configurations used in MG set-ups for the ECOSMIC experiments

The output of each experiment consisted of the recorded values of electricity production, storage and consumption. Each set of 4-6 experiments has had its own **objective of the experiment set** that informed the variations between scenarios. For example based on the knowledge that in Denmark the nights are windy in January (when the TA visit took place) it is interesting to record the energy storage and the exchange with the main grid in case the battery happens to be discharged in the evening and ready to store the excess electricity produced overnight, or in case the battery happens to be full and so the excess energy needs to be put on the main grid. The variations of the initial SoC of the battery determined the different experiments in the set; the investigation of different outputs was the objective of this experiment set which were therefore descriptive in nature (as opposed to validation/ verification objectives).





			
Grid-connected, heavy load, buy-priority	Summer generation, summer load profile, with base load	Initial SoC at minimum, PV unit connected	Battery first to charge/discharge; grid next
Grid-connected, heavy load, sell-priority	Summer generation, summer load profile, no base load	Initial SoC at median value, PV unit connected	Discharge primarily during peak hrs, charge first
Grid-connected, light load, buy-priority	Winter generation, winter load profile, with base load	Initial SoC at minimum, PV unit disconnected	Discharge during peak hrs, charge when profitable
Grid-connected, light load, sell-priority	Winter generation, winter load profile, no base load	Initial SoC at median value, PV unit disconnected	Battery first to charge, EV second; battery first to discharge
Island mode, heavy load			
Island mode, light load			

Table 2: Overview of the scenarios carried out at each of the four facilities

In parallel with the running experiments economic data on the equipment was collected: equipment brands, purchase prices, time of purchase. The data was recorded via HOMER software in that each configuration was separately modelled as a MG and the components (Figure 1, left) were assigned the purchase prices as provided by the respective facility. Based on the configuration and complete economic data the HOMER software carries out a TEA of the given MG set-up.

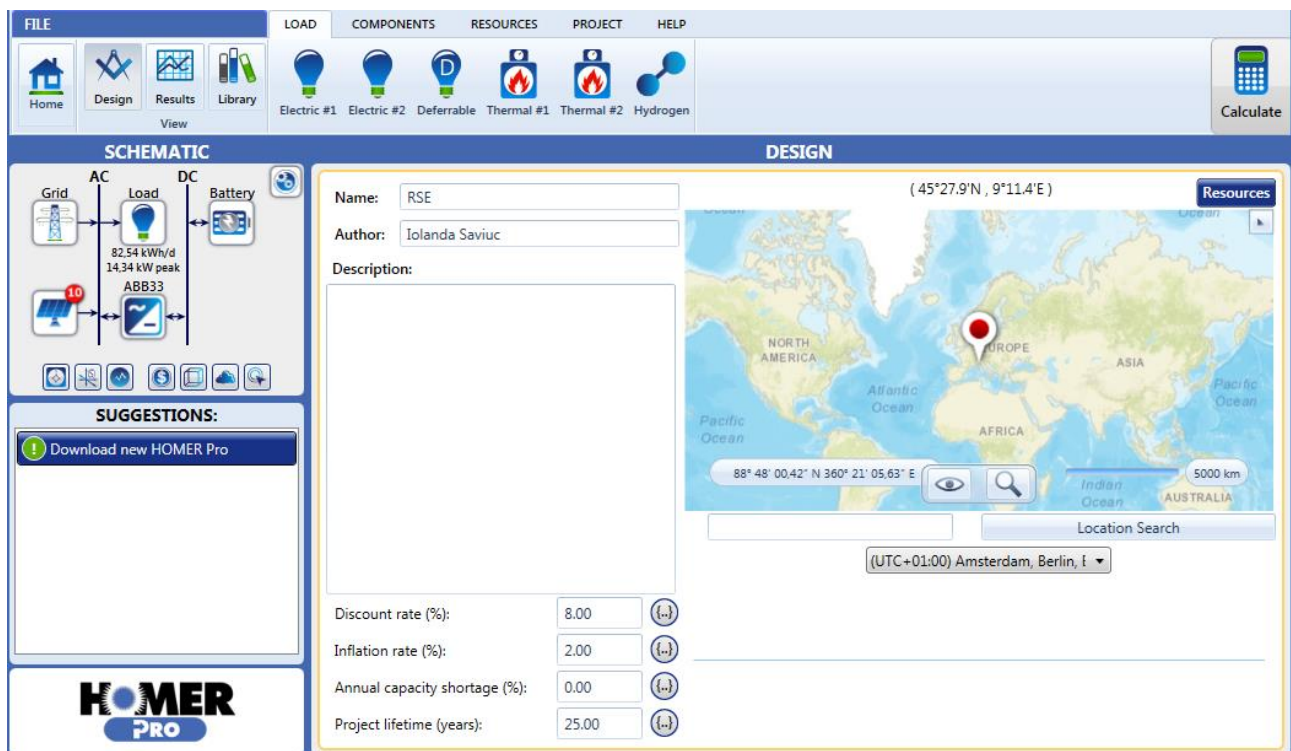


Figure 1: Example interface of the HOMER software in which the economic data was recorded and the TEA was carried out

After filling out the HOMER model, a TEA was carried out on the set-up, which calculated indicators of interest such as NPC, PBP, COE and IRR. An example of the findings is summarized in the following figures (each line in the table represents the indicators calculated by the software for the combination of components depicted as icons in the columns on the left):



































Export...		Optimization Results															
Architecture								Cost				System		Compare Economics			
					PV unit (kW)	Diesel (kW)	Storage	Grid (kW)	Converter (kW)	Dispatch	COE (€)	NPC (€)	Operating cost (€)	Initial capital (€)	Ren Frac (%)	IRR (%)	Simple Payback (yr)
					4,20			999.999		CC	€ 0,0326	€ 4.662	-€ 133,25	€ 5.860	65,4	11	6,6
					4,20		10	999.999	0,0187	CC	€ 0,0378	€ 5.402	-€ 132,23	€ 6.591	65,5	8	7,5
								999.999		CC	€ 0,0700	€ 6.745	€ 750,06	€ 0,00	0		
							10	999.999	0,0187	LF	€ 0,0777	€ 7.486	€ 751,15	€ 730,66	0,121		
					4,20	10,0		999.999		CC	€ 0,0553	€ 7.905	-€ 574,25	€ 13.069	65,4	4	11
					4,20	10,0	10	999.999	0,0187	CC	€ 0,0605	€ 8.645	-€ 573,23	€ 13.800	65,5	3	12
						10,0		999.999		CC	€ 0,104	€ 9.988	€ 309,05	€ 7.209	0		
						10,0	10	999.999	0,0187	LF	€ 0,111	€ 10.729	€ 310,15	€ 7.940	0,121		

Figure 2: TEA on the configuration at CRES


























Optimization Results																
Export...																
Architecture						Cost				System	Compare Economics					
						PV (kW)	1kWh LA	Grid (kW)	Dispatch	COE (€)	NPC (€)	Operating cost (€)	Initial capital (€)	Ren. Frac (%)	IRR (%)	Simple Payback (yr)
						36,0		999.999	CC	-€ 0,0247	-€ 9.549	-€ 1.187	€ 5.800	94,0	24	4,2
								999.999	CC	€ 0,0500	€ 2.659	€ 205,65	€ 0,00	0		
						36,0	10	999.999	CC	€ 0,0285	€ 11.218	-€ 1.128	€ 25.800	94,5	2	19
							10	999.999	CC	€ 0,433	€ 23.053	€ 236,19	€ 20.000	0,127		

Figure 3: TEA on the configuration at RSE
































Export...				Optimization Results													
Architecture								Cost			System		Compare Economics				
					PV (kW)	G1	LA ASM	Grid (kW)	SolaX10 (kW)	Dispatch	COE (€)	NPC (€)	Operating cost (€)	Initial capital (€)	Ren. Frac (%)	IRR (%)	Simple Payback (yr)
								999.999		CC	€ 0,158	€ 6.854	€ 648,63	€ 0,00	0		
					21,0			999.999	10,0	CC	€ 0,125	€ 24.716	-€ 1.935	€ 45.160	88,1		
					21,7		12	999.999	10,0	CC	€ 0,125	€ 24.983	-€ 1.974	€ 45.843	88,5		
					21,0	1		999.999	10,0	CC	€ 0,134	€ 26.606	-€ 1.957	€ 47.285	89,1		
					21,7	1	12	999.999	10,0	CC	€ 0,133	€ 26.878	-€ 2.001	€ 48.022	89,5		
							12	999.999	10,0	CC	€ 0,825	€ 35.834	€ 650,02	€ 28.966	0,105		
						1		999.999	10,0	CC	€ 0,861	€ 37.495	€ 616,36	€ 30.982	7,75		
						1	12	999.999	10,0	CC	€ 0,866	€ 37.684	€ 618,58	€ 31.147	7,73		

Figure 4: TEA on the configuration at VTT

Based on analyses such as those exemplified in Figures 2-4 it is possible to first evaluate each system individually – e.g.: For the CRES case the most economically efficient alternative is to use only the PV unit along with the main grid, as this offers the lowest NPC; For VTT, any option including the PV unit yields a COE significantly lower than the options without PV; Also, in the case of RSE it is remarkable that the option selected as most effective also yields a negative COE.

In a second step it is very informative to make comparisons – e.g. the investment in the most efficient set-up at RSE also pays back in fewer years (4.2) than the most efficient set-up at CRES; the negative operating cost (i.e.: the revenue) can be very high in Finland for certain configurations.

The data collected is capable of supporting various research questions which will be approached in upcoming research publications.

1 General Information of the User Project

User Project	
User Project acronym	ECOSMIC
User Project title	Developing and Evaluating an Economic Assessment Framework for Microgrids -- Based on the Concept of Economies of Scope
Main scientific/technical field	Microgrids
Keywords	DER, Microgrids, Techno-economic assessment, comparability

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Position in organization	Gewoon Hoogleraar and Hoofddocent, respectively
Activity type and legal status of organization	Higher Education Institution

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Age	32
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Organization website	www.uantwerpen.be

Position in organization	PhD student
Activity type and legal status of organization	Higher Education Institution

Host Infrastructure 1	
Name of the Infrastructure/ Installation	Distributed Generation Laboratory (DG-Lab)
Location	CRES - Pikermi, Attiki, Greece
Web Site	www.cres.gr
Access Period	16.10.2017 – 20.10.2017

Host Infrastructure 2	
Name of the Infrastructure/ Installation	Distributed Energy Resources Test Facility (RSE DER-TF)
Location	Ricerca sul Sistema Energetico, Milan, Italy
Web Site	www.rse-web.it
Access Period	11.12.2017 – 15.12.2017

Host Infrastructure 3	
Name of the Infrastructure/ Installation	SYSLAB and ICL
Location	Technical University of Denmark, Roskilde, Denmark
Web Site	www.dtu.dk ; www.powerlab.dk
Access Period	22.01.2018 – 26.01.2018

Host Infrastructure 4	
Name of the Infrastructure/ Installation	Oulu Smart Grid Laboratory (SG-Oulu)
Location	VTT – Oulu, Finland
Web Site	www.vtt.fi
Access Period	5.02.2018 – 9.02.2018

2 Research Motivation

As part of my PhD research at the University of Antwerp (BE) supervised by my promoters, Prof. Steven Van Passel and Prof. Herbert Peremans, I am developing a framework for the economic assessment of MGs. In order to achieve that, I proposed analysing the shortcomings of conventional methods, of which the most popular one is the techno-economic analysis (TEA).

