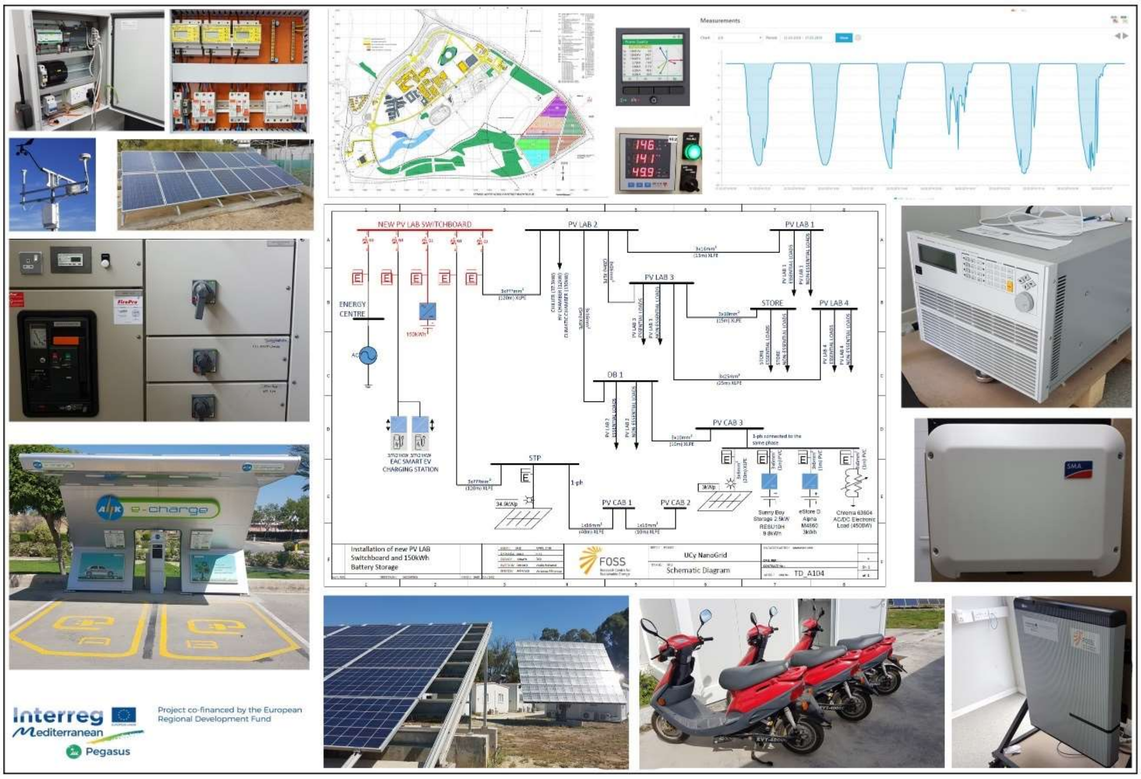
UNIVERSITY OF CYPRUS
PEGASUS Microgrid

Technical and economical evaluation of the FOSS microgrid at the campus of University of Cyprus



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1. Introduction

This report documents the technical and economical evaluation of the pilot microgrid at the University of Cyprus.

The microgrid is located at the FOSS premises, within the campus of University of Cyprus and it is used as a testbed for the University campus microgrid. The target is to transform the large campus of University of Cyprus into a self-consumption controllable microgrid, which will be fed by PV and central and distributed energy storage systems. The campus microgrid will be able to operate either grid-connected, offering at the same time the possibility for ancillary services to the DSO, or isolated in case of a grid fault or other operational necessities.

In order to design the campus microgrid, initial simulation tests are carried out by using commercial software. During the simulation work, exhaustive tests on the already existing system complemented with the new equipment purchased through Pegasus are conducted at the smaller microgrid at FOSS premises to validate results and assist the simulated analysis work.

