European
Commission

Clean energy for EU islands: North Sporades virtual microgrid

Skiathos, Skopelos, and Alonnisos, Greece

North Sporades virtual microgrid

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Introduction

The Northern Sporades are an archipelago in the Aegean Sea along Greece's east coast, northeast of the island of Euboea. It consists of 24 islands, four of which are permanently inhabited: Alonnisos, Skiathos, Skopelos, and Skyros. The islands Skiathos, Skopelos, and Alonnisos (forming the North Sporades archipelago) are interconnected, and Skiathos is also interconnected to the mainland.

A 150/20kV substation of Skiathos with 2x40/50 MVA rating capacity is connected to the mainland's high voltage grid with 30km of 150kV underground and submarine cables. The three North Sporades islands are connected. Six medium voltage (MV) cables totalling 28.7 MW in capacity connect Skopelos to the mainland electrical grid through the nearby island of Skiathos. A total of two MV cables with a combined capacity of 12.2 MW connect Skopelos and Alonnisos (Figure 1). Archipelago still has an older MV interconnection with the mainland from Pelion to Skiathos Island.

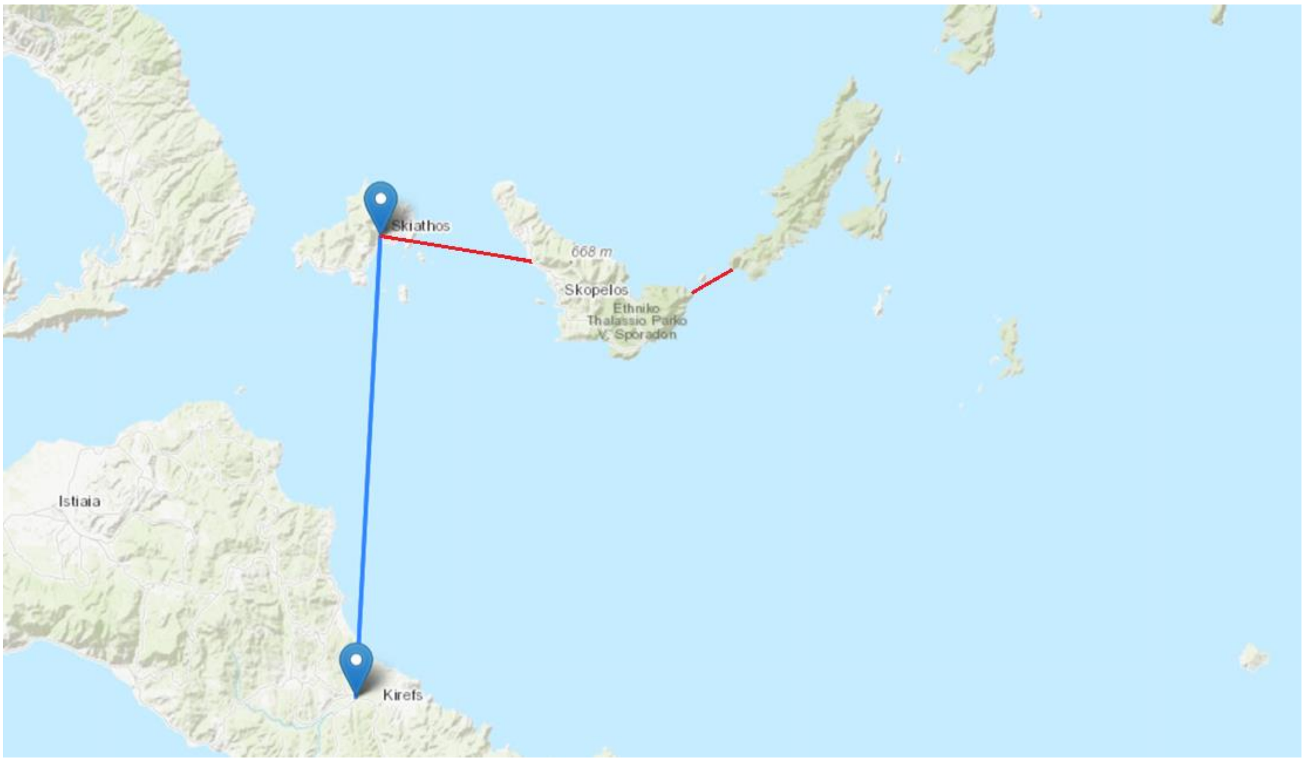


Figure 1: Site location and tie-lines

There are problems with communication and stability on the islands. Additionally, the cost of energy has recently increased significantly for both people and municipalities. All of this has led to the inspiration to encourage the use of solar photovoltaic energy to supply disadvantaged homes and municipal loads with clean energy.

As part of the North Sporades Virtual Microgrid project, the Islands secretariat provided technical assistance with the following tasks:

Task 1: The system will need to include batteries to boost self-consumption and stability in the presence of uncertain PV productions and power disruptions. To complement the solar PV installation that is planned for the islands, in this report, a **hybrid PV plus battery sizing optimization**

problem is solved at the island level to maximize self-consumption and self-sufficiency while preserving grid capacity constraints.

Task 2: All the assets could be interconnected to work together on a single platform in a unified blockchain market. As the first step, the Islands secretariat will first give a **background explanation of peer-to-peer networks, the future of peer-to-peer trading, and an outline of its difficulties as part of the North Sporades Virtual Community project**. After that, a **SOTA analysis and a conceptual design for a peer-to-peer energy market in the archipelago are discussed**. The following fundamental capabilities will be looked at:

- Market functioning;
- Energy management system;
- Pricing mechanism; and
- Information system.

The technical assistance from the secretariat includes the following:

1.1. Sizing of battery: Sizing of the battery to be installed to promote the solar PV penetration.
2.1. Peer-to-peer background: Background, future, and challenges of peer-to-peer trading
2.2. Conceptual design and SOTA Analysis: Discussions on core functionalities mentioned above.
2.3. Technical approach discussion: Overall assessment and detailed analysis of each technique
2.4. Regulation overview: Requirements for the participants in peer-to-peer trading

Task 1: Aggregated ESS and PV requirements to enhance self-consumption and self-sufficiency throughout the Sporades islands

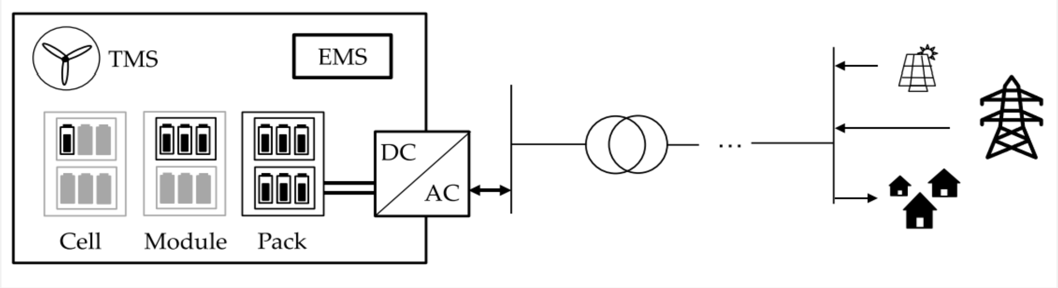
Energy Storage System Technology

The greater the penetration of renewable energy sources in the grid, the greater the need for flexible resources like storage. Storage is needed to stabilise the grid due to the inherent intermittency of the generated power. It is also needed to provide a means for storing energy at peak times so that it can be used during peak demands or when renewable sources are not available.

A formalised schematic drawing of a battery storage system solution, including batteries, power system coupling and grid interface components, is listed in Table 1. This section presents the following sections:

- Feasible and preferred technology options;
- Presentation of the Li-ion battery and its technical features; and
- Basic design of the BESS (Battery Energy Storage System).

Table 1: Formalised schematic drawing of a battery storage system, power system coupling and grid interface components

ID	Battery & Storage System	System Coupling	Grid Integration
Technical	Battery System (Cell, Module, Pack)	Power Electronics (AC/DC)	Application Specific Profile
	Thermal Management (TMS)	Transformer	Local Connection
	Energy Management (EMS)	Environmental Conditions	Grid Level of Integration
Economic	Investment (Batt., Periphery, Casing)	Power Electronics Invest	Profit / Savings via Application
	Degradation and Efficiency	Conversion Efficiency	Stakeholder Involvement
	Sizing & Operation Control	Placement of System	Regulatory Framework
Schematic			

Feasible technologies

In order to select an energy storage option that would be appropriate for the intended application(s), ES-Select is used to score the feasibility of each storage option according to the following criteria calculated as to its data base information:

- Maturity;
- Appropriateness for the selected location (considers availability, mobility, size, weight, scalability, etc.);
- Installed cost in either $/kW or $/kWh basis; and
- Meeting application requirements (considers discharge duration, cycle life, efficiency, etc.).

In Table 2, feasible technology options for solar energy time shift and transmission congestion relief are listed.

Table 2: Feasible technology options for solar energy time shift and transmission congestion relief

Technology	Name	Feasibility score from E-SELECT of DNV
Sodium Nickel Chloride	NANICL	63%
Lithium Ion - High Energy	LIB-e	59%
Hybrid LA & DL-CAP	Hybrid	59%
Valve Regulated Lead Acid	VRLA	54%
Advanced Lead Acid	LA-adv	51%

Based on the ES-SELECT result, NaNiCl has a higher feasibility score than LIB-e. We believe that in terms of reliability, safety, and environmental friendliness, sodium nickel chloride batteries could be considered a good choice for solar PV. However, in terms of performance and cycle life, LIB-e has a competitive advantage.

Technical features

The main technical parameters of a battery are defined below:

- C-rate: A C-rate measures the rate at which a battery is discharged relative to its maximum capacity. A 1C rate means the discharge current will discharge the entire battery in 1 hour. For a battery with a capacity of 100 Amp-hrs, the discharge current is 100 Amps;
- SOC (%): «State of Charge» is the level of charge of an electric battery relative to its capacity. The units of SoC are percentage points (0% = empty; 100% = full) with a safe range of SOCmin and SOCmax;
- SOH (%): «State of Health» is a figure of merit of the condition of a battery (or a cell or a battery pack) compared to its ideal conditions. The units of SoH are per cent points (100% = the battery's conditions match the battery's specifications). SOH at the end of life is assumed to be between 60-80% of the initial capacity as to typical 2-3% degradation per year;
- DoD (%): Corresponds to the difference in SoC between the initial state and the final state of a battery discharge operation;
- Cycle Life: The number of cycles under certain conditions until the battery reaches its end-of-life of typically 70-80% of initial capacity;
- Equivalent full cycle: the number of full cycles performed by the battery system throughout the battery lifetime. More cycles than the Cycle Life can be achieved when the battery is only partially charged and discharged; and

- Round-trip efficiency: Battery efficiency considering both charging and discharging losses. Round-trip efficiency defines the amount of energy recoverable from a storage device relative to the amount initially absorbed.

Lithium-ion batteries include LFP (lithium ferrophosphate), LTO (lithium titanate), NCA (lithium nickel cobalt aluminium), and NMC (lithium nickel manganese cobalt). In 2021, the two leading choices are lithium nickel manganese cobalt (NMC) and lithium ferro (iron) phosphate (LFP).

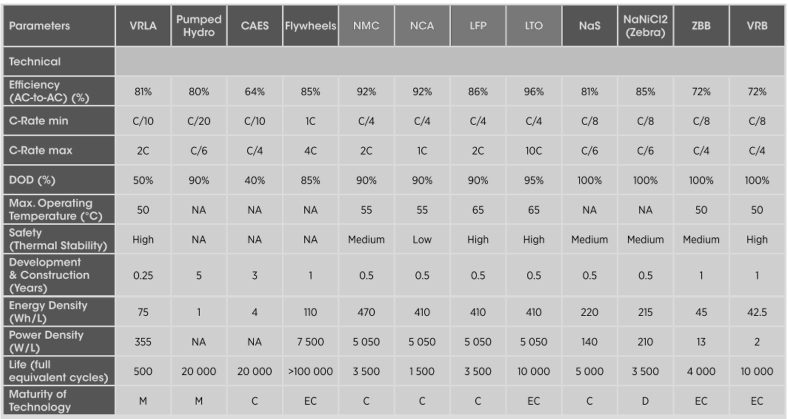
- NMC has energy stored in proportion to weight (with less required space), which also boosts the risk of overheating and thermal failure in high temperatures, which can instantly spread fire from one cell to another.
- NMC is more expensive and only available from a limited number of suppliers.
- LFP will last longer than NMC, even at higher charge/discharge rates. It will lessen the need for replacement during the lifetime of the project.

Compared to other types of batteries, Li-ion batteries present the following features:

- A limited space for equivalent power: a very good density of power and energy, from 200 to 400Wh /dm3 (for cells);
- A possibility to fully charge the battery in shorter times: a large charge power, very close to or even equivalent to the discharge power;
- The virtual absence of memory effect (memory effect = battery performance based on the chronology and fine features of past operations), allowing excellent flexibility of use. It is not necessary to freeze typical operations or to plan specific regular cycling operations to preserve service life and
- Excellent lifetime calendar and cycling.

Sample default values for storage technology mapping are listed in Table 3.