The output of a TEA uses CapEx, OpEx and revenues to provide metrics such as: payback period PBP, net present value NPV, internal rate of return IRR, minimum selling price MSP. The probabilistic distribution of these indicators together with the sensitivity analyses provide insight on the impact of variable MG configurations, and they constitute the main rationale of the experiment sets.

This project was designed to enable a series of TEAs on various MG configurations in residential setting. We hereby aimed at a broad range of technology mixes, MG sizes, operating conditions etc. to derive reliable estimates for the parameters used in the general conceptual framework. In other words, it is a simple and efficient way to enable comparisons between different configurations assessed with the same method.

2.1 Objectives

In order to get the broad range of MG configurations required to arrive at reliable results for my research, I proposed a combination of shorter research stays at more facilities. The TA project of ERIGrid provided the opportunity to a) assess multiple scenarios in the same MG location, and b) compare performances of different MGs in similar scenarios. In addition to experimental and economic data this project took into account specifics of the respective country's energy policy, as it has direct impact on prices of equipment, electricity, CO₂.

During the preparation of the TA visits we quickly identified two domains of work: the economic analysis, of which the greatest part can be carried out through comparison, hence after the completion of all the visits; and the technologic reasoning which would approach each facility individually, take into account the existing equipment, and develop experiment scenarios for the momentary operation of the equipment and be completed before the visit itself. Even though the two levels are interconnected, for purposes of clarity this report will refer to them separately as follows.

The **objective of the project** was to carry out a techno-economic analysis (TEA) of the microgrid (MG) set-ups found on site. The motivation for the multiple visits was to enable comparison between set-ups, driven by questions such "how would a system optimized for Greek conditions perform (economically) in a different environment?". The four facilities proposed for visiting were therefore selected so as to be different in both climate and economic/ policy conditions, e. g. to have different incentive schemes for photovoltaic panels.

The output of each experiment consisted of the recorded values of electricity production, storage and consumption. Each set of 4-6 experiments has had its own **objective of the experiment set** that informed the variations between scenarios. For example based on the knowledge that in Denmark the nights are windy in January (when the TA visit took place) it is interesting to record the energy storage and the exchange with the main grid in case the battery happens to be discharged in the evening and ready to store the excess electricity produced overnight, or in case the battery happens to be full and so the excess energy needs to be put on the main grid. The variations of the initial SoC of the battery determined the different experiments in the set; the investigation of different outputs was the objective of this experiment set which were therefore meant for characterization (as opposed to validation/ verification objectives), in the terms of the holistic test specifications.

The respective objectives of each experiment set are summarized in Table 3.





			
Record generation, consumption and storage in a MG in three plausible operation scenarios: grid-connected and selling excess electricity; grid-connected and storing the excess electricity; island mode. “Heavy” load is the actual residential load; “light” load is obtained by deducting the base load and is made to highlight differences in shape of storage and genset curves.	Record generation, consumption and storage in two plausible operation scenarios of an islanded MG: summer and winter load and production profiles. “Heavy” load is the actual residential load; “light” load is obtained by deducting the base load and is made to highlight differences in shape of storage and genset curves.	Record generation, consumption and storage in a grid-connected MG for four plausible operation scenarios: with and without a connected PV unit, and in each case starting with an empty battery and with a half-full battery, respectively (“median” = midway between max SoC and min SoC).	Record generation, consumption and storage in a grid-connected MG for four plausible scenarios and investigate the capacity left in the system after the discharging tests.

Table 3: Overview of the objectives for plausible (i.e. real-life) experiment sets

2.2 Scope

Each visit was one week long and involved a series of experiments for a residential load profile typical for the location of the respective facility, served by renewable energy sources supported by storage as well as a connection to the main grid and/or a generator based on fossil fuels. The configurations of the MG components (Table 4) and the operation scenarios for each experiment set (Table 3) have been developed together with the facility representatives before each visit; each scenario corresponded to one experiment (usually 24h long), and during each visit an experiment set was completed, consisting of 4-6 experiments, each using the same equipment configuration.





				
Load	4,2 kW	9 kW	25 kW	2,33 kW
PV	4,2 kW	9 kW	10 kW	7,2 kW
Storage	Lead-acid 40,2 kWh	Li-Ion 12,5 kWh	Vd-redox/ Tesla W 27 kWh	Lead-acid 58 kWh
Wind	---	---	11 kW	5,5 kW
Grid	Yes	---	Yes	Yes
Diesel	Diesel generator 10 kW	CHP, natural gas 33 kW	---	---

Table 4: Overview of the equipment used for each experiment set

3 State-of-the-Art

Economic and techno-economic assessment of MGs has received significant attention in the academic research of the past decade. A literature survey conducted in ScienceDirect and IEEE about TEA of MGs reveals ca. 100 journal articles and conference papers published between 2008 and 2017 (none existing before 2008). Most of these works focus on either the TEA of adding/changing a component in an existing MG – an ESS (Kaldellis, 2007) or a biogas engine (Sigarchian et al., 2015) – or the use TEA for solving the problem of MG sizing in the planning stage (Kobayakawa and Kandpal, 2014; Mohammadi, Hosseinian and Gharehpetian, 2012).

Another characteristic which the vast majority of the papers have in common is that they focus on one case study, presenting reports such as “Feasibility study of renewable energy-based microgrid system in Somaliland's urban centers” (Abdilahe et al., 2014). While this approach delivers valuable insight into a selected local landscape and exemplifies the use of the method, it stops short of making comparisons possible between different settings /configurations/countries. This has to do inherently with the specifics of a TEA metrics and the limitation to case-by-case evaluation. To the best of our knowledge, a comparison between indicators in different scenarios/different countries/ different sizes is yet to be carried out.

Other notable approaches in economic assessment of MGs aim at the optimization of operation costs alone. For example, shared storage drives cost advantage of MGs (Lee, Shaw, and Modi, 2014), whereas even simple additions to passively using storage are able to generate benefits under electricity price uncertainty (Milis and Peremans, 2015). Operation scenarios and the decision/timing of electricity selling to the main grid are subject to optimization, and each of them captures one variable that can drive comparisons between MGs.

To summarize, the existing knowledge and practice on the TEA of MGs is still limited and does not support reliably the real needs of practitioners: flexibility in the assessment method (i.e. the evaluation of a system that has been built over time, as opposed to being built at once from scratch), as well as enabling comparisons between systems. This project aimed to contribute to this discussion.

4 Executed Tests and Experiments

During each visit a set of 4-6 experiments was carried out. Each experiment in the set corresponded to an operation scenario relevant for a business-as-usual operation of a residential MG for, usually, 24h. T5 summarizes the experiment sets carried out at each facility.





			
Grid-connected, heavy load, buy-priority	Summer generation, summer load profile, with base load	Initial SoC at minimum, PV unit connected	Battery first to charge/discharge; grid next
Grid-connected, heavy load, sell-priority	Summer generation, summer load profile, no base load	Initial SoC at median value, PV unit connected	Discharge primarily during peak hrs, charge first
Grid-connected, light load, buy-priority	Winter generation, winter load profile, with base load	Initial SoC at minimum, PV unit disconnected	Discharge during peak hrs, charge when profitable
Grid-connected, light load, sell-priority	Winter generation, winter load profile, no base load	Initial SoC at median value, PV unit disconnected	Battery first to charge, EV second; battery first to discharge
Island mode, heavy load			
Island mode, light load			

Table 5: Overview of the experiment sets carried out at each host facility

The experiment sets were carried out by the team of the respective host facility who also programmed the controllers to suit the scenarios and recorded the output data. The User Group representative assisted the preparation of each new experiment, validated the first outputs of the data, and supported on-site with decision-making whenever any unforeseen event happened (error, disruption, inconclusive output).





Table 6: Photos provided by each facility during the visit (upper-left: with CRES representative Evangelos Rikos; upper-right: with RSE representative Maurizio Verga and the support team) or after the visit (lower-left: DTU; lower-right: VTT)

4.1 Test Plan

The scenarios of the experiment sets were developed bearing in mind elements of the holistic power validation and testing.