2. The FOSS microgrid

The microgrid under test, has a 34.9 kWp PV production and the main electrical consumption consists of the building loads (air-conditioning units, lighting, two refrigerators, office equipment, etc.). Apart from the existing loads and systems, new equipment that has been installed includes a programmable electrical load to facilitate alternative load capabilities and emulation of residential consumption profiles, a smart EV charging station and a 10 kWhr battery storage system with a dedicated energy management system, controllable and uncontrollable load of the FOSS lab and a central software management system for data collection, analysis and reporting capabilities.

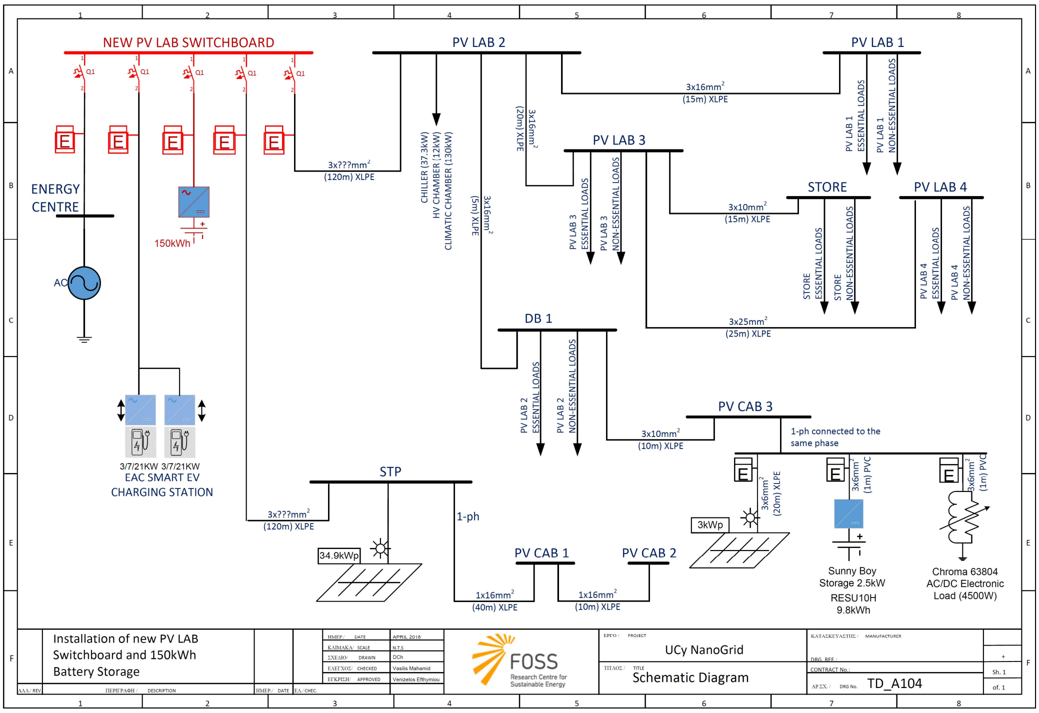

Figure 1: Single Line Diagram of FOSS microgrid

Therefore, the measurements concern the active and reactive power (imported and exported), voltage magnitude for each phase and frequency. For this reason, three new smart bidirectional meters have been installed together with other complimentary sensors and accessories to ensure adequate observability. Figure 1 provides the details about the constituent parts of the FOSS microgrid as it is has become after the installation of a new central AC distribution board. It must be noted that the latest simulations have been done with this layout.

The main components of the microgrid are the following:

- Three-phase symmetrical MV grid
- A central switch for the connection with the main grid (Point of Common Coupling – PCC)
- Active/Reactive power meters
- 150kWh central battery storage system
- Battery emulating the EV charging station
- PV systems installed within the FOSS premises
- Buildings within FOSS:
  - PV Lab 1
  - PV Lab 2
  - PV Lab 3
  - PV Lab 4
  - DB_1
  - Store
- The nanogrid, which consists of a small single-phase PV system, a battery and a controllable load

The several loads with the respective cable connections are also shown at the single line diagram, as it is presented in Figure 1. In this Figure, there are also depicted the characteristics of the EV charging station. The nominal power of the PV system is 34.9kWp.