Table 3: Sample default values for storage technology mapping (IRENA Storage Valuation Framework [1])[1]



Parameters	VRLA	Pumped Hydro	CAES	Flywheels	NMC	NCA	LFP	LTO	NaS	NaNiCl2 (Zebra)	ZBB	VRB
Technical												
Efficiency (AC-to-AC) (%)	81%	80%	64%	85%	92%	92%	86%	96%	81%	85%	72%	72%
C-Rate min	C/10	C/20	C/10	1C	C/4	C/4	C/4	C/4	C/8	C/8	C/8	C/8
C-Rate max	2C	C/6	C/4	4C	2C	1C	2C	10C	C/6	C/6	C/4	C/4
DOD (%)	50%	90%	40%	85%	90%	90%	90%	95%	100%	100%	100%	100%
Max. Operating Temperature (°C)	50	NA	NA	NA	55	55	65	65	NA	NA	50	50
Safety (Thermal Stability)	High	NA	NA	NA	Medium	Low	High	High	Medium	Medium	Medium	High
Development & Construction (Years)	0.25	5	3	1	0.5	0.5	0.5	0.5	0.5	0.5	1	1
Energy Density (Wh/L)	75	1	4	110	470	410	410	410	220	215	45	42.5
Power Density (W/L)	355	NA	NA	7 500	5 050	5 050	5 050	5 050	140	210	13	2
Life (full equivalent cycles)	500	20 000	20 000	>100 000	3 500	1 500	3 500	10 000	5 000	3 500	4 000	10 000
Maturity of Technology	M	M	C	EC	C	C	C	EC	C	D	EC	EC

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[1] ZBB: zinc bromine, VRB: vanadium redox, NaS: sodium sulphur, and CAES: compressed air energy storage

Economical features

In short, based on price alone, conducting an apples-to-apples evaluation of storage systems from different suppliers is challenging, if not impossible. Nonetheless, the National Renewable Energy Laboratory (NREL)[2] has made a comparison of battery storage costs from studies published in 2018 or later in Figure 2.

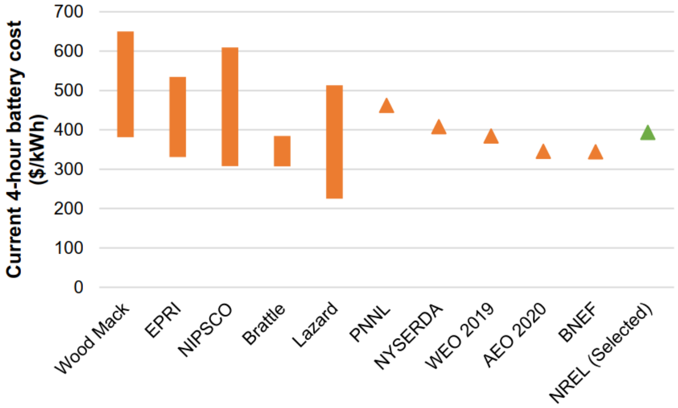

Figure 2 battery storage costs from studies published in 2018 or later (NREL[3])

As to the projected component costs by Bloomberg[4] and NREL significant reductions are expected in the BESS capex (Figure 3).

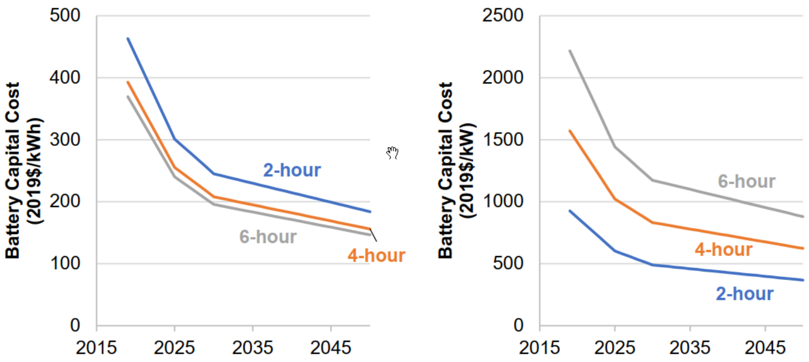

Figure 3 Cost projections for 2-, 4-, and 6-hour duration batteries using the mid cost projection

On a $/kWh basis, longer duration batteries have a lower capital cost, and on a $/kW basis, shorter duration batteries have a lower capital cost. This cost breakdown is different if the battery is part of a hybrid system with solar PV or a stand-alone system. These relative costs for commercial scale stand-alone battery are demonstrated in Table 4.

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[2] https://www.nrel.gov/

[3] https://www.nrel.gov/docs/fy20osti/75385.pdf

[4] Bloomberg New Energy Finance (BNEF). “Energy Storage System Costs Survey 2019,” October 14, 2019.

Table 4: Relative Capital Cost Components for Commercial Building-Scale Battery Systems (NREL[5])

Model Component	$/kWh	$/kW
Lithium-ion battery	192[6]	768
Battery central inverter	15	59
Structural BOS	26	102
Electrical BOS	48	191
Installation labour and equipment	68	272
EPC (engineering, procurement, and construction) overhead	37	148
Sale Tax	18	70
∑ EPC Cost	**403**	**1611**
Land acquisition	0	0
Permitting fee	3	12
Interconnection fee	11	46
Contingency	16	65
Developer overhead	24	97
EPC/developer net profit	22	89
∑ Developer cost	**78**	**310**
∑ Total energy storage system cost	**480**	**1921**

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[5] https://atb.nrel.gov/electricity/2021/commercial_battery_storage#7YHPYQX2

[6] Bloomberg New Energy Finance’s latest report states that current lithium-ion pricing stands at about $137 per kilowatt-hour and will drop as low as $100 per kWh by 2023.

Battery Energy Storage Simulations

Block diagram of the power flows in the network is presented in Figure 4.

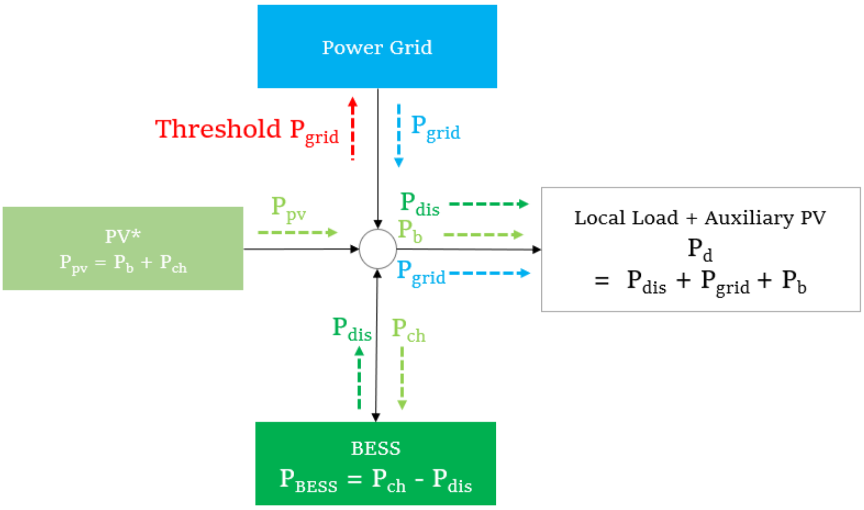

Figure 4: General diagram of the power flows

Methodology

The storage capacity is dispatched in such a way as to increase self-consumption and self-sufficiency of the plant as proposed by the Client. The investigation focuses on a typical grid-connected PV system with a local load and an optional energy buffer. Four components must follow additional rules:

- Locally available energy always has the priority over grid;
- Battery, when not empty, is capable to satisfy instant power demand;
- Battery is charged only from excess of PV energy and never from grid; and
- PV energy excess is curtailed only when battery is full.

The presence of the battery introduces an intermediate layer corresponding to autonomous operation; thus, grid and battery are never used together. If solar power exceeds the load demand, the battery is charged and feeding to the grid is not possible even when battery is full. If solar power cannot satisfy the load demand and battery is not empty, the load is still supplied from local sources only. Fluctuations of irradiance and load demand trigger the transitions among all the states, and there are many paths within the diagram the system may take throughout the day.

The operation of different PV + storage configurations is simulated. As no specific services are defined (for example PV smoothing or frequency support), the proposed operating scheme is based on the constraints below:

- Feed zero in the grid; and
- Maximise self-consumption and self-sufficiency.

Methodology of the study in presented in Figure 5.

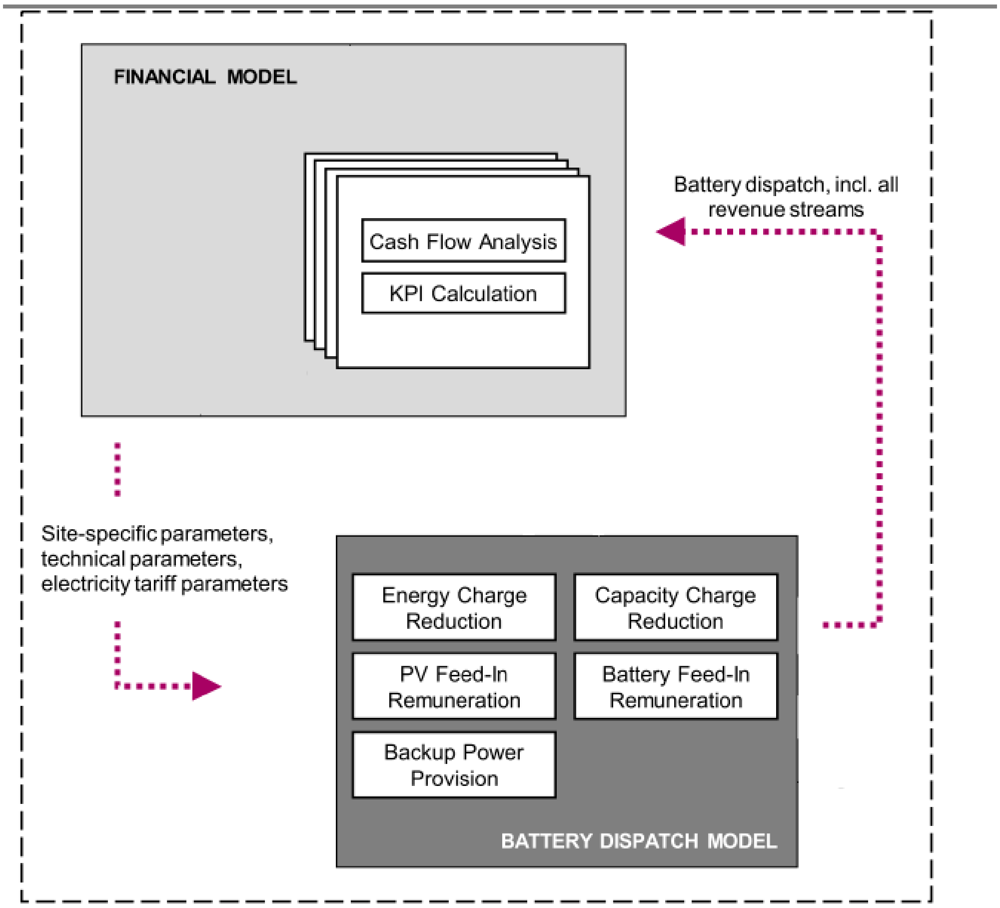

Figure 5 General framework of the study [2]

The rationale for the BESS would be then[7]:

Transmission congestion relief: To limit the maximum injected power to 0MW$_{AC}$, while allowing for more solar energy penetration in the islands grid than a conventional without storage PV power plant.

Solar energy time shift: To shift a portion of generated solar energy to a time when it is most needed (evening peak for instance) and avoid curtailment (higher self-sufficiency and self-consumption).

Battery dispatch model

To maximise self-consumption, the storage capacity is dispatched. If the PV power exceeds the load, the battery is charged until full. The battery is discharged until empty once the PV power exceeds the load. PV, battery efficiency, and inverter efficiency are the losses considered. The demand is thought to be unresponsive [3].

In the following, the Rule-based PV and Battery dispatch algorithm implemented in Python for peak shaving and self-consumption is presented and shown in Figure 6. When employing a battery and the right charging technique, power curtailment can be significantly decreased when the maximum

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[7] It is recommended to add the frequency reserve, PV variation smoothing, frequency regulation or black start support and other monetizable ancillary services as complementary services to stack battery value streams in an optimized way. For such optimization, input data on the needs and price of the corresponding services would be needed as inputs.

amount of power that can be exchanged with the grid is constrained. However, this also may lower the rate of self-consumption (SCR).