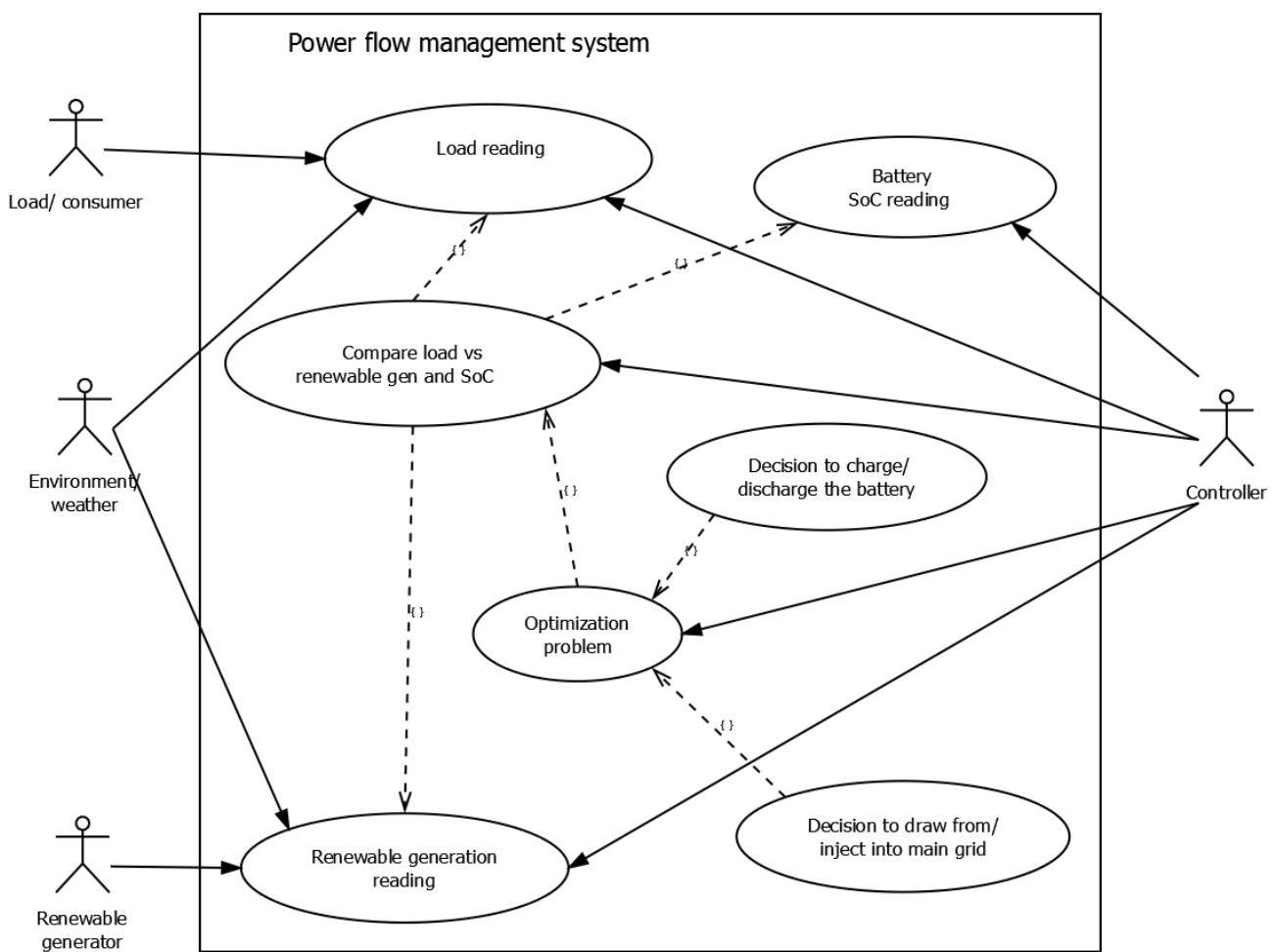


Figure 5: General use case diagram applicable for each of the experiment sets carried out. It aims to define the boundaries of the power flow management system and the actors who can actively influence elements of the system.

All the respective scenarios determining each experiment follow the use case given in the diagram from Figure 5.

4.2 Standards, Procedures, and Methodology

For the objectives of the experiment sets, the modelling methods for the PV generator are exemplified in the following, based on the experiment set carried out at CRES.

PV panels: Among various models for modelling the I-V characteristic of PVs the interpolated model (Khouzam and Hoffmann, 1996) was selected. In this approach, the current or the voltage of a symmetrically operated PV module is described by the following equation set:

$$I = I_{sc} \left[1 - C_1 \left(\exp \left(\frac{V_R}{C_2 V_{oc}} \right) - 1 \right) \right] + D_I \quad (1)$$

$$V = C_2 V_{oc} \ln \left(\frac{1 - (I - D_I)/I_{sc}}{C_1} + 1 \right) - C_{TV} (T - T_{ref}) - R_S D_I \quad (2)$$

where

$$C_1 = \left(1 - \frac{I_{mp}}{I_{sc}} \right) \exp \left(-\frac{V_{mp}}{C_2 V_{oc}} \right) \quad (3)$$

$$C_2 = \left(\frac{V_{mp}}{V_{oc}} - 1 \right) / \ln \left(1 - \frac{I_{mp}}{I_{sc}} \right) \quad (4)$$

$$D_I = C_{TI} \frac{G}{1000} (T - T_{ref}) + I_{sc} \left(\frac{G}{1000} - 1 \right) \quad (5)$$

$$V_R = V + C_{TV} (T - T_{ref}) + R_S D_I \quad (6)$$

MPPT algorithm: The method used for implementing the specific block was the P&O method Hohm and Ropp, 2003. This algorithm is the most commonly used method in PV inverters and is based on the perturbation of the voltage and the observation of the resulting power deviation. Depending on the change of power the algorithm infers if the system moves to or away from the maximum point of operation. In the following figures (Figure 6 and Figure 7) the operating principle of the P&O method together with the flowchart implementation diagram are shown.

PV inverter: The model selected and used for the PV inverters of the system takes into account the energy efficiency of the inverter only. In this respect, the model used for the inverter efficiency was a lookup table with two input signals, such as the DC voltage and the input power. Based on the combination of the two inputs one efficiency value is selected from the table and multiplied by the input power in order to calculate the power injected to the AC grid.

Power controller: The control part that specifies also each scenario of the tests makes use of the power values for the PV and the loads. Based on the net imbalance of the two quantities and according to the selected scenario the battery inverter setpoint is determined as follows:

$$\text{Buy-priority:} \quad P_{bat-setpoint} = \begin{cases} 0, & P_{PV} < P_{Load} \\ P_{Load} - P_{PV}, & P_{PV} > P_{Load} \end{cases} \quad (7)$$

$$\text{Sell-priority} \quad P_{bat-setpoint} = \begin{cases} 0, & P_{PV} > P_{Load} \\ P_{Load} - P_{PV}, & P_{PV} < P_{Load} \end{cases} \quad (8)$$

$$\text{Islanded operation} \quad P_{bat-setpoint} = P_{Load} - P_{PV} \quad (9)$$

In the formulas above it is implied that the battery absorbs power when the setpoint is negative and produces when positive.

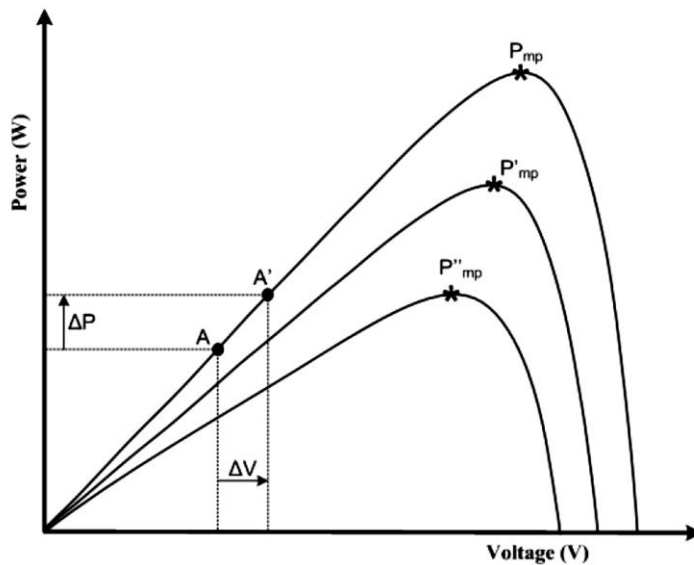


Figure 6: Operating principle of the implemented P&O method

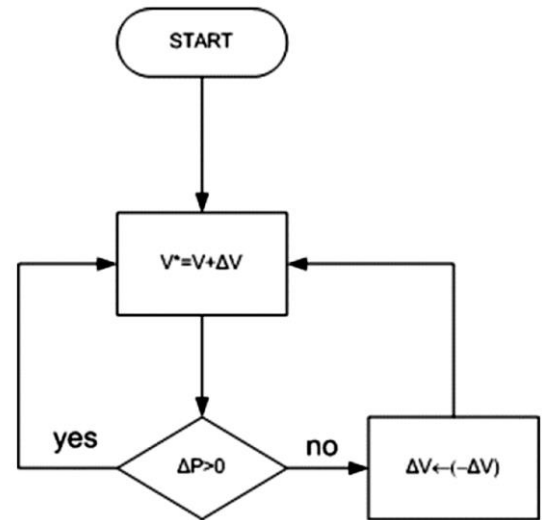


Figure 7: Flowchart of the implemented P&O method

The economic data (i.e. input data for the TEA) – equipment, quantities, output prices – have been collected by means of interviews with the ERIGrid representatives at the respective facilities and by observation of different operation scenarios (i.e. different loads/ load profiles with ongoing experiments, etc.)

4.3 Test Set-up(s)

As outlined in the overall objectives of the project, the scenarios were aimed to use similar equipment configurations. The summary in Table 4 shows how the core of each configuration was identical: PV unit, storage and load. Therefore the description of the first test set-up (chronologically, the visit at CRES) serves as a base for the following descriptions, listed chronologically afterwards.

4.3.1 Test Set-up at CRES

Figure 8 offers an overview on the hardware connections between the components used for the experiment set at CRES.

- One AC source, namely the AC LV grid of CRES
- One breaker which connects the MG to the public utility
- Two line segment for the connection of loads to the MG and to the battery inverter
- One busbar upon which loads and transducers are connected
- One automated load bank consisting of resistive loads (4.5kW per phase)
- One active power transducer for monitoring and recording the actual load power
- One irradiance sensor positioned on a horizontal level
- One ambient temperature sensor

- One battery bank
- One single-phase battery inverter
- Three Interbus Analog Input modules for the signals' monitoring
- One Interbus Digital Output module for the load control
- The MG SCADA system
- One computer used as the real-time simulator