The nanogrid consists of the following:

- Single-phase PV system of 3kWp
- Battery Energy Storage System of 9.8kWh
- Controllable load of 4.5kW

The load types within the FOSS microgrid are as follows:

- 13 A/C Units for both Cooling and Heating
- 25 PCs
- 1 fridge
- 1 EV charging station
- Necessary office loads of 5 buildings (lights, sockets, etc.)

3. Software used for simulation work DigSILENT PowerFactory

In order to evaluate the FOSS microgrid pilot from technical point of view, the DigSILENT PowerFactory software was used. Regarding the economic evaluation of the microgrid, a Cost-Benefit Analysis (CBA) is carried out, considering the current regulatory system in Cyprus.

The DigSILENT PowerFactory is a leading power system analysis software application for use in analysing generation, transmission, distribution and industrial systems. It covers the full range of functionality from standard features to highly sophisticated and advanced applications including windpower, distributed generation, real-time simulation and performance monitoring for system testing and supervision. It combines reliable and flexible system modelling capabilities with state-of-the-art algorithms and a unique database concept. Also, with its flexibility for scripting and interfacing, it is suited to highly automated and integrated solutions in business applications.

Complex studies for the integration of renewable generation into electrical networks are one of the key issues of nowadays network planning and analysis. PowerFactory combines extensive modelling capabilities with advanced solution algorithms, thereby providing the analyst with tools to undertake the full range of studies required for grid connection and grid impact analysis of photovoltaic (PV) plants and all other kind of power park modules using renewable energies:

- Steady-state load flow calculations considering voltage-dependent reactive power capability limits, power park controllers with setpoint characteristics, etc.
- Short-circuit calculation acc. to IEC 60909 (incl. 2016 edition)
- Power quality assessment according to IEC 61400-21, plus capability to consider frequency-dependent Norton equivalents
- Balanced and unbalanced stability and EMT analysis
- Models for all established generator/converter types, controlled shunts and STATCOMs
- Dynamic models acc. to IEC 61400-27-1 and WECC
- Model frequency response analysis (Bode and Nyquist Diagrams)
- Interface for real-time measurement data from DIgSILENT monitoring system PFM for online grid code compliance supervision or model validation

The circuit designed in DigSILENT PowerFactory software has been tested for the steady-state, transient and dynamic operation as per the above models.