$Step\ k: (k = t_1, t_1 + T_s, \dots, t_1 + KT_s):$

$$P_{dis}(k) = Min(P_{dis}^{max}(k), Max(0, \frac{P_d(k)}{\eta_{INV}} - P_{pv}(k)))$$

$$P_{ch}(k) = Min(P_{ch}^{max}(k), Max(0, P_{pv}(k) - \frac{P_d(k)}{\eta_{INV}}))$$

$$P_{dis}^{max}(k) = Min(P_{BESS}^{max}, \frac{x(k-1) \times \eta_{BESS}}{T_s})$$

$$P_{ch}^{max}(k) = Min(P_{BESS}^{max}, \frac{C - x(k-1)}{T_s})$$

$$x(k) = x(k-1) + T_s \times (P_{ch}(k) - \frac{1}{\eta_{BESS}} P_{dis}(k))$$

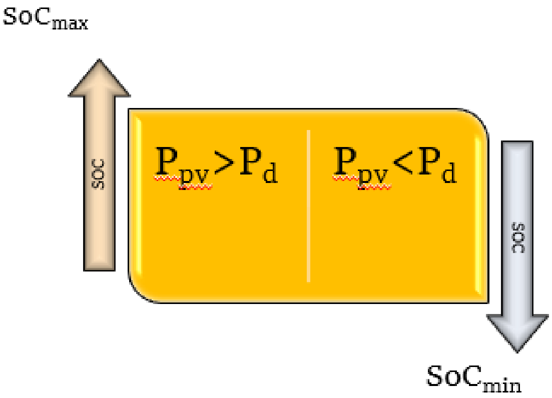

Figure 6: Rule-based PV and Battery dispatch for self-consumption and peak shaving

Financial model

The output of the Energy Flows from the ESS dispatch simulations step is used to run a financial analysis. From the client's perspective, the financial KPIs of the grid-connected solar-battery system are calculated:

- By considering the grid as a zero-investment generator producing at the retail price
- The energy fed to the grid is taken into account as a negative cost (in this case, no injection is allowed, and no feed-in tariff is in place, which makes this term always zero);
- It is assumed that there is a second investment in the battery after 10 years to model degradations and replacements;

- Annual Investment: The investment in the battery and PV systems as a constant annuity. Capital Recovery Factor (CRF) is used to calculate Annual Investment[8] from the Net System Cost (sum of total PV and battery investment and re-investment considering investment supports) and O&M costs;
- Annual operation and maintenance cost (O&M) of PV and Battery are calculated as a fraction of total PV and battery investments, respectively;
- Annual Grid Connection Costs: According to the provided information, grid connection and usage costs (fixed cost, variable grid cost per kW, self-consumption, and feed-in grid costs) are assumed to be zero while modelled in the studies.

The levelized cost of a grid-connected solar home battery system can be determined from the user's perspective by treating the grid as a zero-investment generator that produces at the retail price. In light of this, it is also necessary to consider the energy supplied to the grid as a negative cost. The cost of the PV and storage systems is accounted for as a constant annuity [4]:

$$Annuity = \left[PV_{investment} + Battery_{inevstment} \times (1 + \frac{1}{(1+i)^{N_{Batt}}})\right] \times CRF + PV_{O\&M} + Battery_{O\&M}$$

It is assumed that there is a second investment in the battery after 10 years in the heart of the 20-year project lifetime. OM is calculated as a multiplication of the storage and PV sizes. capital recovery factor calculated by:

$$CRF = \frac{i \times (1+i)^{N_{PV}}}{(1+i)^{N_{PV}} - 1}$$

where i i is the weighted average cost of capital (WACC) and NPV is the PV system lifetime in years. In addition to the basic profit calculations from the investments and incomes, the levelised cost of electricity **from a prosumer perspective** can be defined as:

$$LCOE = \frac{Annuity + Cost_{EnergyFromGrid} - Revenue_{EnergyToGrid}}{Energy_{Load}}$$

$Revenue_{EnergyToGrid}$ is zero in the defined use case. $Cost_{EnergyFromGrid}$ includes both the grid and retailer costs. It is also useful to isolate the contribution of the battery by calculating the levelised cost of storage:

$$LCOS = \frac{Battery_{Annuity}}{Energy_{FromBattery}} = \frac{Battery_{re+inevstment} \times CRF + Battery_{O\&M}}{Energy_{FromBattery}}$$

Sizing metrics

The battery sizing indices are defined as below:

Self-Consumption Index: $SCI = \frac{Consumed\ PV\ energy}{Generated\ PV\ energy}$

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[8] Reference Annual Investment (Total investment without the subsidies) is also calculated which in this case is exactly the same as the Annual Investment due to no investment supports.

The SCI is referred to more frequently and quantifies the efficiency of energy usage. A high self-consumption has numerous advantages for the prosumer as well as the grid operator. If energy is consumed simultaneously with production, the grid is unused. This gains importance when you consider that all PV installations will be generating electricity at the same time, which can cause grid congestion and excess generation. There, the share of wind and solar energy keeps increasing; sunny and windy days will lead to and have already led to, cutting of renewable generation. By storing and self-consummating, grid interaction and possible congestion can be avoided, while the prosumer can profit from cheap PV energy instead of grid prices. If clients provide an energy buffer, the need for a spinning reserve is also lower.

This means that CO2-producing power plants that provide an ability to deliver power if demand rises can eventually be closed. Generally, we can conclude that a high SCI benefits the prosumer, the grid operator, and the environment.

$$\text{Self-Sufficiency Index: } SSI = \frac{Consumed\ PV\ energy}{Total\ Consumed\ energy}$$

The SSI is closely related to SCI, but the denominator differs in being total consumption instead of total generation. The Self-Sufficiency index mainly quantifies how much the incoming PV generation is used to supply the total consumption. Both indexes are susceptible to load shifting and energy storage, influencing the amount of PV energy consumed. The denominator of the self-consumption index can only be influenced by changing the PV infrastructure or its outlay; the SSI’s denominator can be manipulated through load shedding and, thus, also through software packages.

Case study of Sporades

The proposed solution aims to cover the load demand not covered by the PV Plant in order to simulate storage for 0 MWh to 50 MWh (with 5 MWh as the step size) with a duration range of 0 MW—55 MW (with 5 MW as the step size) combining with PV production capacities of 0 MWp to 55MWac (with 5 MW as the step size). For this simulation, we are assuming that the plant is not allowed to feed the grid for a higher self-consumption.

Assuming 1 MWp as the rating power of the PV production time series (by doubling the 500kW PV production of the three islands), additional PV capacities are estimated proportionally. To properly evaluate the potential for self-consumption and the levelised cost of a PV battery storage system, realistic time series of both electricity demand throughout the year should be used. The battery is assumed to have one cycle per day by which it would need replacement after 10 years of operations.

Assumptions

Due to the lack of information on the local and total load and potential solar production of the studied islands, it may be necessary to make assumptions to analyse the sizing problem, draw conclusions, or make decisions. However, it's important to acknowledge these assumptions and to be aware of their potential impact on the results. Making assumptions should not be seen as a substitute for gathering more information but rather as a way to work with what is available and to make the best use of it.

- As negotiated with the local project partners, the sizing problem is solved at the North Sporades archipelago island level more willingly than per island or per PV installation. Three islands are modelled as a copper plate scenario connected to the main grid with an 80 MVA interconnection constraint.

- There is no available data regarding the peak load or annual energy demand of the Sporades islands. However, a good estimation based on similar islands is 28 MW of peak demand and 70 GWh of annual energy demand for the North Sporades archipelago. the consumption data of Kythnos island for 2019[9]. Using a peak/peak ratio of 8.18 (= 28 MW / 3.42 MW), the load of Kythnos is scaled up as an estimation of the total load of the Sporades islands (Figure 7). Using this estimation, the total energy consumption of the islands would be 80GWh, which is acceptable in comparison with the actual value of

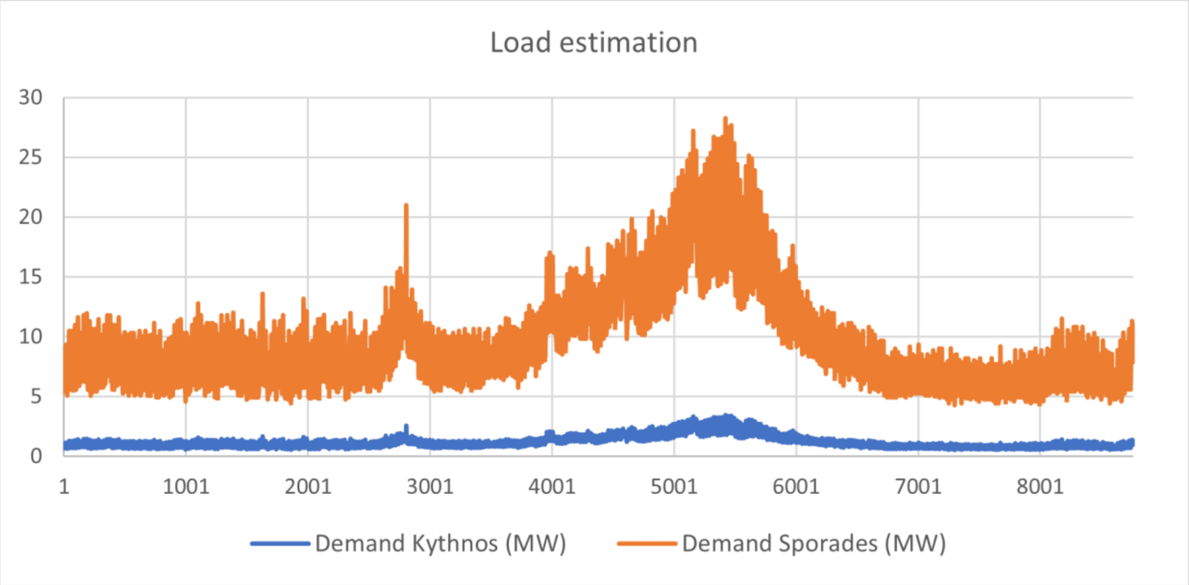

Figure 7: Load of consumption data of Kythnos island for 2019 used to estimate the load of Sporades islands for 2022

- Electricity prices are extracted from https://www.rae.gr/6891-2/?lang=en.

Table 5: Energy and grid fees of Greece

Regulated charges	
A) Transmission network	
Capacity charge	0,13 (€/kVA*days of consumption/365 days)
Energy charge	0,00542 €/kWh
B) Distribution network	
Capacity charge	0.52 €/kVA
Energy charge	0,0213 €/kWh
C) Public utility services	
Residential (low voltage) Daytime consumption	€/MWh
0-1600 KWh/4-months	**6.9**
1601-2000 KWh/4-months	**50**
2001-ΑΝΩ KWh/4-months	**85**

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[9] Kythnos island is a small, non-interconnected island in the Cyclades, but it could assist on estimating a similar profile for North Sporades, as it is indicative for the demand seasonality of almost all Greek islands.

Residential (low voltage) Night consumption	€/MWh
0-1600 KWh/4-months	**6.9**
1601-2000 KWh/4-months	**15**
2001-ΑΝΩ KWh/4-months	**30**
D) GHG emissions tax €/kWh	
0.017	

According to Table 5, assumed financial inputs of the economical assessment are presented in Table 6.

Table 6: Economic Assessment Assumptions

Economic parameters	Value	Unit
Retail Energy Price	85	€/MWh
Support to self-consumption	0	€/MWh
Grid fees for self-consumed electricity	0	€/MWh
Fixed grid tariff per year	36	3 €/month
Fixed cost per installed grid capacity (Maximum yearly kW)	0.65	€/kW
Fixed cost per consumed grid energy	0.027	€/kWh
Tax and levies for self-consumed electricity	0	€/MWh
Purchase price of electricity fed to the grid (N/A due to the zero-injection limit)	65	€/MWh
Grid fees for electricity fed to the grid	0	€/MWh
Tax and levies for electricity fed to the grid	0	€/MWh
Investment support, % of investment	0	%
Investment support is proportional to the size	0	€/kW
Discount rate	0.097	%
Variable for the net metering scheme	0	1

- PV potential (Actual MWp/1 rated MWp) is assumed to be equal to the sum of the PV productions in all three islands divided by the rated capacity 0.500 MWp.

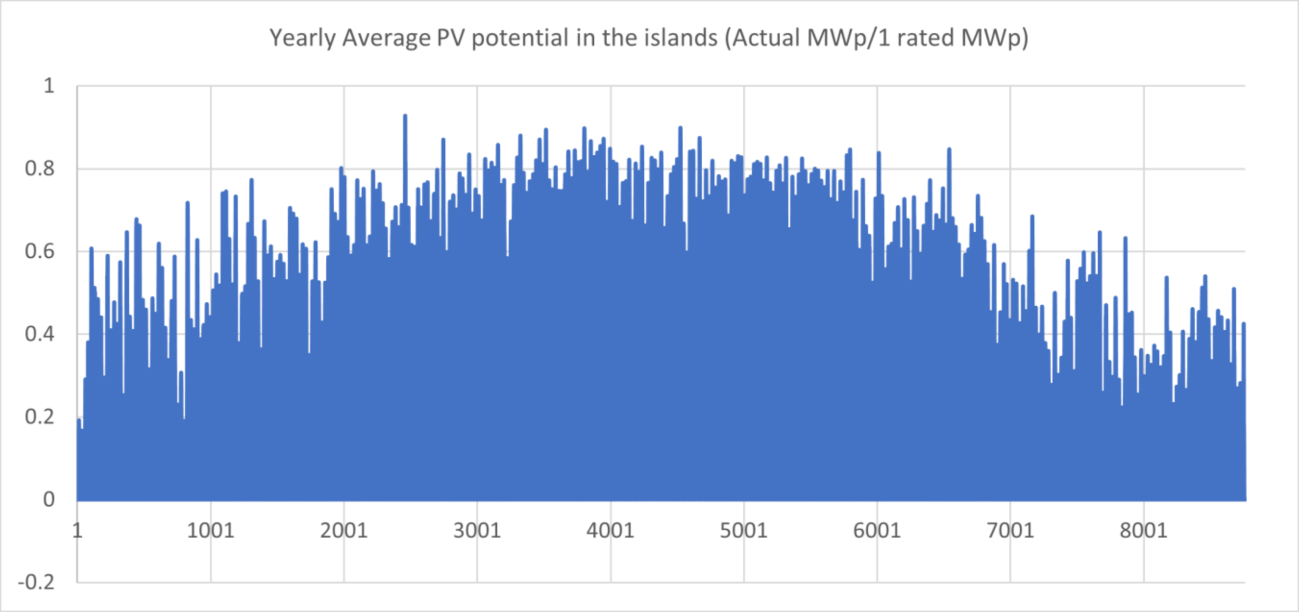

Figure 8: Yearly Average PV Potential in the islands (Actual MWp/1 rated MWp)

Results

All the detailed results of the daily operation are provided as an electronic annex to this report.