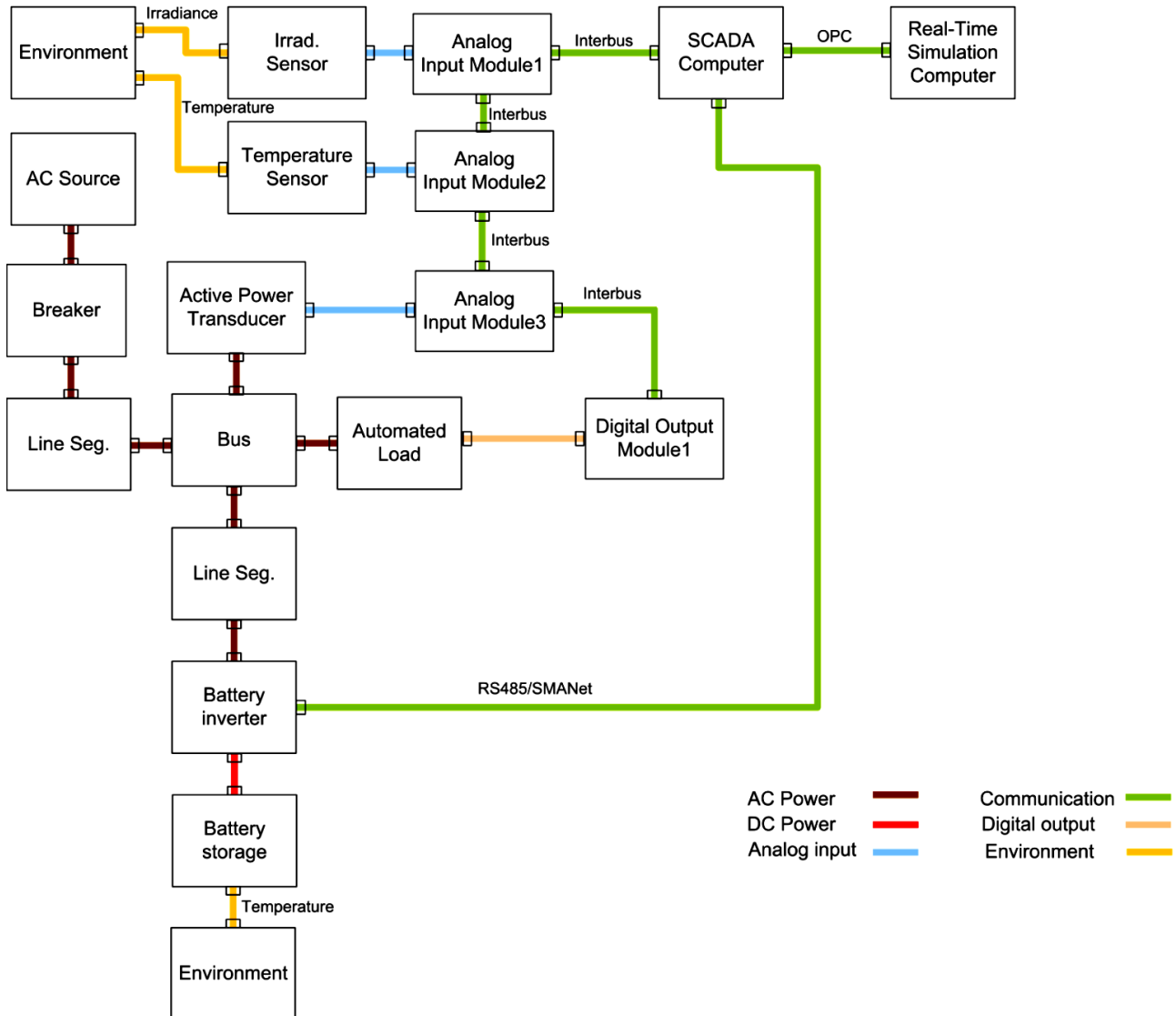


Figure 8: Experimental setup showing the hardware interconnections of the used components for one experiment set

Each experiment at CRES was 24h-long.

4.3.2 Test Set-up at RSE

For the experiment set at RSE the initial scenarios were aimed to being similar to the ones carried out in the first experiment set. However due to a technical problem shortly before the visit, the connection to the public utility was affected. Therefore the scenarios were adapted to islanded-mode only, and the modifications to the initial set-up were as follows:

- The PV unit was emulated from the DC grid on the RSE premises, based on the local generation profile
- For the balancing of the MG, the experiment set used a CHP in generator mode. However

due to the non-stop availability of electricity from the CHP and to the fact that heat production by the CHP was disregarded, it was possible to model the CHP as effectively a connection to the main grid.

All the other components (including the monitoring in SCADA) were the same as in the previous experiment set. All experiments were 24 long.

4.3.3 Test Set-up at DTU

As depicted in Figure 9, the experiment set carried out at DTU included the components connected by the green line: a smart house as a load (Flexhouse), a wind turbine (Gaia), a PV unit (Solar in Cell 1 of the diagram), a connection to the main grid (200kVA), and a battery (in Cell 2 of the diagram)

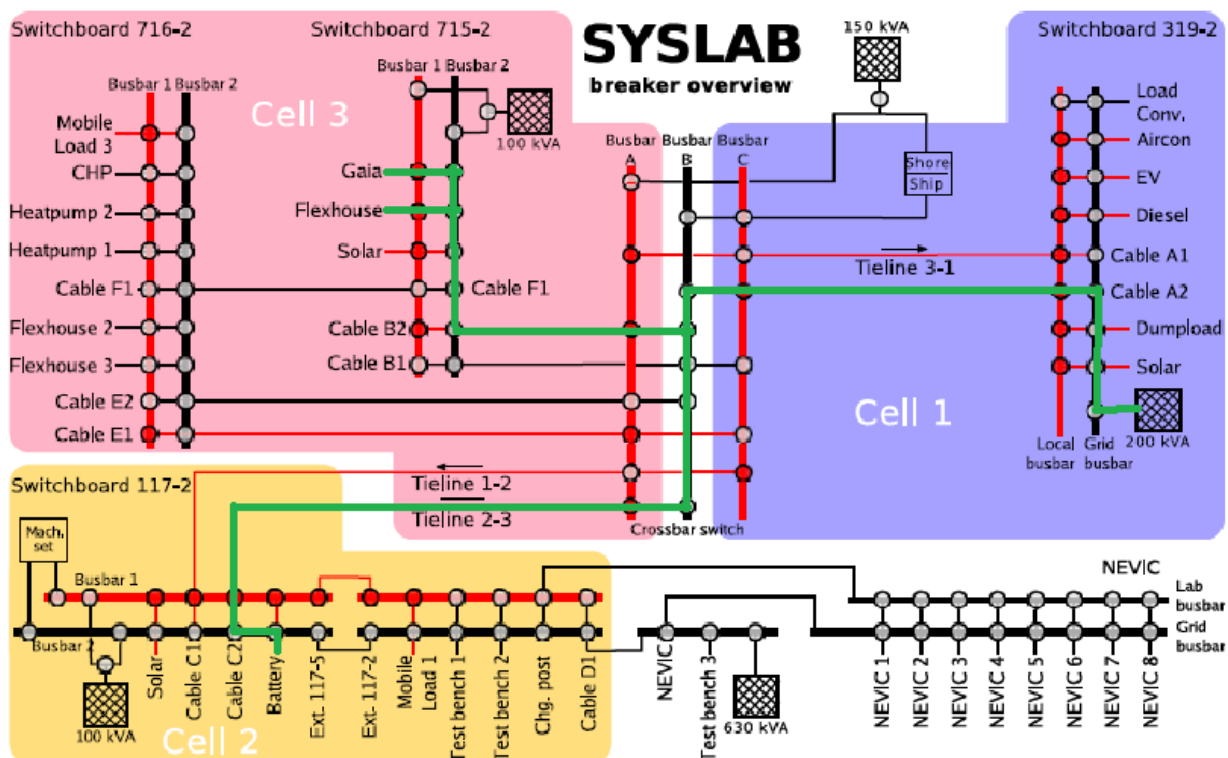


Figure 9: Equipment and configuration provided by DTU for the experiment set

The particularity of the configuration at DTU was that the battery actually used is a Vanadium-redox battery and had a very large capacity for the purposes of the experiment. Therefore it was necessary to simulate a Tesla wall and use the battery with the limits and profile of a Tesla wall.

Another particularity at the DTU premises was that the two experiments including the PV unit were scheduled to run during the first two days (see Table 5). However the weather turned out to be sunnier *after* the days in which the PV unit was connected, prompting the question whether an experiment including a PV should be redone so as to obtain sunnier data. The decision was to not redo keep the recorded data, as it is representative for a typical January day in Denmark and is therefore very interesting for analyses of economic performance.

Finally, for administrative reasons, the experiments at DTU were each 23 hours long.

4.3.4 Test Set-up at VTT

At VTT the set-up was similar to the one at DTU. Figure 10 is a still image taken from the real-time

public account of the smart grid, which shows via an animated image at <https://smartgrid.vtt.fi/smart-grid> the power flow (direction of the arrows) and the amount of power exchanged (values next to the arrows).

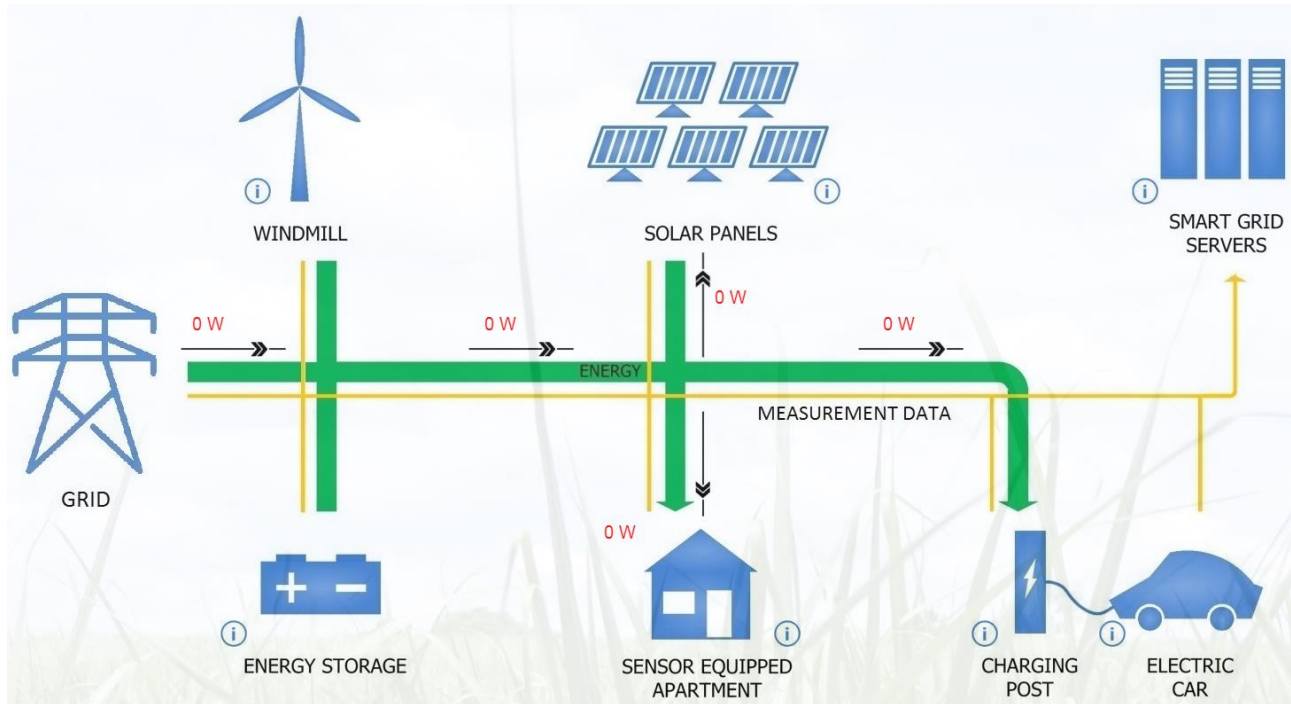


Figure 10: Equipment set-up for the experiment set at VTT

In the case of the set-up at VTT following particularities need to be noted:

- The load was also a smart house on the premises of VTT
- During the time of the visit the local climate was largely in windstill. Just as in the case at DTU, the decision was to record the scenario as it was planned, as it was found to be reflective of the real operation of a MG set-up in Finland.
- The electric car connected was used in one of the experiments as an additional load.