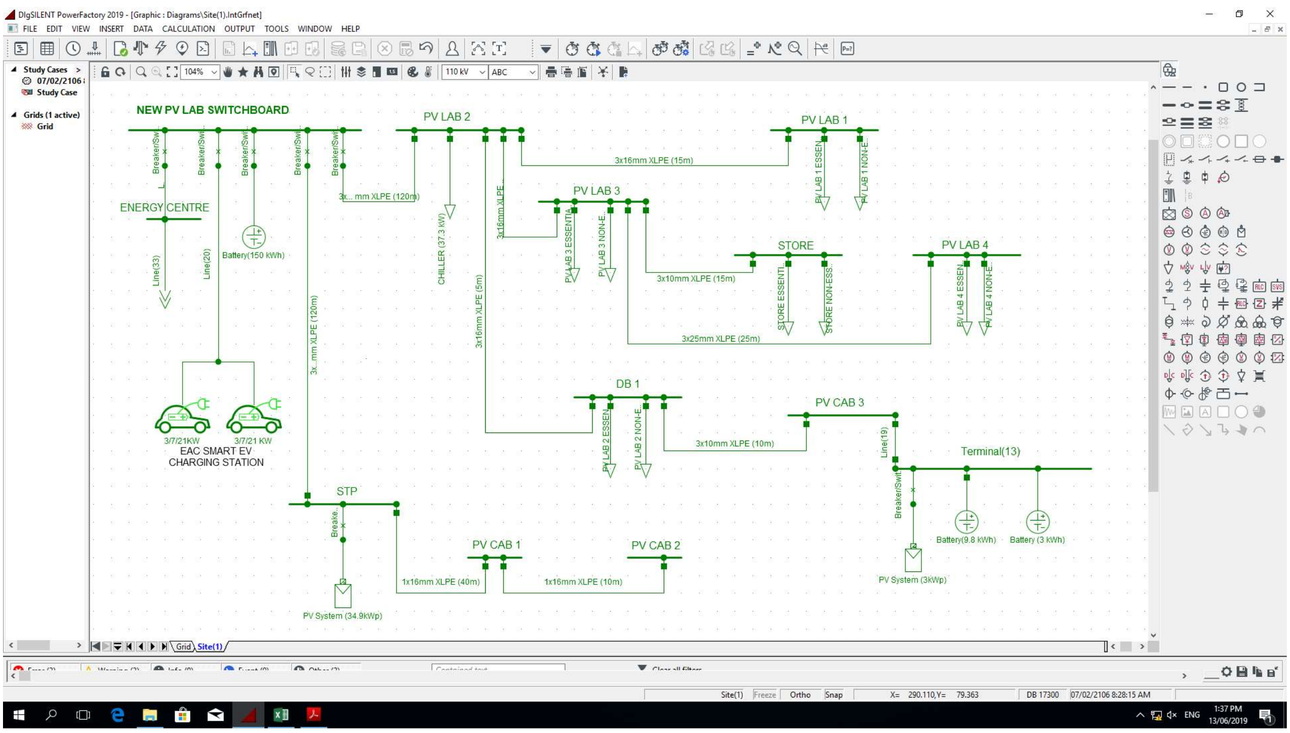

Figure 1 FOSS DigSILENT model

4. Economical evaluation of the microgrid

The simulation studies conducted in support of the techno - economic study presented in this report are described in detail in the earlier submitted report “Description of the adopted methodology for data processing (including first results)”.

The objective of the economic analysis is related to the current operation of the FOSS microgrid. The viability and the feasibility of a microgrid with PV intermittent generation and Battery Energy Storage System is studied, while the billing scheme followed in this analysis is the net-billing scheme, which is the actual tariff agreement with the local supplier and is described in Annex 1.

In this section a cost benefit analysis of the FOSS microgrid pilot is evaluated and the extended data acquisition of the PEGASUS pilot project is used in order to enhance the reliability of the followed approach and contribute to the correct sizing of the equipment.

4.1 Electrical Consumption

In order to perform the Cost-Benefit Analysis (CBA), the electrical consumption of the FOSS microgrid is initially presented. For this reason, electricity consumption and demand profiles have been extracted based on measurements provided by the PEGUSUS smart meter at the point of common coupling., with a 15-minute interval, for the period July 2018 to June 2019. The load profile has been analysed based on the following classification: Working days, from Monday to Friday, and non-working days, such as public holidays, Saturdays, Sundays and non-office days. The analysis considers these two basic classifications in order to distinguish all the possibilities of the consumption profiles. The current and future average daily electricity consumption of the University campus under these classifications can be seen in Figure 4, where a consumption peak in August is obvious. The reason behind the peak is the type of electrical loads, which mainly consist of electrical cooling, due to high temperatures in Cyprus and the occupancy of the offices in this period. The high consumption period is within the summer months June-to September. The second peak period is during the cold months between January and March in which period electric heating is used.