Daily Operations

Combining the PV generation model and the battery dispatch algorithm, simulating a whole year of operation is straightforward. This results in time vectors of the battery state of charge or of the power bought and sold to the grid, targeting the optimum level of curtailment. The various models and data processing are implemented in the Python language. An example of the system operation is given Figure 9.

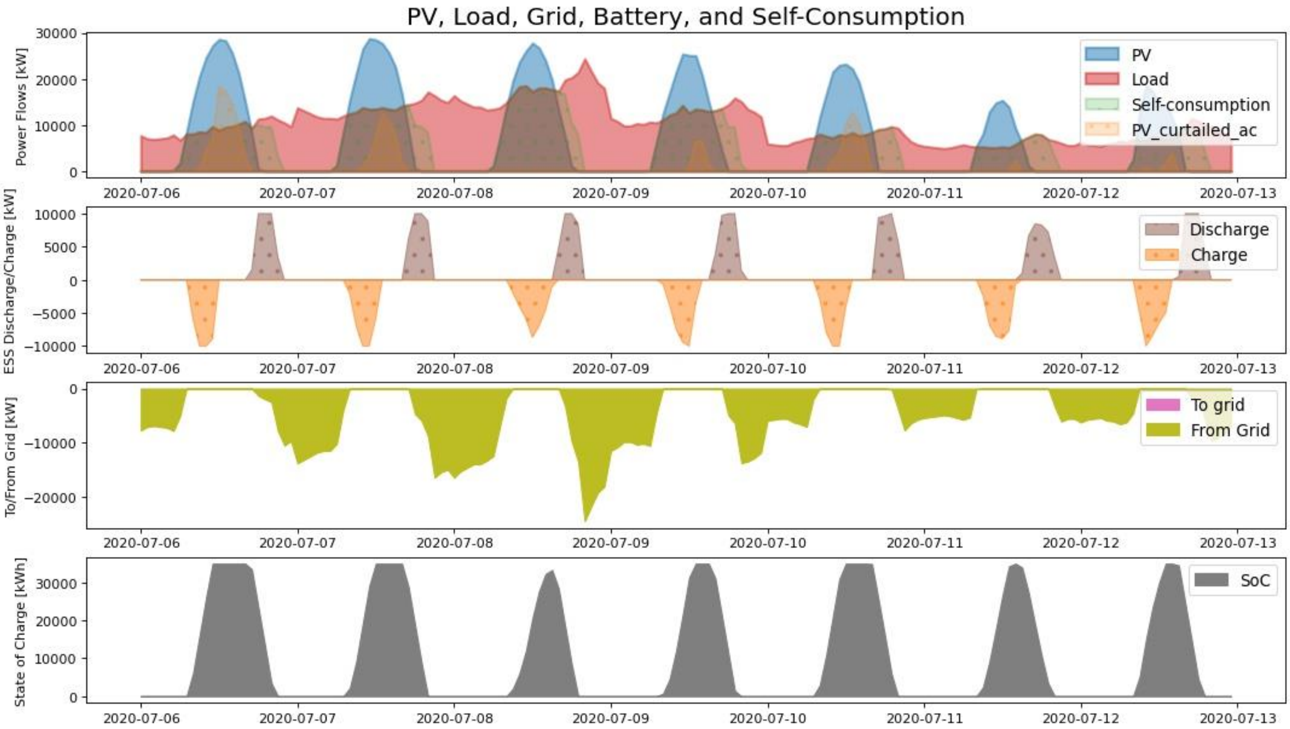

Figure 9: Sample daily power flows with 35MWp PV and 35MWh, 10MW, 3.5h battery

Daily operations are used in the next step to calculate yearly KPIs as to each combination of PV and battery to be fed to the financial analysis.

Technical KPIs

For the yearly simulations / calculations, the following technical KPIs are used:

Energy From Grid kWh	Energy Load kWh
Energy To Grid kWh	Battery Production Energy kWh
PV Auxiliary AC kWh	Battery Consumption Energy
Energy PV kWh	Battery Energy Losses kWh
Residuals kWh	Inverter Energy Losses kWh
Self-Consumption Index %	Yearly Average DoD
Energy Self-Consumption kWh	Number of Full Cycles
Self Sufficiency Index %	AC Energy PV Curtailed

When performing a yearly simulation, the main variable of interest is the total amount of self-consumption. In this work, the self-sufficiency rate is defined as the ratio between the self-consumed energy and the total yearly energy demand. Residuals are calculated to check the operational strategy. Some performance-related battery indicators are average Depth of Discharge (DoD) and number of equivalent full cycles.

- Residuals = Energy PV – Energy PV Curtailed + Energy from Grid – Energy to Grid – Battery Energy Losses – Inverter Energy Losses – Energy Load
- Average DoD = Battery Production Energy / (365 × Battery Capacity)
- Number of Full Cycles = 365 x Average DoD

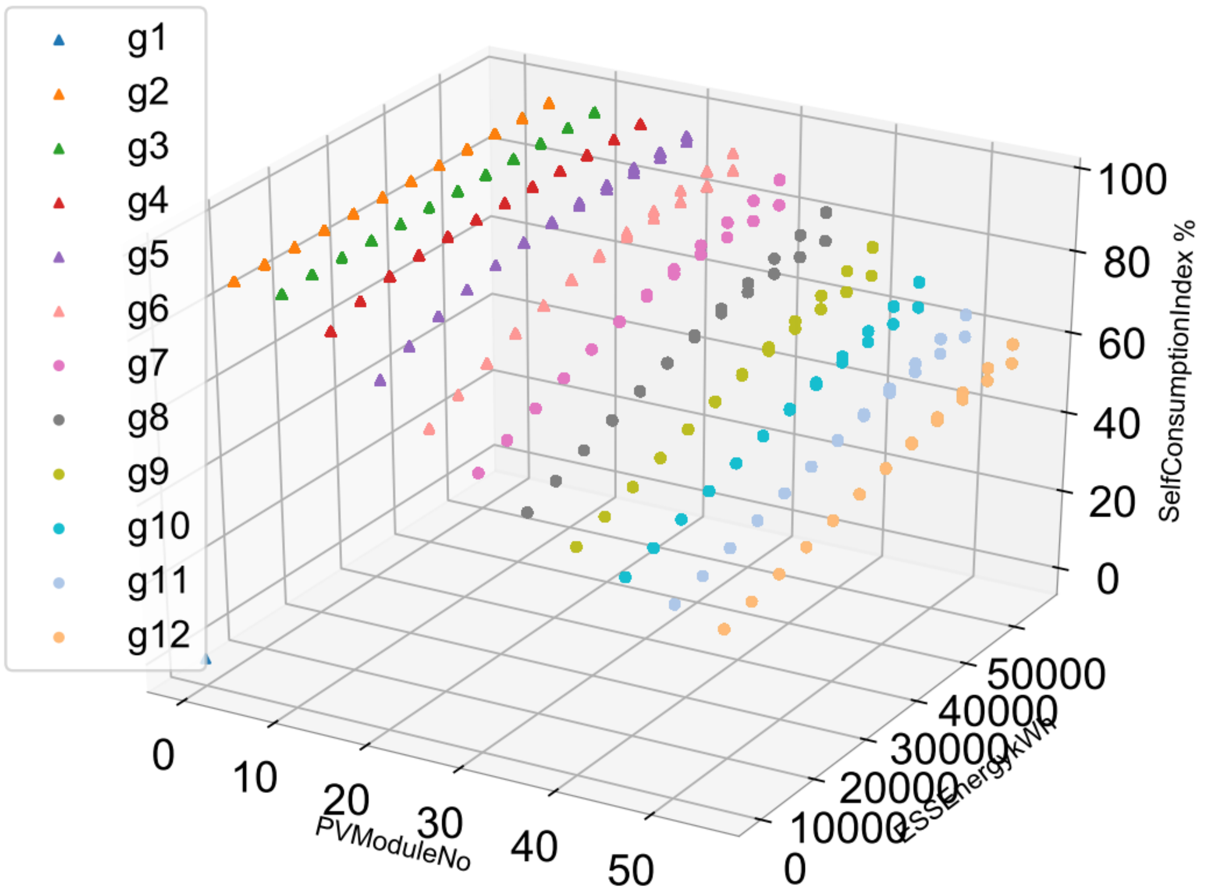

Figure 10: Yearly self-consumption (%) vs PV (MW) and Storage (kWh): gi represents (i-1)*5MWp PV production capacity

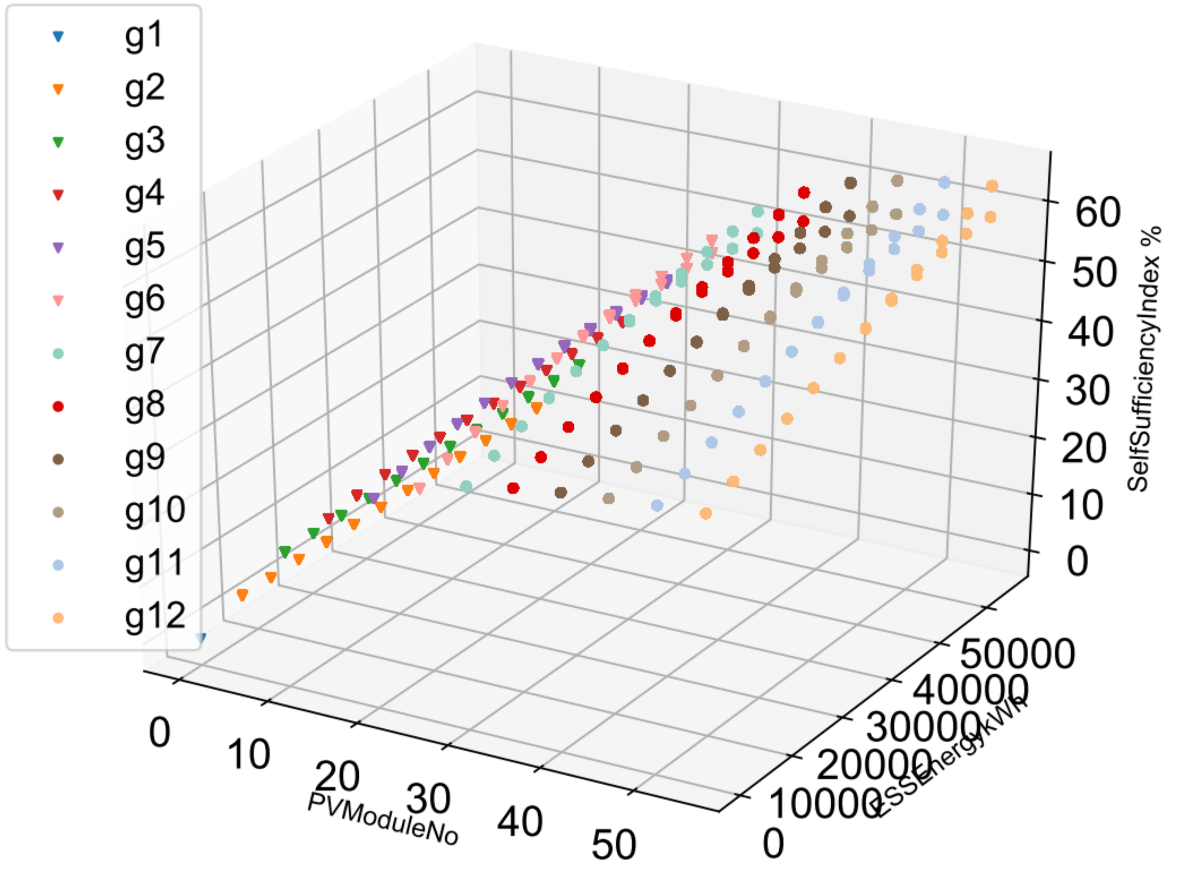

Figure 11: Yearly self-sufficiency (%) vs PV (MW) and Storage (kWh): gi represents (i-1)*5MWp PV production capacity

As seen from Figure 10 and Figure 11SC index decreases with the increase in PV installed capacity on the island.

- The SC index could be interpreted as to the required curtailment or energy losses (as to the zero-injection rule and the limited power/energy capacity of the battery), while SS index refers to the amount of energy absorption needed from the grid (which could not be supplied locally).
- Considering that all the battery power capacity scenarios are represented in these 3D plots, SC and SS indices are almost independent of the battery power capacity variations.
- SC index is decreasing by adding new PV productions to the island, while the more the PV capacity, the more PV curtailments due to the zero-injection limit.
- SS index is increasing by adding new PV productions to the island, while the more the PV capacity, the less power from the grid.
- Increasing battery energy capacity would result in higher self-consumption and self-sufficiency rates in all the PV production scenarios.