4.4 Data Management and Processing

Experimental output data was recorded in either Excel (*.xls), text files (*.csv) or Matlab (*.mat) and shared via email or Dropbox for post-processing.

Primary processing of data involved plotting of the outputs, which was carried out in either Matlab or in R.

Economic data was recorded in HOMER and in a descriptive log file to allow comments and notes.

5 Results and Conclusions

The results and conclusions of this report follow the twofold objectives of the TA visits, as stated in Section 2.1 (Objectives).

The objectives of the individual experiment set were to characterize the behaviour of a selected MG configuration under several scenarios. The results of the tests are summarized in the plots grouped below by configuration (facility).

The overall objective of the project is to learn from comparison between different set-ups based on techno-economic assessment carried out via HOMER. The results and first insights are exemplified in the next subsection.

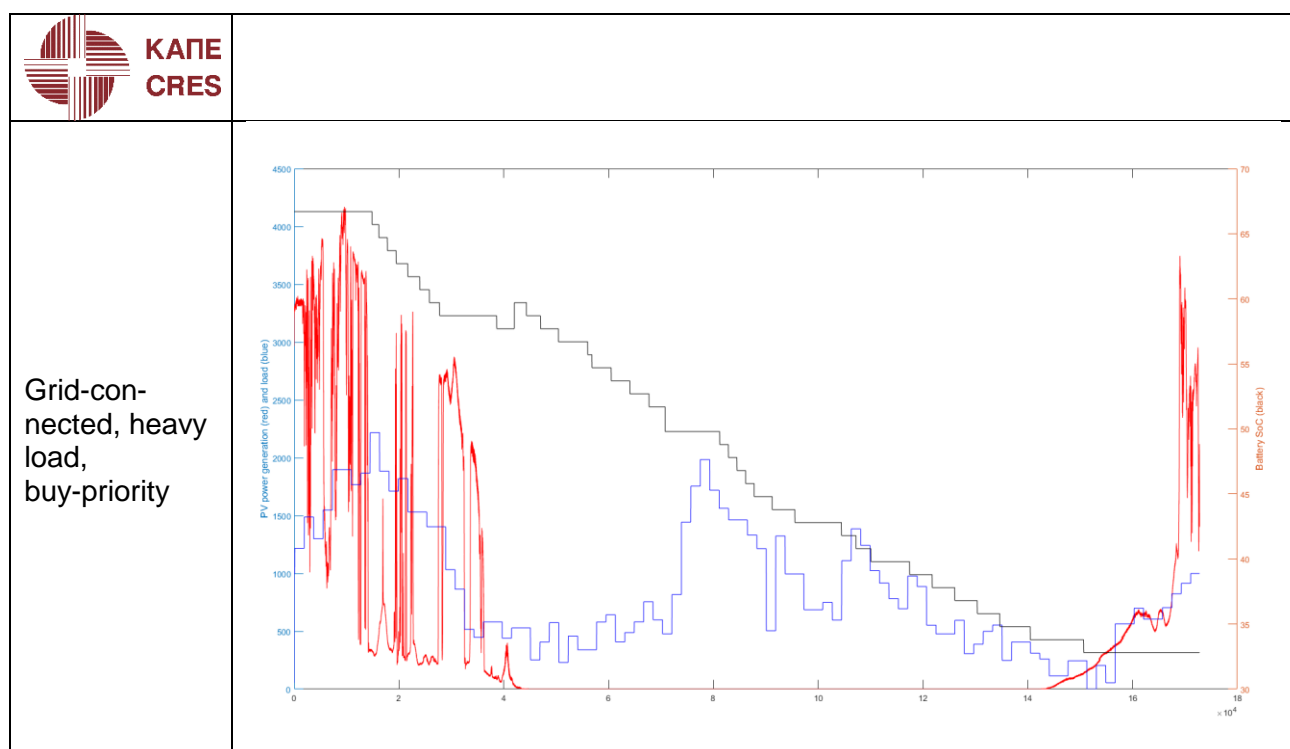
It is important to note how the results from subsection 1 interact with and support the results from subsection 2.

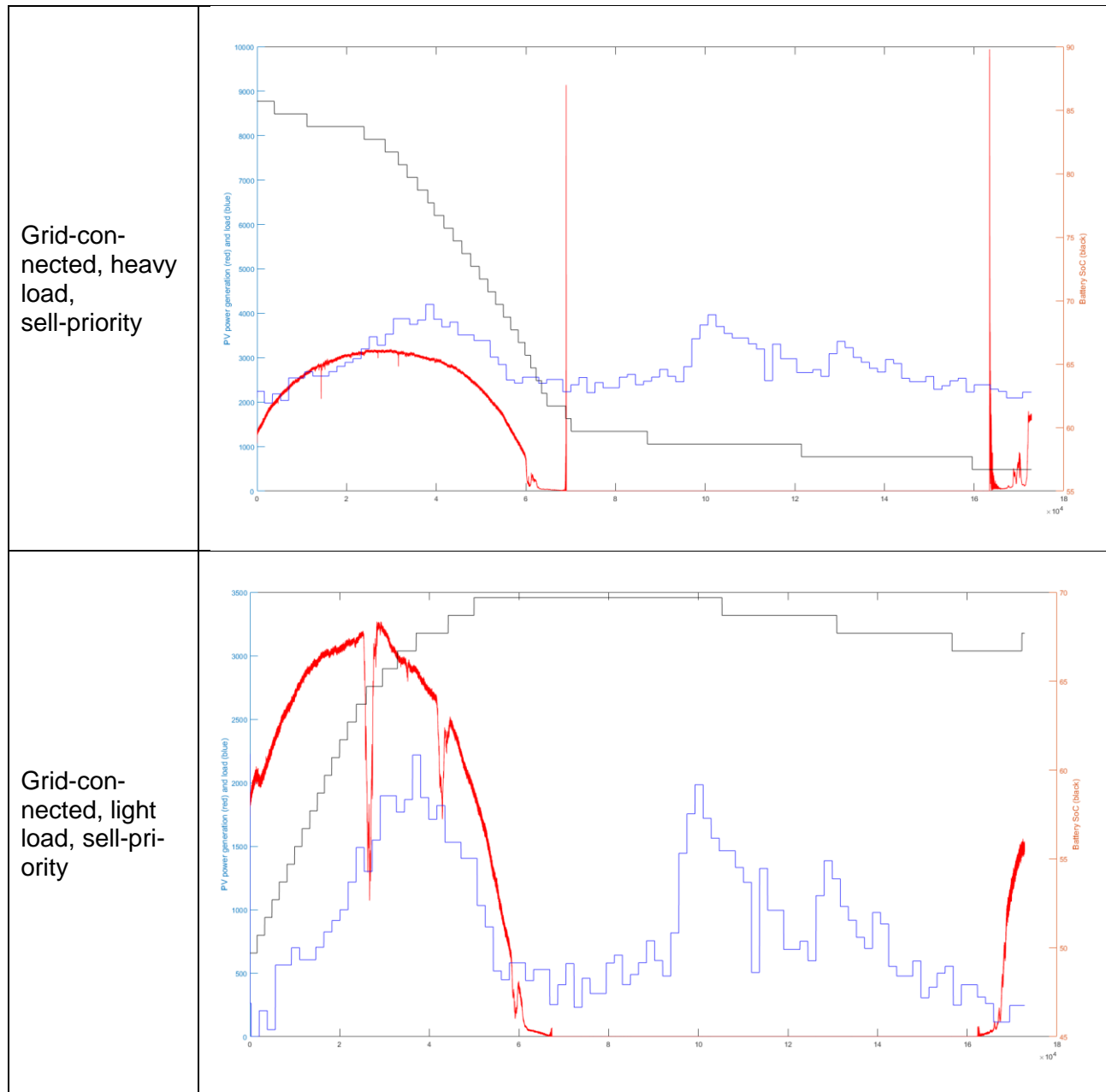
5.1 Results from the experiment sets

The account for each experiment set is summarized in plots grouped in tables corresponding to each scenario. Each plot shows the PV production (red) and the load served (blue) against the left y-axis, and the battery SoC (black) against the right y-axis.

It is important to note that, as it is apparent from the plots summarized below, measurement errors have occurred, especially in the case of battery readings. However the trend lines are informative and reflect a reality which needs to be taken into account in the optimization phase of the design of a MG system that is meant to run reliably and independently for long periods of time. The implications of this situation are both technological and economic