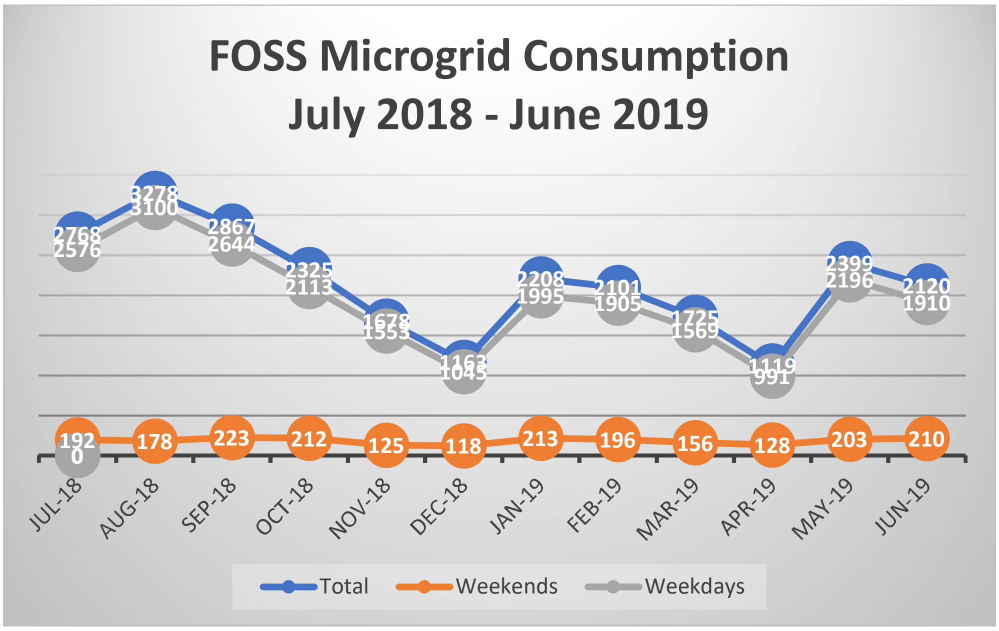

Figure 4 Current average daily electricity consumption of the microgrid

4.2 PV energy production

In this report, actual measurements from the existing PV installation are used as shown in Figure 5, where the monthly yield of the 34.9kWp PV installation is shown. It must be noted that the capacity of the PV installation is larger that what is required by the actual load. This has been installed for research purposes where different technologies are investigated. For the cost and benefit analysis purposes the optimum size of PV installation for the specific microgrid consumption shall be examined. The same applies for the storage in which case it is well understood that the 150 kWh battery capacity is much bigger than the one required, but it is to be installed for testing purposes.

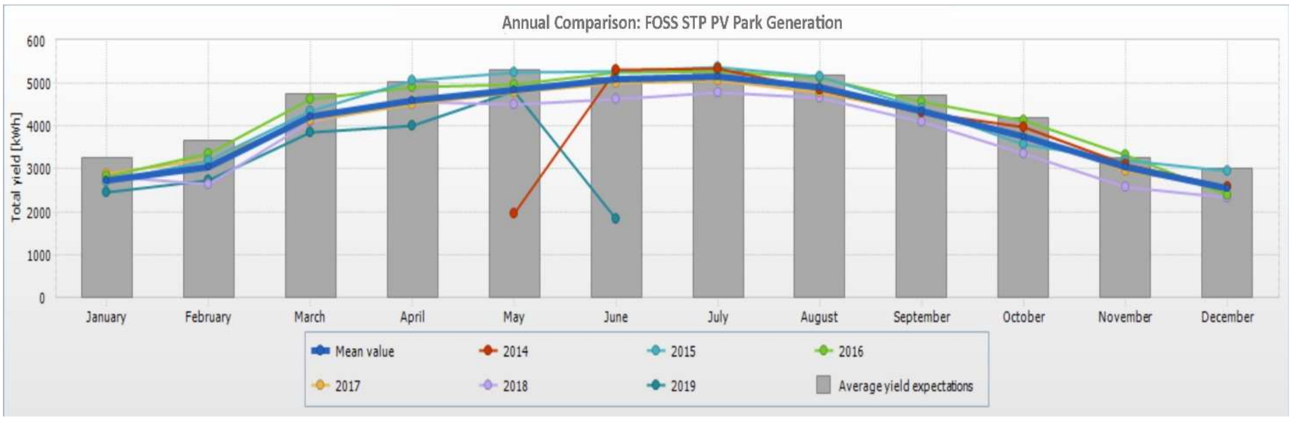

Figure 5 Monthly yield from the 34.9kWp PV installation

4.3 Optimization strategy

The optimization method decides the optimum BESS size that will minimize the costs of the electricity bill for the FOSS microgrid. The BESS is generally charged during periods that PV generation exceeds the microgrid loads, in order to maximize the self-consumption and minimize grid purchases during peak hours. In order to find the most feasible investment option, different BESS sizes are considered.