The most profitable (least cost) scenario resulted in a concurrent SC and SS with a greater value than 50% (SC: 73% and SS: 50%) is (PV: 35MW, BESS: 35MWh, 5MW). An optimised combination of SC and SS should be decided based on the economic performance of the system. Targeted SC and SS levels would have a direct impact on the investments and profits. Battery and PV sizing are optimised as to their impact on the energy bill traded off with the required annual investment. profit

Economic performance of the system

The levelised cost of the system and the battery system can be calculated by considering the relevant regulatory and business-related parameters. Accordingly, the saving on the energy bill is considered as a negative cost (SC: Self-Consumption income and PS: Peak Shaving income). The investment in the battery and PV systems is considered as a constant annuity. Investment terms are assumed to be:

- PV Cost per kW: 1196 €,
- Battery Cost per kWh: 480 € (From Table 4),
- PV Lifetime: 20 years,
- Battery Lifetime: 10 years,
- O&M Battery: (4 €* ESS Energy kWh) + (20 € * ESS Power kW)
- O&M PV = 14 € * PV Capacity MW
- Battery replacement Cost per kWh: Battery Cost per kWh * 0.725

Calculated yearly Economic KPIs are as below.

Annual Grid Cost (Energy and Power grid charges)	Income FtG (Feed to Grid: Not applicable)
CRF (Capacity Recovery Factor)	Income SC (Self Consumption Income)
Net System Cost	Cost BtG (Bought from Grid)
NPV Battery reinvestment	Profit = Annual Investment - Peak shaving Income - Self Consumption Income = Yearly Balance – Base case Balance

Annual Grid Cost (Energy and Power grid charges)	Income FtG (Feed to Grid: Not applicable)
Annual Investment	Yearly Balance = - Annual Investment - Cost BtG – Annual Grid Cost
Battery Investment	LCOE (Levelized Cost of Energy)
PV Investment	LCOE_stor (Levelized Cost of Storage)
Income PS (Peak shaving Income)	PR (Profitability Ratio) = Profit / Annual Investment * 100

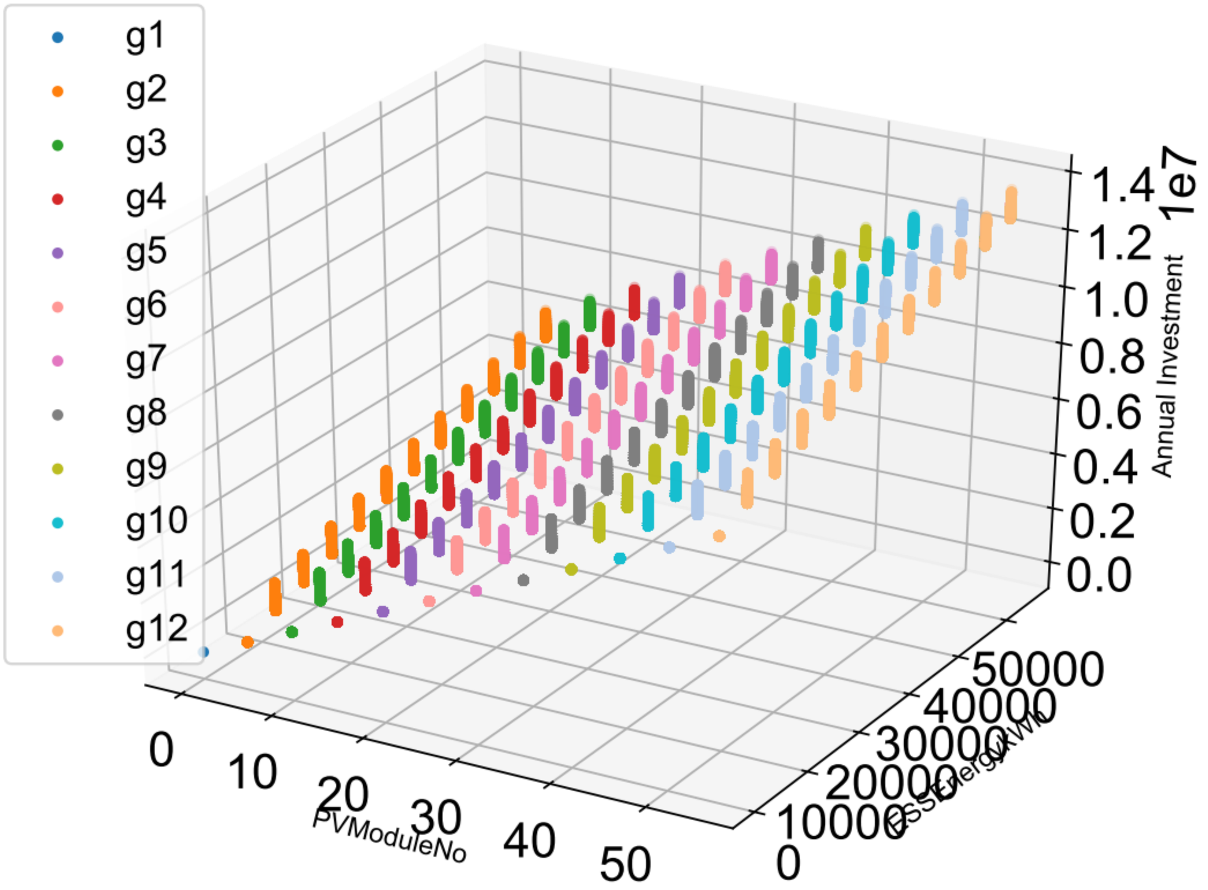

Figure 12: Annual investment vs PV (MW) and Storage (kWh): gi represents (i-1)*5MWp PV production capacity

In Figure 12, the annual investment indicator as one of the main indicators in financial profitability calculations is presented versus the MW_P of the PV installation and the Storage Capacity (kWh) for all the simulated battery power capacities. As expected, the annual investment is increasing almost linearly with both PV and battery size augmentations. Changes in the battery power capacity would slightly change the annual investment cost (shown as bars in Figure 12).

Most of the scenarios would result in negative profitability due to the high capital cost of the system and the limited scope of value propositions from the storage. In all the scenarios, profitability is less than zero except for the ones with new PV installation and no battery addition.

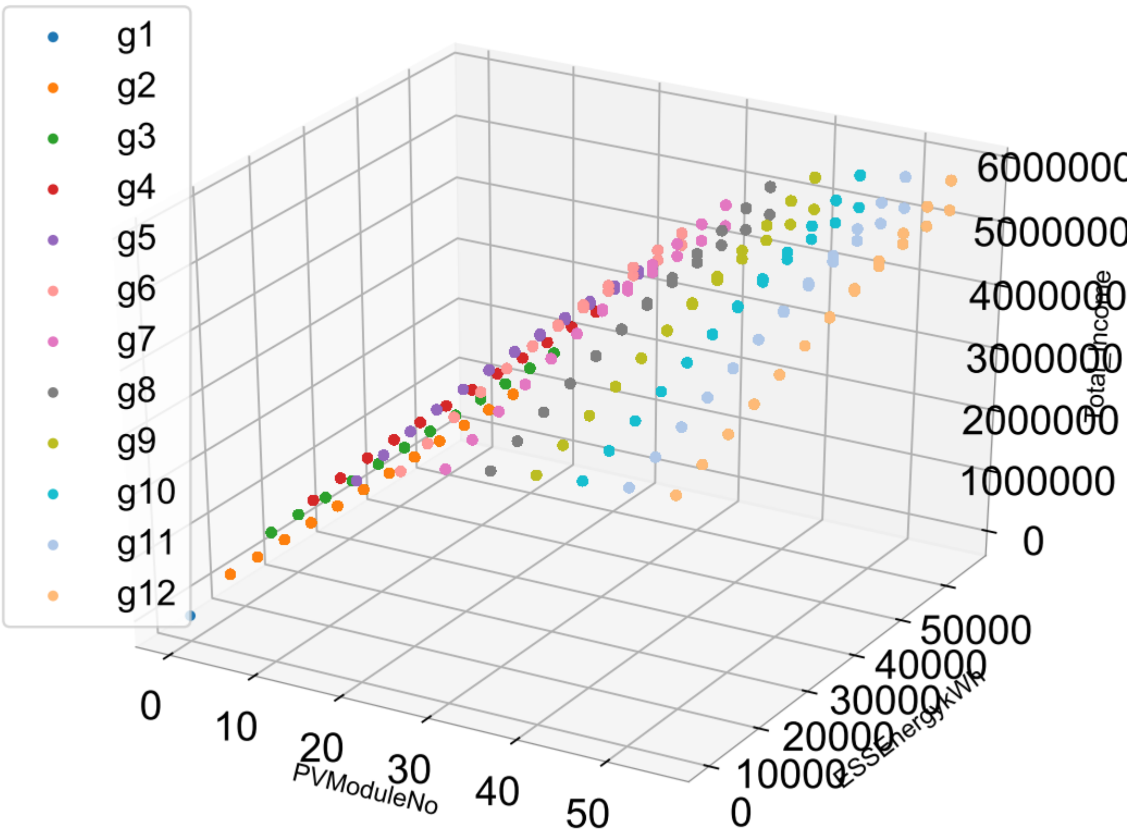

Figure 13: Total Income (Savings from self-consumption and peak shaving) vs PV (MW) and Storage (kWh): gi represents (i-1)*5MWp PV production capacity

In Figure 13, the total income indicator as the other main indicator in financial profitability calculations is presented versus the MW$_P$ of the PV and the Storage Capacity (kWh) for all the battery power capacities. As expected, savings are increasing almost linearly alongside PV and battery size augmentations with a saturation for large capacities. The impact of the battery power capacity changes on the total income is negligible.

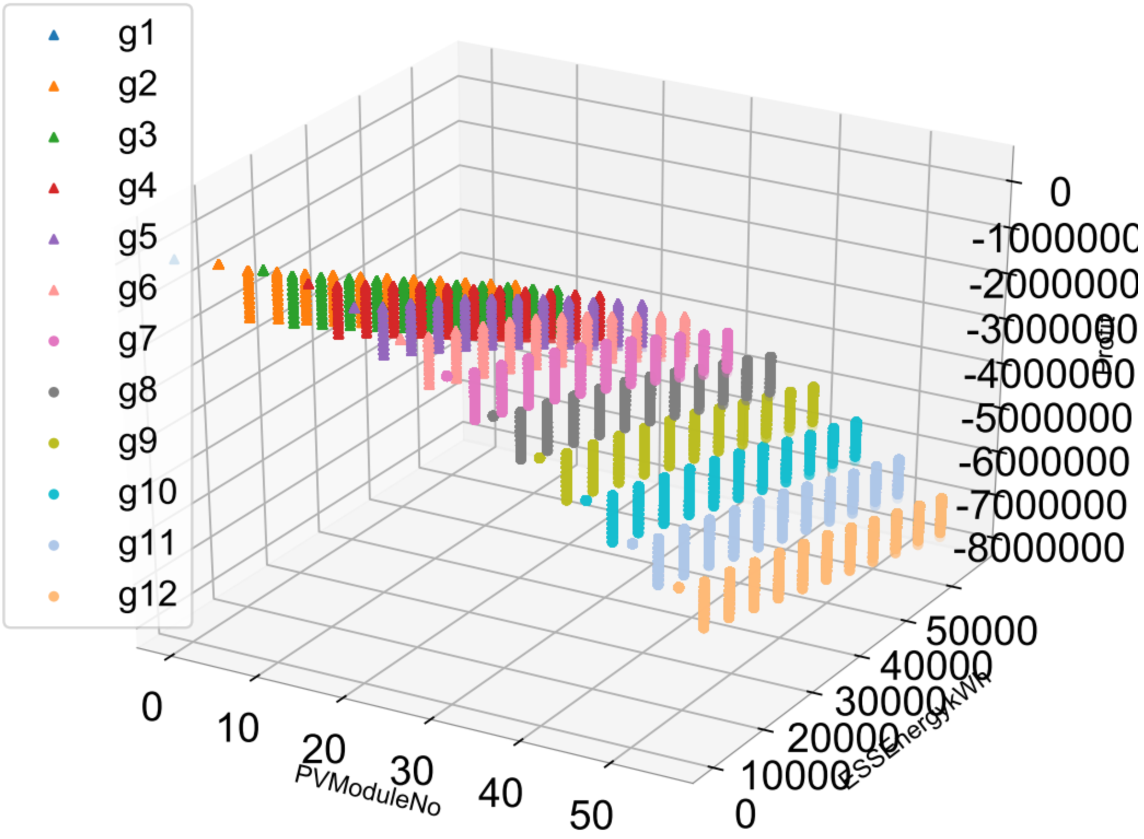

Figure 14: Profit vs PV (MW) and Storage (kWh): gi represents (i-1)*5MWp PV production capacity

In Figure 14, net yearly NPV profit (Costs - Benefits) indicator as the main indicator in financial profitability calculations is presented versus the MW$_P$ of the PV and the Storage Capacity (kWh) for all the battery power capacities. As expected, profitability is decreasing almost linearly with saturation at large capacities along with both PV and battery energy size augmentations. The impact of the battery power capacity changes on the total income is negligible (shown in bars).