5.1.1 Output of the experiment set carried out at CRES





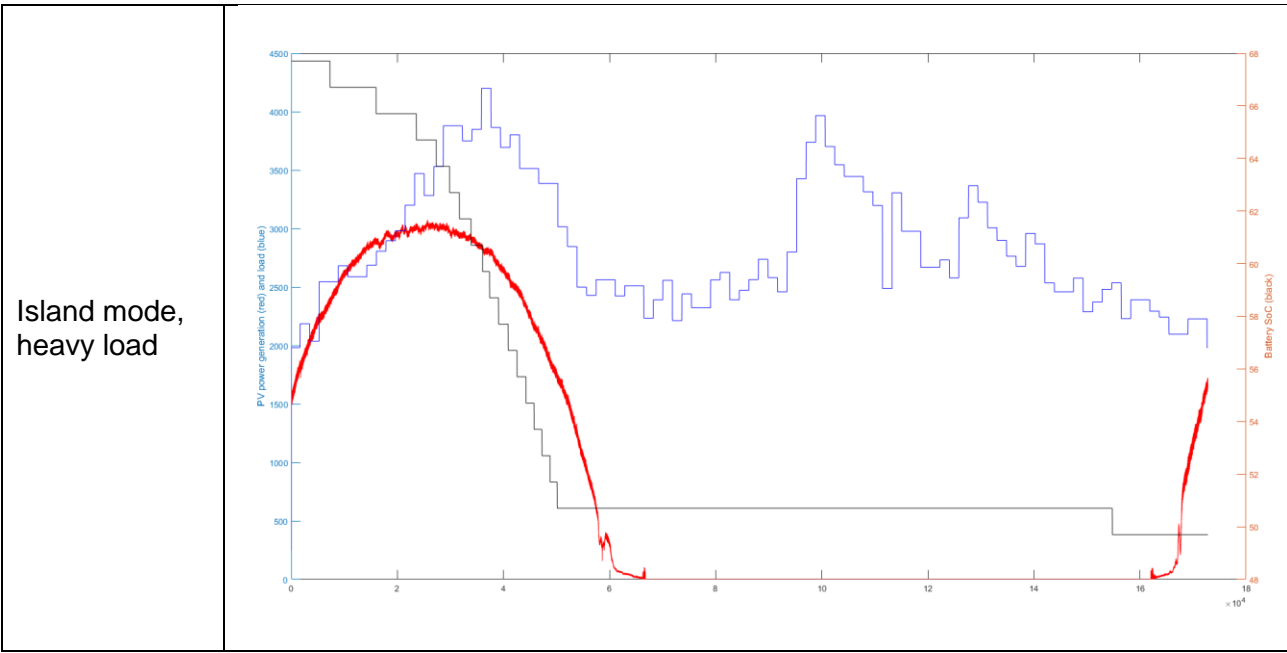
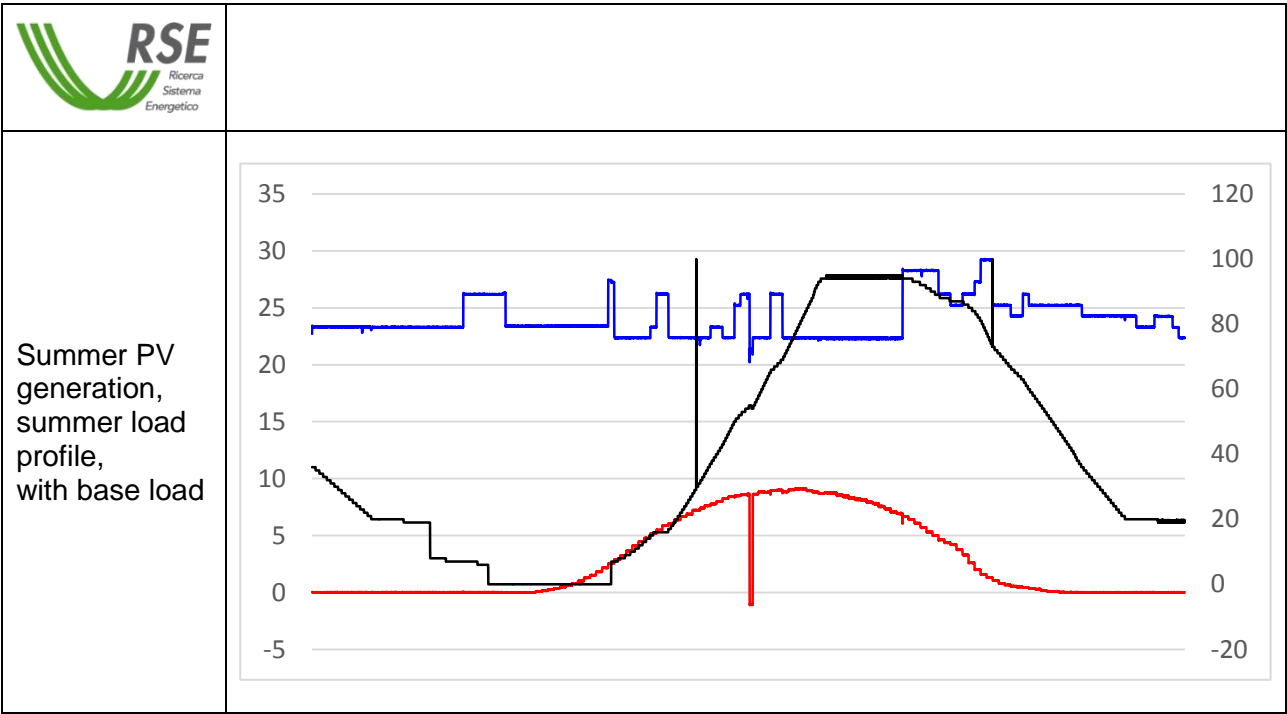


Table 7: Overview of the experiment set carried out at CRES

5.1.2 Output of the experiment set carried out at RSE



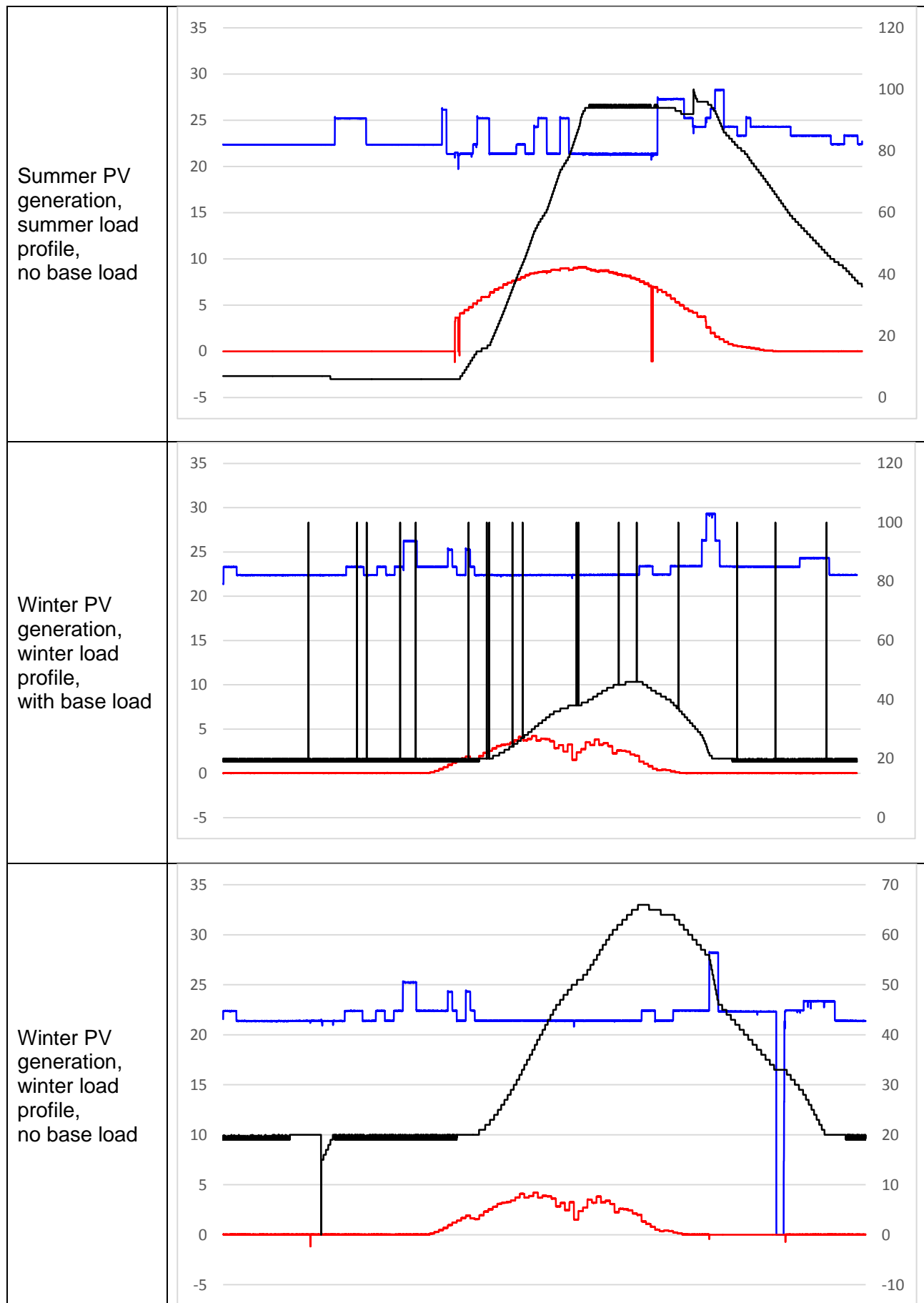
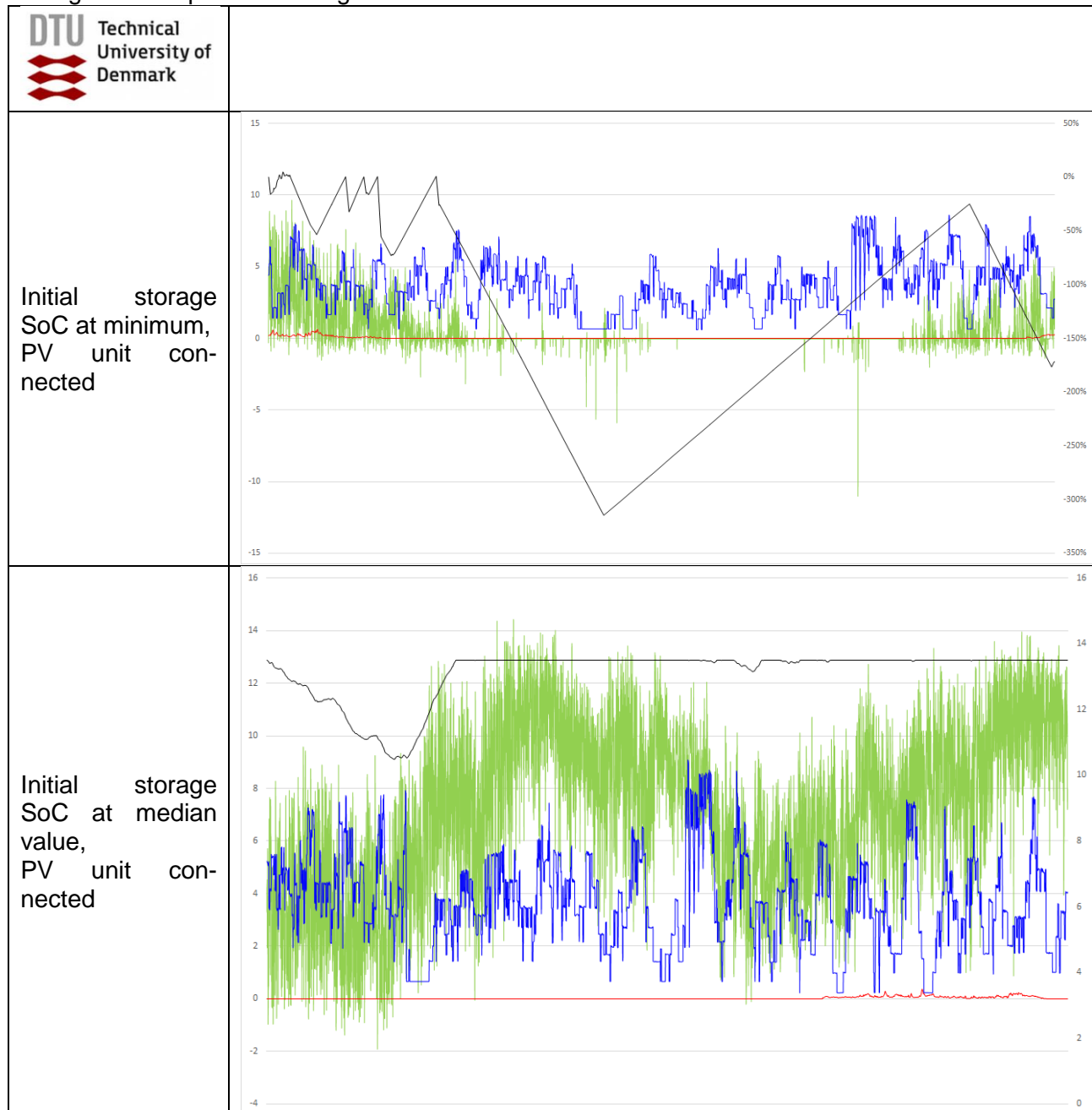