Table 1 Monthly energy analysis of FOSS Microgrid

Month	Consumption (kWh)
January	2,208
February	2,101
March	1,725
April	1,119
May	2,399
June	2,120
July	2,768
August	3,278
September	2,867
October	2,325
November	1,678
December	1,163
Annual	***25,751***

4.4 Profitability Results and sensitivity analysis

The economic profitability analysis considers the initial investment phase of the microgrid. Different configurations have been studied, namely:

- No PV, no Storage
- PV, no storage
    - 10 kWp PV
    - 15 kWp PV
    - 20 kWp PV
    - 30 kWP PV
- PV & storage
    - 30 kWh Storage
    - 50 kWh Storage

The results of the studied configurations for the initial phase of investment can be seen in the Table below:

Table 2 Monetary saving of assessed microgrid configurations

Description	Annual energy cost in €	PV in kWp	Storage in kWh	Savings in €	Capital cost in €	Payback period in years
Without PV & S	5.291	-	-	-	-	-
With PV (without S)	2.983	10	0	2.308	10.000	5 years
With PV & with S	2.634	10	30	2.657	22.000	12 years
With PV (without S)	1.709	15	0	3.582	15.000	5 years
With PV & with S	1.089	15	50	4.202	35.000	13 years
With PV (Without S)	1.592	20	0	3.699	20.000	6 years
With PV & with S	980	20	50	4.310	40.000	14 years
With PV (without S)	1.547	30	0	3.744	30.000	10 years
With PV & with S	968	30	50	4.323	50.000	19 years

The 15 kWp without storage is the optimal investment for the PV park since it is generating adequate energy to meet the annual demand: 25.213 kWh generated to meet a demand of 25.751 kWh. Together with 50 kWh of storage the payback period is 13 years but without any added benefits that are referred to below. Hence, the PEGASUS microgrid delivers results that evidently contribute to improved management of local resources and generate flexibilities that can offer valuable services to the local grid of the DSO. The sizes used for generation and storage at the PEGASUS grid are oversized to offer the added needs of the PV lab of the university in meeting research objectives.

4.5 Benefits for the DSO

Energy demand of the system is expected to be increasing year by year and may lead to blackouts, or failures. The increasing load demand leads to increased grid congestion or increased voltage drop, while the opposite effect of voltage increase may happen in case of injecting a high PV production directly into the grid. If an operational limit (such as thermal limit of the line) is reached, new investments on network components are needed to mitigate this issue. The presence of distributed generation and energy storage within the microgrid can reduce the maximum load demand, thereby extending the life cycle of grid components. This allows a deferral of grid investments to the future, with associated benefits to the DSO. Since maximum demand occurs only a few hours per year, the microgrid operation can provide a reliable way to avoid Transmission and Distribution grid reinforcements by relieving peaks in demand, compensating for large feed-in from renewables and generally helping to balance the system and stabilize the grid. An estimation of the financial gains can be made, based on the assumption that the estimated grid investments of the DSO are avoided.

A first estimation of the financial gains is modelled by the difference in maximum peak demand between the Basic Load Curve, and the Resulting Load Curve after the operation of the microgrid. The equation used to estimate the ratio of investment savings is the following:

$$PD_{ratio} = \frac{PD_{RLC}}{PD_{BLC}} \qquad (1)$$

where PD_{BLC} is the peak demand of the base scenario curve, PD_{RLC} is the peak demand of the load curve after the microgrid operation and PD_{ratio} is the ratio between the maximum values of the two load curves.

In Table 3, the results of the whole campus are presented as an indication of the benefits that can be achieved through the achievable peak reduction. The whole campus is used since results are available and thus the evaluated benefits can be monetised and compared. The whole campus microgrid operation allows internal DG sources and BESS to reduce the peak demand of the campus at the PCC. A peak demand reduction of at least 3.08% is achieved in year 2019 and a peak demand reduction of 6.45% is achieved in year 2023. The load curve is reshaped, and peak demand is maintained at the same level for the whole investment period. Taking into account that the average annual load growth in Cyprus ranges at 1.5%, this reduction in peak grid loading allows distribution network investment and upgrade costs to be deferred for the 20-year planning horizon of the investment.