In Figure 15, net yearly NPV profit (Costs - Benefits) indicator as the main indicator in financial profitability calculations is presented versus Storage (MW) and Storage (MWh) for all the PV power capacities. Profitability is decreasing along with battery energy and power augmentations, while without battery,

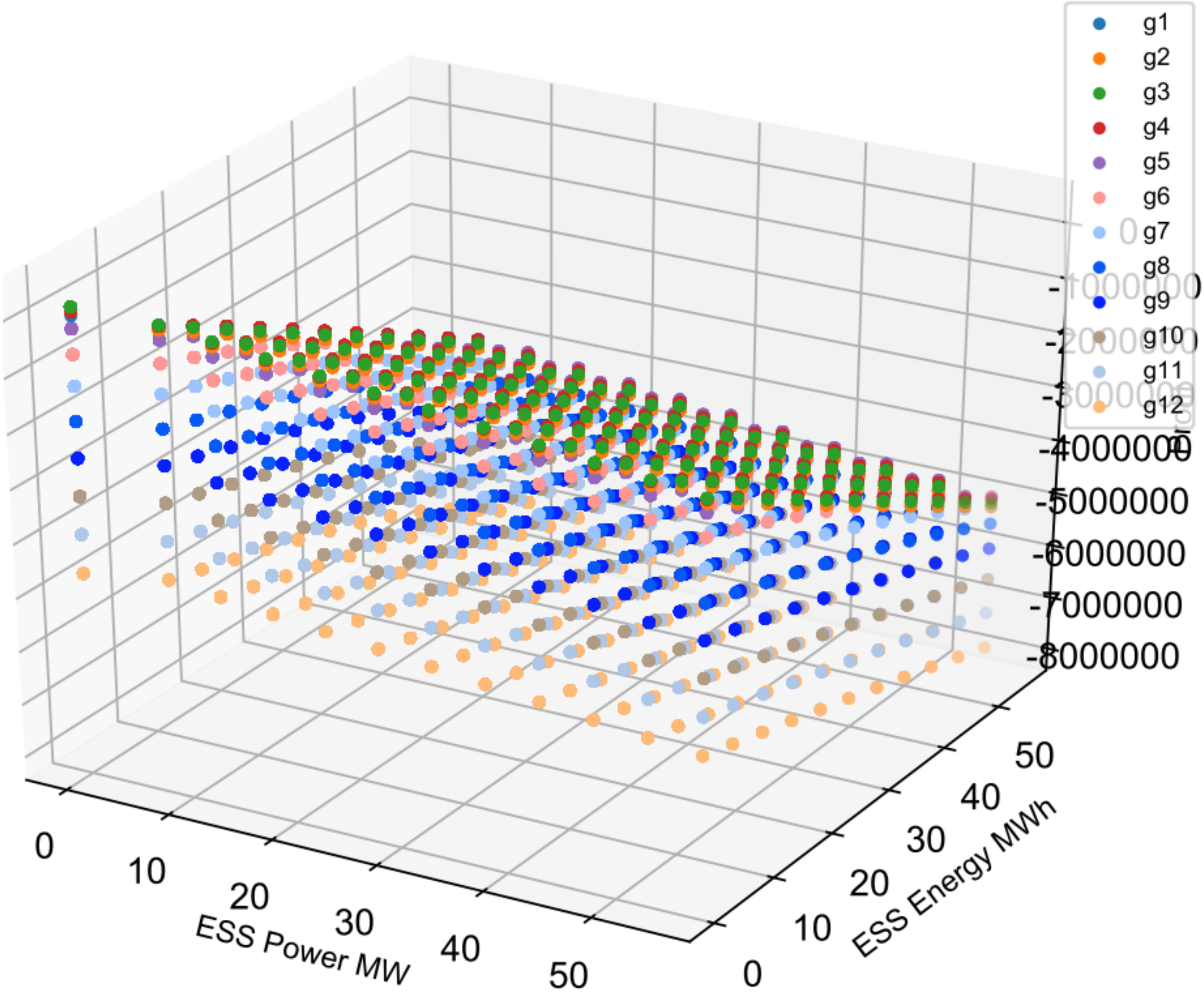

Figure 15: Profit vs Storage (MW) and Storage (MWh): gi represents (i-1)*5MWp PV production capacity

Table 7: Positive net profit scenarios (all with no battery energy system)

PV Capacity MWp	**ESS Power kW**	**ESS Energy kWh**	**Net Profit (Euro)**
5.00	0.00	0.00	86263.28
10.00	0.00	0.00	162066.63
15.00	0.00	0.00	74621.02

As presented in Table 7, the most profitable scenario is the addition of only 10MWp PV capacity to the island with no battery included while resulting in 94% self-consumption and 18.6% self-sufficiency. Best scenarios based on the LCOE are shown in Table 8.

Table 8: Best scenarios based on the LCOE

PVModuleNo	**10**	**5**	**15**	**20**	**10**	**15**	**5**
ESSPowerkW	0	0	0	0	5000	5000	5000
ESSEnergykWh	0	0	0	0	5000	5000	5000

SelfConsumptionIndex %	94.41	95	88.09	79.05	94.94	90.98	95.03
SelfSufficiencyIndex %	18.59	9.35	26.02	31.14	18.70	26.88	9.35
AnnualGridCost	1789020	1990046.5	1627349.9	1516024.3	1786717	1608744	1989982
Income_PS	404572.8	203547.19	566243.75	677569.4	406877	584849	203611
NetSystemCost	11960000	5980000	17940000	23920000	15049419	21029419	9069419
AnnualInvestment	1516161	758080.65	2274241.9	3032322.6	1991641	2749722	1233560
Income_SC	1273655	640796.7	1782619.2	2133088.8	1280909	1841192	640999
Cost_BtG	5574693	6207551.6	5065729.1	4715259.5	5567440	5007156	6207350
TotalIncome	1678227	844343.93	2348862.9	2810658.2	1687786	2426042	844609.9
Balance	-8879875	-8955678.8	-8967321.1	-9263606	-9345798	-9365622	-9430893
Profit	162066.6	86263.27	74621.023	-221664.3	-303855	-323680	-388951
LCOE_to_Consumption	-0.110214	-0.111155	-0.111300	-0.114977	-0.116	-0.11624	-0.11705
LCOE_stor	-	-	-	-	5.57179	0.6	200.2

Conclusions

The main conclusions are:

(1) The self-consumption function of PV and battery sizes is non-linear, almost asymptotically.
(2) The cost of domestic Li-Ion storage is most likely still too high for a large-scale market uptake in Europe;
(3) The profitability of batteries and future uptake depends primarily on the indirect subsidies for self-consumption and new revenue streams provided by the structure of retail prices and regulations;
(4) Achieving 100% self-consumption (i.e., allowing for full off-grid operation) is unrealistic for the studied island.
(5) The most profitable scenario involves adding only 10MWp PV capacity to the island without a battery, resulting in 94% self-consumption and 18.6% self-sufficiency.
(6) Technical and Financial KPIs are almost independent of the battery power capacity.

At the system level, while high solar PV generation can jeopardise the static and dynamic security of the grid during the middle of the day, storage can absorb part of this electricity and reinject it at a later stage for several value propositions, thereby stacking revenues for greater profitability. It can do this whether in a market or a vertically integrated setting. Indirectly, storage can support cost reduction, deferring the need for generation and transmission capacity by reducing the need for peaking plants and easing line congestion.

Task 2: State-of-the-Art Analysis and Perspectives on Peer-to-Peer Energy Trading in the Sporades Islands

The Clean Energy Package of the European Union seeks to put the EU and its member states on pace to meet the 2030 climate targets. Recognising Energy Communities (EC) as the new actors to the energy market, Renewable Energy Directive (EU) 2018/2001 (RED) and the revised Electricity Directive (EU) 2019/944 (ED) have introduced four levels of integration for different sizes of consumers from Renewables/Jointly Acting Renewables Self-Consumers (RSC/JRSC) to Renewable/Citizen Energy Community (REC/CEC) [5]. The EU's "Clean Energy for EU Islands" Initiative in 2017, offers robust and multilevel support to insular communities.

According to the RED, RECs shall be 'autonomous from individual members and other traditional market actors that participate in the community as members or shareholders', which includes municipalities. For CECs, the ED states that only the decision-making powers 'should be limited to those members or shareholders that are not engaged in large-scale commercial activity and for which the energy sector does not constitute a primary area of economic activity'. Accordingly, the operation of the energy community and its technical systems is not under the control of anyone recognised authority. The directives, however, mandate that energy communities be founded by the participants and incorporated in some legal form, such as a registered association or a cooperative society. From this vantage point, it appears appropriate to adopt P2P trading by distributed ledger blockchain technology because no intermediary is needed, and operations may well be carried out independently.

With the launch of the "Clean Energy for EU Islands" Initiative in 2017, the EU gives support to insular communities in order to set-up energy communities on European islands. Experience with energy communities is limited in Greece. There are the Sifnos Energy Community (SEC), the Minoan Energy Community (MEC), and the Energy Community of Chalki (ChalkiOn) while in other cases (Ikaria, Tilos, Agios Efstratios, and Kythnos), there is no operational energy community yet [6].

Background and overview

As of now, the topology of the current electrical power grids of islands employs a top-down strategy in which the electricity is dispersed from the production unit. As the number of prosumers as proactive consumers that can transact their energy as good and service is growing on the islands, establishing a local electricity market in the Sporades islands based on the Peer-to-peer (P2P) trading will allow for a bottom-up approach to empower prosumers [7]. P2P trading could emerge as an innovative way to:

- sell electricity from prosumer to consumers;
- effectively and highly value local flexibility; and,
- assist grid management by reducing peak demand, lowering reserve requirements, and curtailing network loss.

P2P energy trading refers to the direct exchange of energy between individuals or communities, rather than through a centralised intermediary. P2P trading as a form of LEM (Local Energy Market) will encourage RES more effectively on a prosumer level than the current centralised energy market and can be utilised to integrate significant amounts of fluctuating RES into the energy system.

Blockchain technology can potentially revolutionise the way energy is traded, particularly in the context of peer-to-peer (P2P) energy trading. Blockchain technology can facilitate P2P energy trading by providing a secure, decentralised platform for recording energy transactions and managing access to the grid.

There have been a number of studies and pilot projects exploring the use of blockchain for P2P energy trading. One early example is the Brooklyn Microgrid project, which used the Ethereum blockchain to enable P2P energy trading between neighbours in Brooklyn, New York [8]. Another example is the Australian project Power Ledger [9], which is using blockchain to enable P2P energy trading between households and businesses.

Overall, the State of the art (SOTA) of blockchain-based P2P energy trading is still in its early stages, but the potential for this technology to revolutionise the energy industry is significant [10]However, further research is needed to fully understand the technical, economic, and regulatory challenges that must be overcome to fully realise blockchain's potential for P2P energy trading.

Recent studies have also explored the potential of blockchain for P2P energy trading in virtual communities [11]. These virtual communities can be formed by individuals or organisations with common interests in renewable energy, energy efficiency, or sustainable living. These studies have found that blockchain technology can enable these virtual communities to become self-sufficient in terms of energy generation and consumption and can also promote the adoption of renewable energy sources [12].

The peer-to-peer (P2P) energy trading platform for the virtual energy community of islands can be made using blockchain technology. Without the aid of a central intermediary, community members can purchase and sell energy directly to one another in this system. A decentralised digital ledger called a blockchain, which is kept up by a network of computers, is where transactions are recorded. All energy trades within the community can be recorded in a secure, open, and tamper-proof manner thanks to blockchain technology. Smart contracts can also be used to automate the buying and selling of energy, improving the system's effectiveness and efficiency.

Key aspects

The following architectural elements would normally make up a blockchain-based P2P energy market:

1- **Blockchain Technology**: The underlying blockchain platform that makes it possible for peers to transfer energy assets in a secure and transparent manner. This might be a private blockchain like Hyperledger Fabric designed especially for the energy industry or a public blockchain like Ethereum. Private permissioned and consortium blockchains are preferred in applications with defined authorities or entities with management responsibilities.

2- **Smart Contracts**: Energy trading (purchasing and selling) is automated using smart contracts, which are self-executing contracts coded on the blockchain. When specific circumstances are satisfied, such as when the price of energy reaches a particular level or when a generator has produced a specific amount of energy, they can be programmed to conduct transactions automatically.

3- **Producers of energy**: These are people or organisations (Municipalities of the islands in this case) who produce energy from renewable resources. They would link the blockchain to their energy-producing equipment and promote the energy they produce to consumers.

4- **Energy consumers**: Consumers are people or businesses (This could be the Municipalities of the islands, in this case) who purchase energy from energy producers. They would keep their energy assets in a digital wallet and use them to pay for their energy use.

5- **Marketplaces**: These are digital platforms that link energy providers and customers, enabling peer-to-peer (P2P) trading of energy assets. Marketplaces could also come with other features like reputation systems, pricing discovery, and conflict resolution procedures.

6- **Data Management**: A blockchain-based P2P energy market must have effective data management that can handle massive amounts of data, including energy consumption, production, and market data.

7- **Communication infrastructure**: To ensure that data is exchanged between the various system components in real-time and to ensure the system is highly available, a secure and dependable communication infrastructure is required.