Table 8: Overview of the experiment set carried out at RSE

5.1.3 Output of the experiment set carried out at DTU

In the experiments carried out at DTU a windmill was involved. Colour convention remains as before, adding the wind production in green.



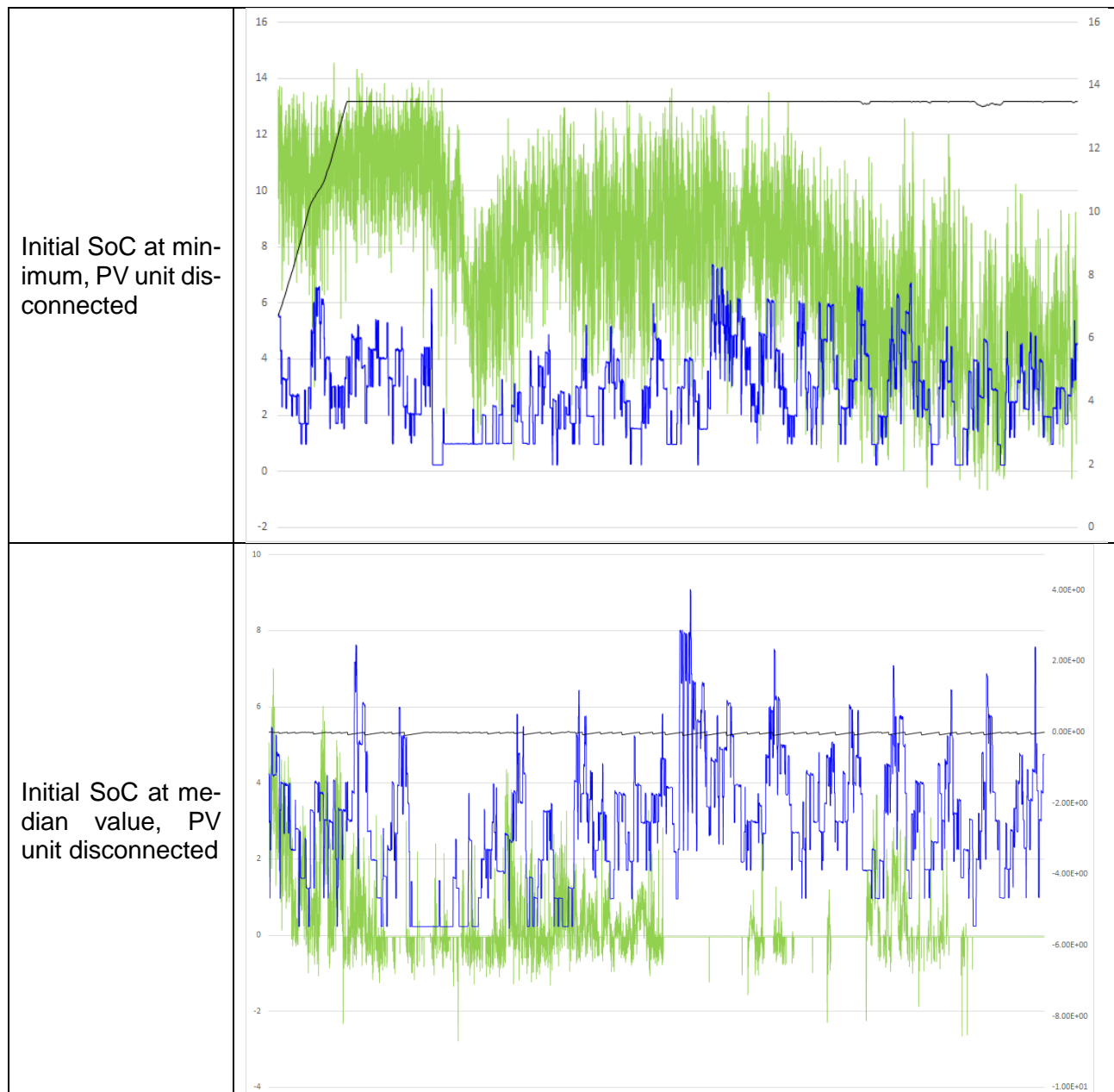
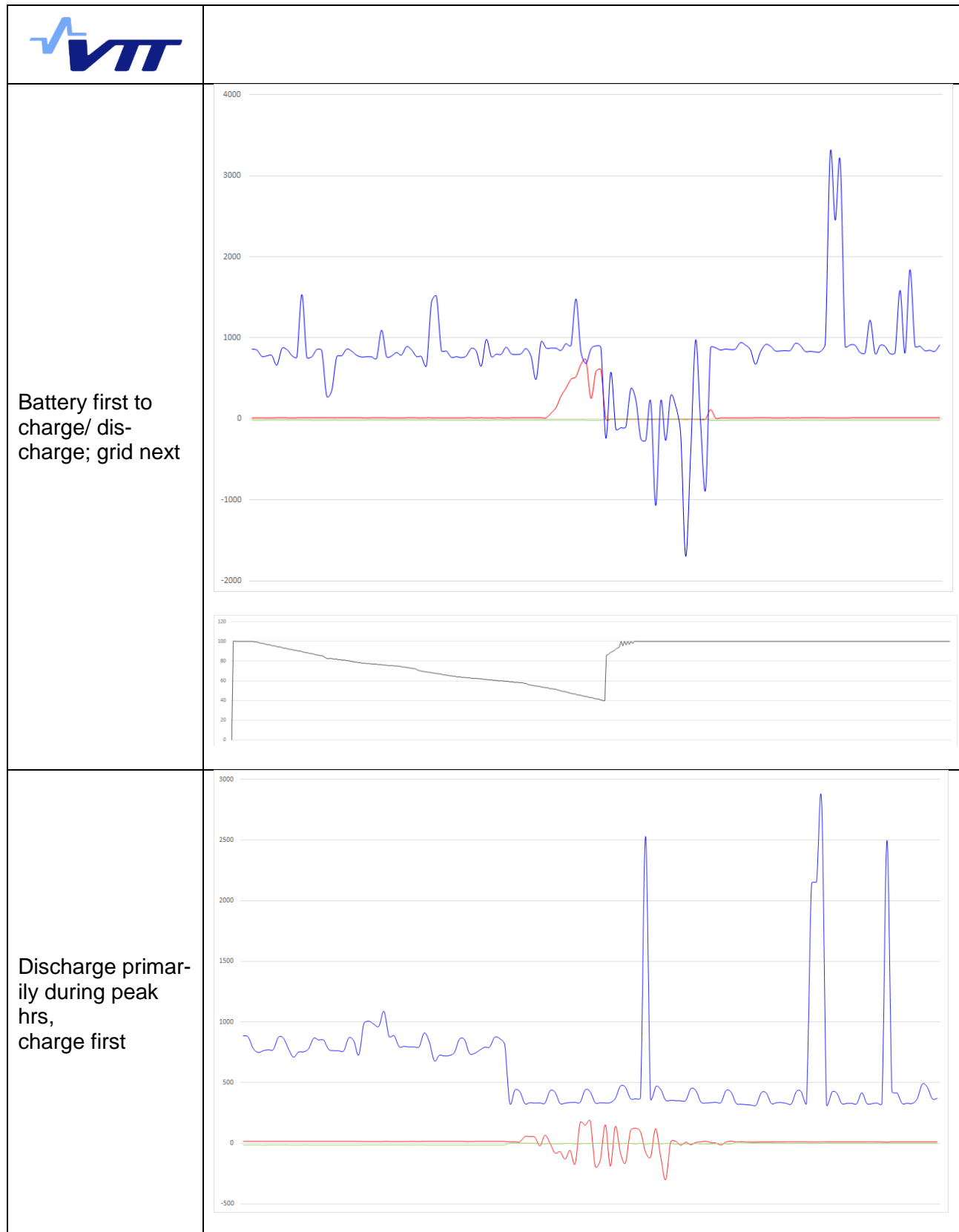


Table 9: Overview of the experiment set carried out at DTU

5.1.4 Output of the experiment set carried out at VTT

In one of the scenarios the electric vehicle was used as an additional load. The curve describing the EV behaviour is coded in magenta (last graph).