In order to estimate the financial benefits of the differed grid investments, economic data of the DSO of Cyprus regarding the Transmission and Distribution Network development, upgrade and maintenance costs from 2012 to 2016 were examined. These costs range from 16.86 to 50.26 million € per year, resulting to average annual costs of 31.34 million €. To obtain typical figures, the estimated upgrade cost of the distribution grid of Cyprus was taken into consideration and the average marginal grid investments per total system capacity were used as an approximation for the cost per megawatt of investments. Thus, it was estimated that the microgrid operation results to annual grid deferral savings of 21,200 € per year.

The postponed future grid investments in 20 years are then valued and discounted over the years in order to obtain a NPV. The NPV of all the postponed investments is calculated using the total cost of the planned grid investments for the scheduled year i and the interest rate as follows:

$$NPV_{inv} = \sum_{i=1}^{20} \frac{C_i}{(1+r)^i} \qquad (2)$$

where NPV_{inv} is the NPV of all the postponed investments, C_i is the value of the postponed investment of the i^{th} year and r is the discount rate that refers to the interest rate used in cash flow analysis to determine the present value of future cash flows.

Furthermore, reduced grid losses, which can be represented by the difference between the grid losses before and after the microgrid operation, have a potential to represent savings in monetary terms for the DSO. Total savings from avoided PV generation grid losses take into account the system availability and grid connection power losses (ηPPC) that are saved due to increased self-consumption of the PV generated energy. These losses, based on grid data of the past 5 years, range on average at 4.42% in the island of Cyprus. The annual financial benefit of the avoided distribution losses is calculated as follows:

$$\pi_{losses} = \sum_{d=1}^{365} [\eta_{PPC} * PV'_{cons_i} * P_{PV}] \qquad (3)$$

where P_{PV} is the wholesale electricity price that is offered by the utility for the energy that is sold to the grid and PV'_{cons_i} is the amount of PV generation that is directly consumed or stored by the microgrid in a single day.

Reducing the losses through the microgrid operation, provides the DSO with an economical incentive to support microgrid integration if the benefits are significant enough. The function that expresses the NPV of the DSO profit is formulated for the 20-year period year using the following equation:

$$NPV_{DSO} = NPV_{inv} + \sum_{i=1}^{Y} \frac{\pi_{losses} + PV_{excess}}{(1+r)^i} \qquad (4)$$

where PV_{excess} is the annual amount of PV generated energy that is fed back to the grid without compensation.

Table 3 Peak demand before and after of the whole campus microgrid operation in years 2019 and 2023

Month	2019			2023		
	PD_{BLC} (kW)	PD_{RLC} (kW)	PD_{Ratio} (%)	PD_{BLC} (kW)	PD_{RLC} (kW)	PD_{Ratio} (%)
January	424.49	411.33	96.90	891.3	822.7	92.30
February	485.33	470.30	96.90	1160.0	1044.2	90.02
March	465.49	443.85	95.35	1046.0	942.2	90.08
April	483.28	439.65	90.97	1127.6	928.1	82.30
May	645.46	563.97	87.35	1316.3	1130.9	85.92
June	777.42	624.58	80.34	1421.8	1044.3	73.45
July	792.83	690.30	87.07	1291.7	1158.7	89.70
August	684.89	532.45	77.74	1036.6	757.9	73.11
September	736.11	604.83	82.17	1573.8	1319.7	83.86
October	650.71	600.98	92.36	1336.7	1237.0	92.54
November	512.31	496.51	96.92	1101.9	1027.0	93.20
December	462.11	447.83	96.91	919.7	860.34	93.55

The operation of the microgrid results in monetary benefits of 1,002,282.4 € for the DSO. Since there is size difference between the that of the whole campus microgrid and the microgrid of the PV lab under investigation through PEGASUS, of approximately 1000 times smaller the gains through the PEGASUS microgrid are expected to be of the order of €1.000. The gains obtained under this scenario are derived from the reduction of distribution grid losses and the deferral of grid investments. It is assumed in this study that the DG and BESS investment can be a direct substitute to the "wires and poles" assets; thus, the same discount rate has been applied to both cases. Nevertheless, it is apparent from the obtained results that the microgrid operation would be both beneficial and profitable for the DSO.