8- **Identity management**: To ensure that only authorised users may access the system and that the identities of the users are verified, a strong identity management system is required. This might incorporate encryption, multi-factor authentication, and digital identity verification.

9- **User Interface**: To make the system simple to use for both energy providers and consumers, a user-friendly interface is crucial. The users should be able to access their energy assets, trade energy, and examine market statistics through this interface, which might be a web-based portal or a mobile app.

In Figure 16, a vision for Sporades P2P energy marketplace is presented assuming two participants. DERs could automatically assist a better local balance in terms of both power and energy if adequate P2P energy trade mechanisms are designed [13].

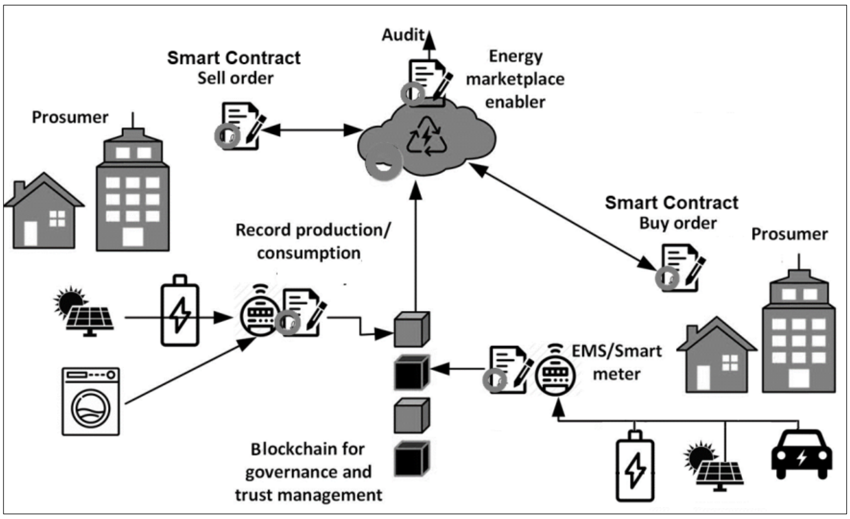

Figure 16: A vision for the Sporades P2P energy marketplace

Literature review

P2P energy trading is a promising trading strategy that is the subject of numerous research studies. The P2P energy market is introduced from several angles to enhance system performance by boosting scalability, reducing power losses, analysing the effects of transaction processes on the network, and looking at various business model types [14]. A summary of several types of research aimed at achieving different types of objectives for P2P trading platforms are:

- Price-based mechanism;
- Participating prosumers and incentivizing;
- Reducing energy expenses;
- Revealing asynchronicity and uncertainty;
- Securing prosumer transactions; and
- Ensuring network stability.

Research projects

Three different categories of customer-centric electricity decentralised markets are designed and prototyped for the transition of electricity end-users to active market participants with the capability of trading energy and/or flexibility from their resources [15].

Table 9: Overview of key European R&D projects

Project Name	**Funded by:**	**Descriptions**
P2P–3M (Multi-times, Multi-scales, Multi-qualities) [16] 2016	EPSRC of the United Kingdom	Technical and market arrangements with diverse social requirements trying to align the technical and market arrangements with the diverse social requirements: The P2P sharing/trading system operates at multiple timescales, from real-time energy trading to long-term energy sharing agreements. It also supports multiple energy qualities, including electric power, heat, and cooling.
P2P-SmarTest [17] 2015	Horizon 2020 program of the EC	Decentralised market design, trading platforms, physical and ICT infrastructure, and policy: A hierarchical Control structure and ICT architecture in Day Ahead and Intra-Day timeframe to facilitate P2P trading between cell of microgrids for energy market and AS.
Quartierstrom, P2PQ [19] 2017	Swiss Federal office of Energy	Market design, Grid operation, and Setup: blockchain based platform incorporating double auction algorithm, a locational grid tariff to encourage the local consumption, no incentive mechanism to sell the surplus energy of the community to the grid.
NRGcoin, Smart Contract for green energy [20]: SCANERGY 2013	European Union's Seventh Programme	Virtual currency based (1kWh=1NRGcoin) trading platform, co-exists with wholesale market regardless the retail value of electricity, injection of green energy is only incentivised when consumed locally near to real time, DSO acts as a local market supervision entity, the adaptive attitude (AA) bidding strategy is used, .
LAMP [21] 2017	German Federal government	Industry-academia collaborative project with the focus on the energy market analysis, social participation and acceptance of LEM evaluation, and technological consideration of blockchain

		characteristics, Intra-Day market, A merit-order based market mechanism every 15 minutes, a simulated LAMP market in a multiagent simulation to evaluate the projected market prices, user behaviour, and level of self-consumption.
DOMINOES 2017	H2020-EU	Development of a centralised market platform that enables prosumer to engage with other prosumers and also with other market players: DSO in local grid management, energy community to maximise its economic benefit, retailer to self-optimise its portfolio and DSO/TSO to mitigate imbalance
PEBBELS	Federal ministry for Economic Affairs and Climate Actions	Blockchain based decentralised market structure within community without violating grid constraints; Proof of concept, Lab based simulation and pilot site demonstration; To lessen the impact of potential forecasting mistake, energy/flexibility trading is offered on both the ID and DA markets . The project's market matching process is based on auctions, and a P2P blockchain technique will be used to settle contracts.

Commercial platforms

The blockchain, peer-to-peer trading and energy communities industry is relatively new and constantly evolving. Since blockchain technology and its use in energy trading are still in their early stages, and new platforms are constantly appearing, it is hard to rank top either EU or non-EU platforms of blockchain peer-to-peer trading in a virtual energy community. It's challenging to list the top ones because the popularity and position of these platforms frequently fluctuate. However, some of the top platforms that are now active and offering blockchain-based P2P energy trading in Europe include GreenCom Networks (Germany)[10], Sonnen (Germany)[11], Conjoule (Germany)[12], SunContract (Slovenia)[13], Grid Singularity (Austria)[14], Share&Charge (Germany)[15], WePower (Lithuania), PowerPeers (Netherlands)[16], Exergy (EU)[17], and Enerchain (Germany)[18].

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[10] https://greencom-networks.com/

[11] https://sonnengroup.com/sonnencommunity/

[12] Conjoule: https://www.conjoule.com/

[13] https://suncontract.org/

[14] https://gridsingularity.com/

[15] https://shareandcharge.com/

[16] https://www.powerpeers.com/

[17] https://exergy.energy/

[18] https://www.enerchain.com/

Some non-European blockchain-based platforms for peer to peer trading in a virtual energy community are: Power Ledger (Australia)[19], LO3 Energy's TransActive Grid (United States)[20], Grid+ (United States)[21], EcoChain (Singapore)[22], ImpactPPA (United States), The Sun Exchange (South Africa)[23], Electron (UK)[24], Grid+ (US)[25], Energi Mine (United Kingdom)[26], and ImpactPPA (United States)[27].

It is important to note that some of the aforementioned businesses may not have their main offices in Europe, but some have developed projects or pilot programs there. Likewise, some of the aforementioned platforms may not be exclusively dedicated to the virtual energy community but instead can engage in virtual energy community trading.

As for some exemplary comparisons:

- Grid Singularity vs. Power Ledger: In contrast to Grid Singularity, which is more focused on offering a decentralised energy data exchange platform with a marketplace for energy trading, Power Ledger is a platform that concentrates on P2P energy trading and extra features, such as carbon trading and virtual power plants.

- Grid Singularity vs. GreenCom Networks: While Grid Singularity is more focused on offering a decentralised energy data exchange platform and a marketplace for energy trading with an emphasis on data privacy and transparency in the energy market, GreenCom Networks also focuses on developing a decentralised energy management system that enables more efficient use of energy resources and supports the integration of electric vehicles and renewable energy sources.

- PowerPeers vs. Share&Charge: Both PowerPeers and Share&Charge are blockchain-based P2P energy trading platforms, with PowerPeers emphasising the development of a decentralised energy management system that enables more effective use of energy resources, supports the integration of electric vehicles and renewable energy sources, and a market for trading in energy. With an emphasis on security and transparency in the EV charging business, Share&Charge focuses on the decentralised sharing and charging of electric vehicles.

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[19] https://www.powerledger.io/

[20] https://lo3energy.com/

[21] https://gridplus.io/

[22] https://ecochain.com/

[23] https://thesunexchange.com/

[24] https://electron.net/

[25] https://gridplus.io/

[26] https://energimine.com/

[27] https://www.impactppa.com/

- The Sun Exchange and Electron: Both platforms want to open up the clean energy industry to individuals and democratise access to it. However, while Electron focuses on the UK, The Sun Exchange mostly focuses on developing countries. Additionally, The Sun Exchange permits solar project investments, while Electron permits intracommunity energy sales and purchases.

The list is not exhaustive, and new platforms are emerging as technology evolves and matures. Although they may seem similar, different platforms have different functionalities and integrate with different external services, and it is essential to select the one best suited for the business needs.

Conceptual design

This use case describes how prosumers and consumers within the island can trade electricity without any intermediary. As a result, RES deployment and flexibility are increased due to consumer and prosumer empowerment. This will be defined as a virtual community of the municipalities of the islands with different assets and energy management systems. It mimics a hypothetical situation where each of the traders individually interacts with any other traders, with the DSO for (local flexibility) and with its own retailer. Stakeholders will have access to a blockchain trading platform and buy/sell energy on the accessible marketplace.

According to the building blocks of a P2P marketplace (Figure 16):

- The marketplace has two main layers: The first is a trust management platform based on blockchain and smart contracts. This blockchain records all information from trusted sources, namely EMSs and other relevant sources and can be queried through smart contracts. So, information from smart meters about consumption, available flexibility, and energy storage and production can be stored in blockchain.

- On top of this trusted database, p2p marketplaces are built for information and energy transaction management. The marketplace would include smart contracts for accessing trusted blockchains and placing orders. It should also provide a central interface for facilitating interactions between stakeholders and the exchanged goods as well as transaction management and bidding. The marketplace transactions would function as buy, sell, or query orders. So, each action is enabled through a smart contract interface provided by the marketplace. There would be an ordering engine where orders are matched and finally executed.

- All regulatory aspects behind P2P energy trading and marketplace administration are assessed and translated into proper blockchain network configurations and smart contract logic.

Use case architecture

Structure of the island's virtual energy community: like every community, there will be some producers/prosumers (e.g., buildings equipped with photovoltaic panels), some consumers (e.g., offices as well as e-car charging points), and potentially a (community-owned) storage unit. In Figure 17, energy flow is shown with dashed lines, cash and information flows with continuous lines.

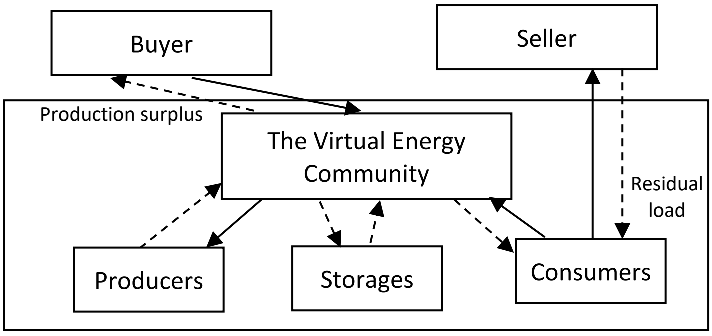

Figure 17: Involved actors within and outside (traditional) the virtual energy community

To maximise self-consumption within the community, producers' excess energy will mostly be distributed to consumers in four cases (pricing methodology):

- In comparison to any other (conventional) buyers outside the community, the producer makes more money when selling energy to the community or any individual consumer within the community.
- When consumers buy energy locally, or from any producer of the community, they pay less than they would from any other (conventional) source.
- Energy that cannot be temporarily assigned to a consumer at a given time can be temporarily stored by the energy community, and,
- Any extra energy can be sold to conventional suppliers outside the community. The community's producers and storage facilities are unable to meet all the remaining consumer demand, so a traditional supplier is used to fill this gap.

Three distinct structures could be used for P2P trade in the LEM: hybrid, totally decentralised, and community-based. While completely decentralised P2P trading occurs without the help of a centralised entity, community-based P2P trading is managed by a community operator. In contrast, the financial component of a hybrid P2P trading structure is decentralised between various entities, and a responsible local energy market operator simply ensures the power grid's security. Modern power grids can easily implement hybrid P2P trading structures due to their operational appropriateness [22].

Use case diagrams

This pilot would include the following roles:

- Platform operator – organisation in charge of maintaining the P2P energy trading platform. Runs the order matching engine that finds perfect matches between buy and sell orders on the marketplace. Tracks/records EUR/energy balance of all actors.
- Users – referring to platform users who want to trade energy. Each user can be Producer, a Consumer or can have both roles. A consumer would submit buy orders while a producer would submit sell orders.

- Utility company – oversees maintaining the physical infrastructure through which the energy that is being traded needs to be transported. The utility can also participate in the marketplace and buy energy, or transact energy privately with selected producers.

The following diagram (Figure 18) shows these roles and their allowed activities inside the P2P energy trading system.