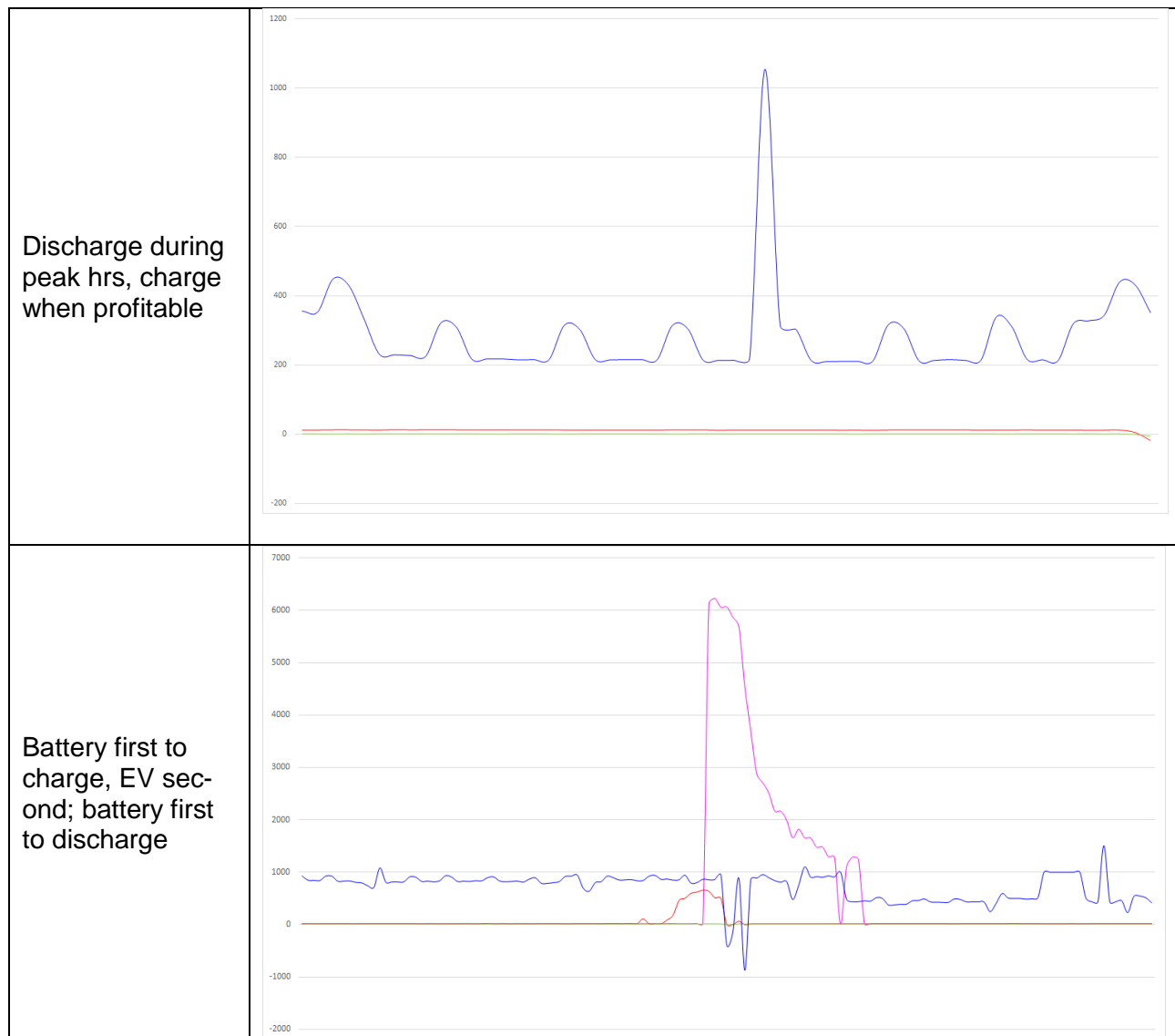


Table 10: Overview of the experiment set carried out at VTT

The battery discharge rate during the first day scenario has been recorded also via direct readings at the panel:



Table 11: Visual exemplification of the battery discharge rate in the first scenario

5.2 Results from the economic survey

During the course of the experiments, economic data was collected, guided by the requirements of the HOMER modelling software. In total, 2 categories of information were collected from each facility. In some of the cases data was incomplete or not provided as of the editing of this report.

- For the determination of CapEx
 - Equipment brand and type (e.g. PV cells: number of cells, type, technology, brand)
 - Year of acquisition
 - Whether the price includes VAT/ discounts
 - Installation costs (specialist installer hourly wage, wire lengths, board, etc)
- For the determination of OpEx
 - Maintenance schedule, if any
 - Maintenance cost
 - Downtime associated with maintenance, if applicable
 - Purchase price for electricity from the main grid

The data was then completed with publicly available information on each country's inflation rate, derating factor, etc.

One particular aspect of the analysis reflects the current ongoing research in economic literature, to which this project is attempting to contribute: the shortcomings of conventional techno-economic analysis. For a relevant and informative analysis it is unavoidable to use dedicated software, which can solve optimization problems specifically for MGs.

However the software (HOMER) assumes the scenario in which an investment is being planned, so all the purchase prices and associated costs are aligned at the value of current year. On the other hand, as it became quickly evident during the TA visits, MG set-ups are rarely built from scratch at once; rather, they arrived at their current form through a sequence of expansions, additions and improvements.

To solve this problem, the solution proposed was to recalculate the price of each equipment based on a derating factor and the number of years since it has been functioning. By doing so, the new price is the effective market price of the respective piece of equipment if it were to be bought second-hand today. Additionally, the lifetime of the project was reduced accordingly.



































Export...		Optimization Results															
Architecture								Cost				System		Compare Economics			
					PV unit (kW)	Diesel (kW)	Storage	Grid (kW)	Converter (kW)	Dispatch	COE (€)	NPC (€)	Operating cost (€)	Initial capital (€)	Ren Frac (%)	IRR (%)	Simple Payback (yr)
					4,20			999.999		CC	€ 0,0326	€ 4.662	-€ 133,25	€ 5.860	65,4	11	6,6
					4,20		10	999.999	0,0187	CC	€ 0,0378	€ 5.402	-€ 132,23	€ 6.591	65,5	8	7,5
								999.999		CC	€ 0,0700	€ 6.745	€ 750,06	€ 0,00	0		
							10	999.999	0,0187	LF	€ 0,0777	€ 7.486	€ 751,15	€ 730,66	0,121		
					4,20	10,0		999.999		CC	€ 0,0553	€ 7.905	-€ 574,25	€ 13.069	65,4	4	11
					4,20	10,0	10	999.999	0,0187	CC	€ 0,0605	€ 8.645	-€ 573,23	€ 13.800	65,5	3	12
						10,0		999.999		CC	€ 0,104	€ 9.988	€ 309,05	€ 7.209	0		
						10,0	10	999.999	0,0187	LF	€ 0,111	€ 10.729	€ 310,15	€ 7.940	0,121		

Figure 11: Example of TEA results carried out on the equipment from CRES after price adjustments

In Figure 11 the analysis is carried out for all (feasible) combinations of equipment and the economic performance is compared against the benchmark highlighted in green, namely the purchase of electricity from the main grid only. The combinations are listed in ascending order of their net present cost (NPC), and the first result of the analysis is that the configuration with the lowest NPC (best economic performance) is the one involving only PV panels and a connection to the main grid. Incidentally, this configuration also has the lowest payback period PBP of 6.6 years, and a high fraction of renewable energy used (65.4%).

Using the same method, similar analyses was carried out on the equipment from of VTT in Oulu, Finland, as shown in Figure 12.

Optimization Results													
Architecture								Cost		System		Compare Economics	
	PV (kW)	G1	LA ASM	Grid (kW)	SolaX10 (kW)	Dispatch	COE (€)	NPC (€)	Operating cost (€)	Initial capital (€)	Ren Frac (%)	IRR (%)	Simple Payback (yr)
				999.999	10,0	CC	€ 0,158	€ 6.854	€ 648,63	€ 0,00	0		
	21,0			999.999	10,0	CC	€ 0,125	€ 24.716	-€ 1.935	€ 45.160	88,1		
	21,7		12	999.999	10,0	CC	€ 0,125	€ 24.983	-€ 1.974	€ 45.843	88,5		
	21,0	1		999.999	10,0	CC	€ 0,134	€ 26.606	-€ 1.957	€ 47.285	89,1		
	21,7	1	12	999.999	10,0	CC	€ 0,133	€ 26.878	-€ 2.001	€ 48.022	89,5		
			12	999.999	10,0	CC	€ 0,825	€ 35.834	€ 650,02	€ 28.966	0,105		
		1		999.999	10,0	CC	€ 0,861	€ 37.495	€ 616,36	€ 30.982	7,75		
		1	12	999.999	10,0	CC	€ 0,866	€ 37.684	€ 618,58	€ 31.147	7,73		

Figure 12: Example of TEA results carried out on the equipment of VTT from Oulu after price adjustments

In the Finnish example the option with the lowest NPC is the connection to the main grid. However the next best alternative includes the solar panels and, even with a significantly higher NPC, it provides the lowest levelized cost of energy (COE).

The findings at RSE are similar to the ones at CRES, in that the configuration with only a PV unit and a connection to the main grid is the most economically sound one.



















Export...				Optimization Results											
Architecture					Cost				System		Compare Economics				
					PV (kW)	1kWh LA	Grid (kW)	Dispatch	COE (€)	NPC (€)	Operating cost (€)	Initial capital (€)	Ren Frac (%)	IRR (%)	Simple Payback (yr)
					36,0		999.999	CC	-€ 0,0247	-€ 9.549	-€ 1.187	€ 5.800	94,0	24	4,2
							999.999	CC	€ 0,0500	€ 2.659	€ 205,65	€ 0,00	0		
					36,0	10	999.999	CC	€ 0,0285	€ 11.218	-€ 1.128	€ 25.800	94,5	2	19
						10	999.999	CC	€ 0,433	€ 23.053	€ 236,19	€ 20.000	0,127		

Figure 13 : Example of TEA results carried out on the equipment of RSE

However in the Italian case the fraction of renewable energy is the highest so far, making the PV unit especially useful.

5.3 Conclusions and further research

The economic results indicate that comparison based on TEA between different set-ups is possible and will be informative. On the other hand, the results from the experiment sets suggest how economic efficiency might be improved through an adjustment in the operation scenario of the microgrid.

These are two of the research questions that are being investigated for the next research papers, which are due to be published as part of my PhD.

However the results of the experiment, which are being made public with this report, are examples which could perhaps support the exchange between smart grid facilities in the efforts toward standardization.

Open Issues and Suggestions for Improvements

The experiment sets have been operated by the ERIGrid representatives from the respective facility and have run according to plan. It was to expect for lengthy experiments to come with small impediments along the way, such as an unexpected interruption in data transmission, an aberration in the registering of measurement data or a sudden spike in voltage triggering the disruption of the system.

6 Dissemination Planning

User Group is considering publishing these results in open-access journals such as *Energies* and to disseminate them at academic workshops and conferences.

The results of this work will also be used in the courses taught on 'Energy economics' and 'Electricity economics' at the Applied Economics faculty of Universiteit Antwerpen.

Individual dissemination methods can include individual e-mails, blogs, newsletters, policy briefs.

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8 Annex

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8.3 Annex 1

Preliminary reports as presented to each facility within one month after the completion of the stay (attached).

8.4 Annex 2

Collection of test specification sheets (attached).