5. Conclusions

In this report, the economic evaluation of the FOSS microgrid case is examined. The technical evaluation has already been presented in the report "Description of the adopted methodology for data processing (first results) and the paper "Promoting Effective Generation and Sustainable Uses of electricity (PEGASUS) – The case of the FOSS lab area nanogrid".

The representative simulation tests presented the steady-state, transient and dynamic operation of the microgrid. Moreover, the different operational schemes (grid-connected, islanding, transition among different operations) were analysed.

The Simulations show that the microgrid is capable of both grid-connected and islanded operation. In the grid-connected operation mode, the control strategy is based on the optimization of self-consumption and the maximization of self-sufficiency of the microgrid. In the islanded operation mode, the aim of the microgrid control strategy is to provide a stable and high-quality power supply to the connected loads. Proper power balance and voltage control is achieved by ensuring that frequency deviations are restrained among certain allowable limits. Furthermore, transition between grid-connected and islanded modes is simulated. Islanding does not require any additional measures as the islanded control strategy is sufficient enough for a seamless transition. For transition from islanded to grid-connected mode, which is a planned event, a synchronization procedure is developed. A smooth mode-transmission is achieved by modifying certain parameters of the BESS, and consequently the microgrid, with a synchronization procedure to connect the islanded microgrid with the utility.

The viability and the feasibility of a microgrid with PV intermittent generation and Battery Energy Storage System is studied, while the billing scheme followed in this analysis is the net-billing scheme, which is the actual tariff agreement with the local supplier and is described in Annex 1.

A cost benefit analysis of the FOSS microgrid pilot is evaluated and the extended data acquisition of the PEGASUS pilot project is used in order to enhance the reliability of the followed approach and contribute to the correct sizing of the equipment. The results show that 15 kWp without storage is the optimal investment for the PV park since it is generating adequate energy to meet the annual demand. The fact that the installed capacities are larger than the ones that the cost and benefit analysis show is only contributed to the fact that FOSS microgrid is the University of Cyprus experimental microgid used as a testbed for many other projects and additionally to the design of the microgrid on the UCY campus.

Annex 1 Pricing Schemes

Net-Billing tariff

The energy bill payment of the university is estimated using predefined Time of Use (ToU) tariffs. There are several consumption tariffs and eight different price periods (P1-P8), that are based on the definition of different electrical seasons and type of days. Table I shows the ToU tariffs, the hourly energy price and the fixed power fees, including taxes, that are paid by the University.

Table 1 ToU tarriffs applied to the UCY electricity bill

Months	Days	Hours	Price Periods	Energy Price (€ kWh^{-1})	Fixed Fee (€)
October to May	Monday to Friday	16:00 – 23:00	P1	0.1783	0.086 per day
		23:00 – 16:00	P2	0.1644	
	Weekends	16:00 – 23:00	P3	0.1738	
		23:00 – 16:00	P4	0.1605	
June to September	Monday to Friday	09:00 – 23:00	P5	0.2229	
		23:00 – 09:00	P6	0.1745	
	Weekends	09:00 – 23:00	P7	0.1771	
		23:00 – 09:00	P8	0.1719	

The pricing scheme of this report takes into account the addition of a net-billing service on top of the ToU pricing scheme. Thus, all the PV electricity injected into the grid is remunerated at the avoided generation cost, but energy not injected in the grid and it is self-consumed the following costs should be paid net billing charge for the grid services, green tax and public service obligation.

Public service obligation in € cents / kWh (self or purchased)	0.083
Green tax in € cents / kWh (self or purchased)	1.00
VAT applied on all traded energy (exported or imported)	19.00%
Net billing charge for all energy self-consumed in € cents per kWh	1.63
RES cost – Avoidance cost in € cents/kWh	12.11