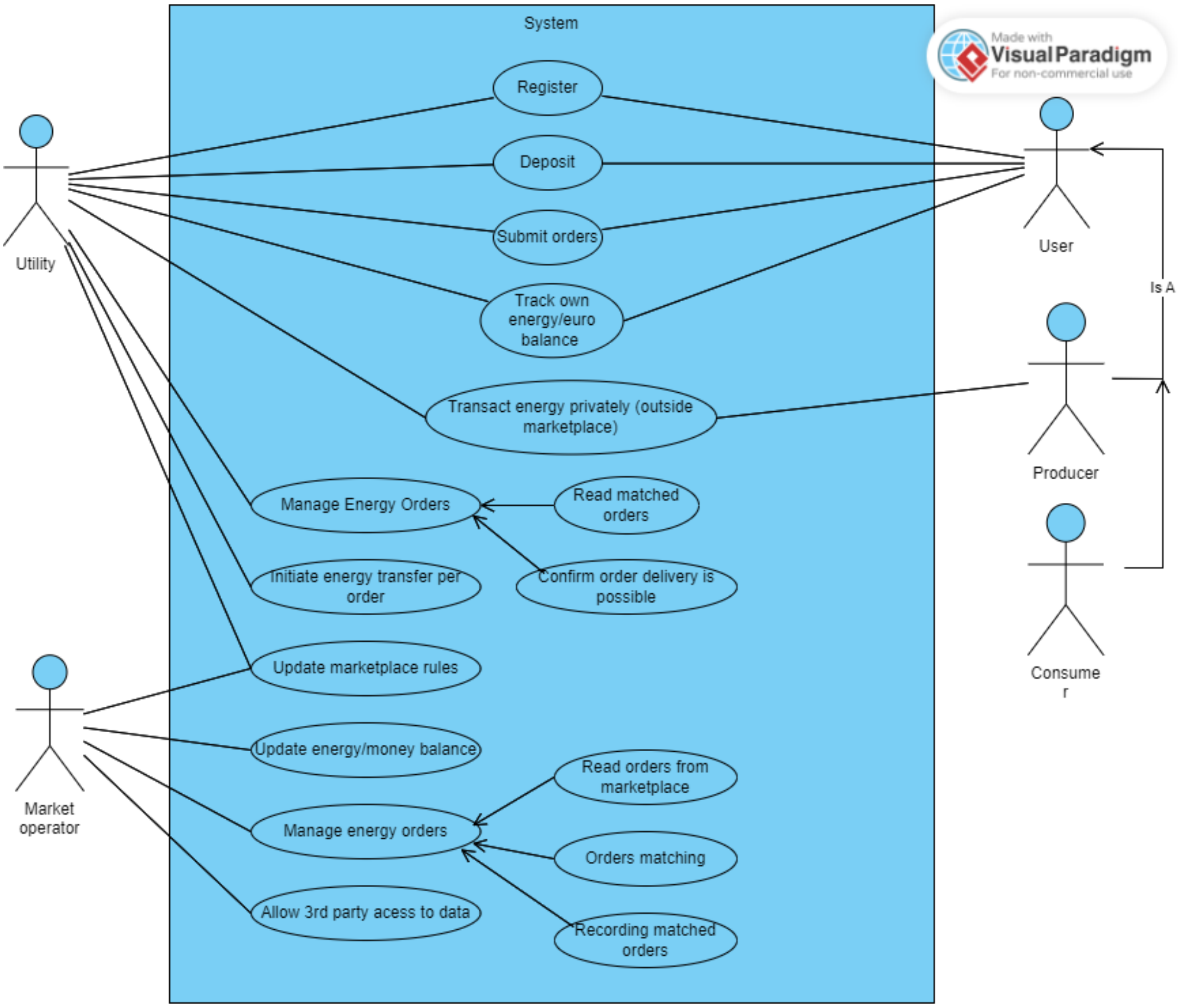

Figure 18: The proposed P2P trading energy marketplace diagram

There are four stakeholders: Platform operator, Users (Producers and Consumers) and Utility company. They have to exchange relevant information through four blockchain channels (channels separate data access physically and logically): Marketplace, Accounting, Utility-To-Producer and Orders-And-Delivery:

- All actors have access to information on the marketplace (buy and sell orders), but while Producers/Consumers/Utility companies can create new orders, the Platform Operator can only read data from this channel.
- The accounting channel stores information about the balances in EURO and kWh for every platform user. Only the Platform Operator can update these balances, while all other stakeholders can read their balances.

- The Utility-To-Producer serves private transacting opportunities that go on between a Utility Company and a Producer directly, where orders are immediately settled (there are no matching orders).
- The Orders-And-Delivery store all matched orders after a bidding window has been closed. Platform Operators run the order matching engine; thus, it has write access to this channel's data. The utility Company also has write access since the possibility of transport/delivery of every matched order must be confirmed.

A business use case diagram of a sample energy trading marketplace is presented in Figure 19.

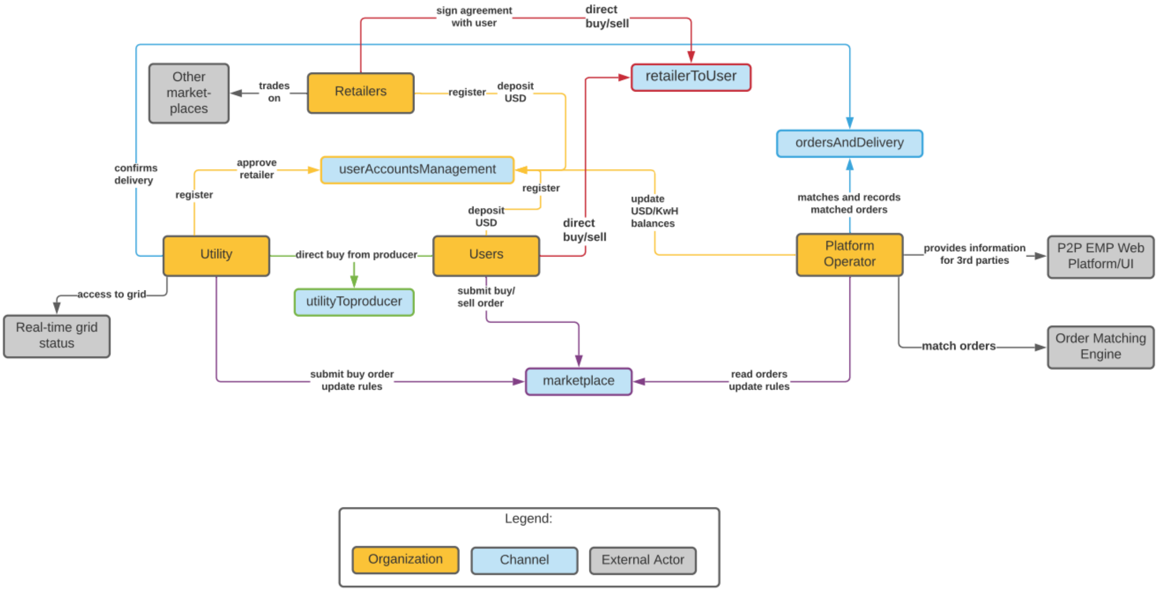

Figure 19: Business use case diagram [23]

Numerous supportive measures must be taken in order to support energy trade. The information about the digital assets that will be stored on the blockchain and the smart contracts that will interact with those assets is shown in the diagram below. The blockchain system should integrate with a Web UI/Platform that will allow a convenient way for users to perform their activities.

Technical overview

The two tiers of P2P trade are the financial layer and the physical layer [9]. The financial layer uses a secured information platform to manage local trade setup and decision-making approaches. While the physical layer oversees the dispatching of energy within actual power grids while adhering to network restrictions set by licensed energy providers. The financial layers, including the Energy management system, Information system, Market operation, and pricing structure, simply offer players a secure link to guarantee that each and every participant has an equivalent approach toward the financial layer. Metering, communication, and grid connection infrastructures compose the physical layer [24].

- Through a particular bidding system, a prosumer's EMS provides an energy supply guarantee while participating in P2P trading. An EMS uses a transactive meter to obtain accurate and real-time access to the prosumer's supply and demand data to achieve this. Based on this information, it builds a demand/production profile and then chooses a bid pricing strategy to participate in energy trade with the prosumer's side.

- Market functioning includes market allocation, a well-defined bidding structure, and payment regulations. Pricing methods must reflect the status of energy inside the P2P network. A high-performing and secure information system lies at the core of the peer-to-peer energy network. There are three types of markets: 1) decentralised-based market, 2) community-based market, and 3) composite-based market.

Regulation overview

Several legal fields, including civil law, consumer protection law, tax law, e-commerce law, and data protection legislation, need to be considered while using Blockchain technology. In this section, an analysis of the literature on regulation and future challenges of peer-to-peer trading and the energy community in the electricity market are discussed. In the broader context of the Social and Solidarity Economy, a new type of cooperative was introduced by the Greek Law on "Energy Communities," which was adopted in January 2018 [25]. The Law gives shape to many of the abstract governance characteristics and rights, privileges, and obligations in these directives while being adopted without the RED II and EMD in mind [26]. A comparison of legal concepts in Greek law to EU regulation is presented in Annex 1. Based on the Bridge report [26]The legal concept of Energy Communities in Greek law is compared with EU regulation. Greek law allows an EC to exercise the same activities as envisioned for REC and CEC, as well as some additional ones, such as energy innovation, energy poverty reduction, and promoting energy sustainability.

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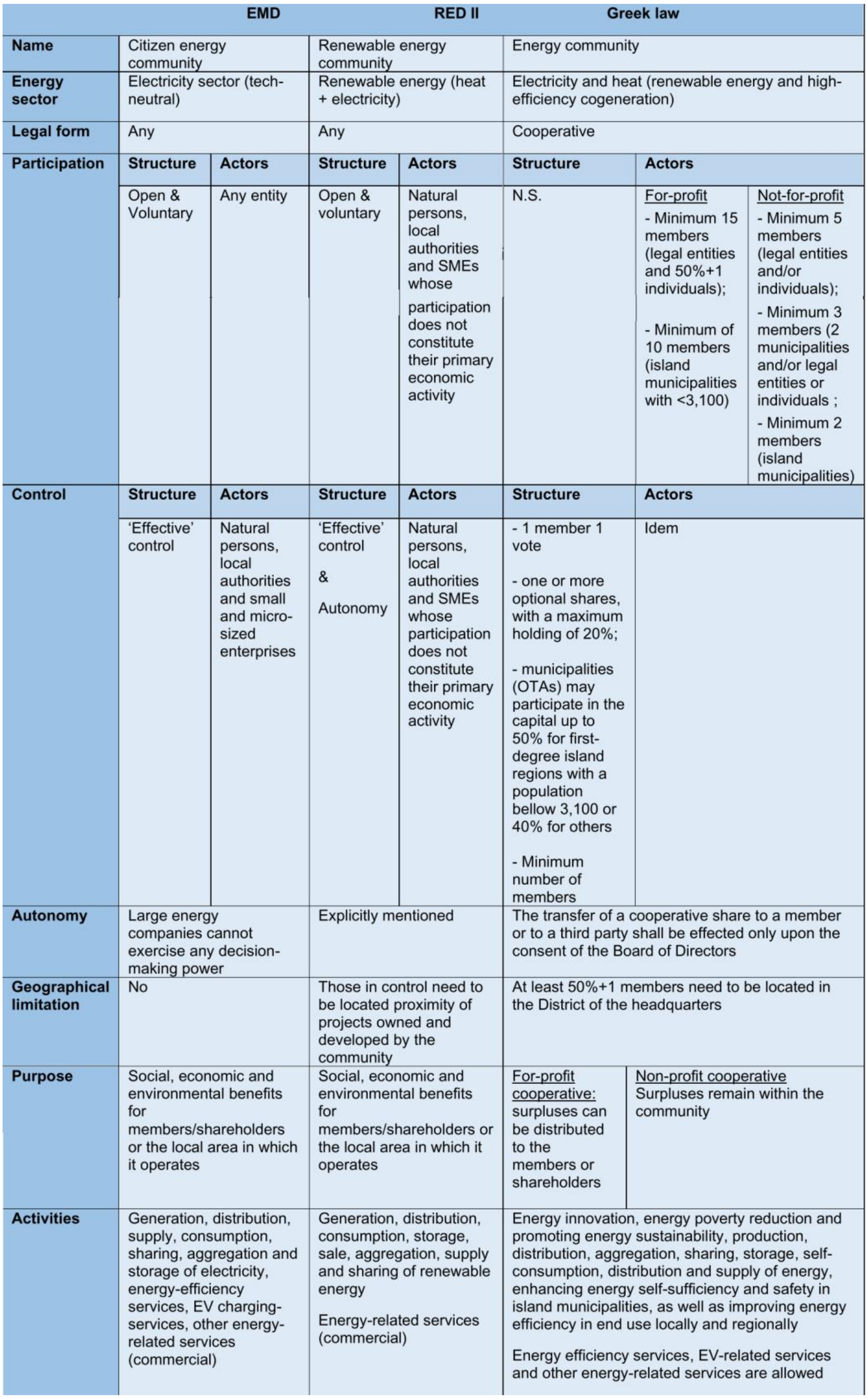
Appendix

A.1. Comparison REC legal concept in Greek law to EU regulation

Table 10: Comparison REC legal concept in Greek law to EU regulation



	EMD		**RED II**		**Greek law**		
Name	Citizen energy community		Renewable energy community		Energy community		
Energy sector	Electricity sector (tech-neutral)		Renewable energy (heat + electricity)		Electricity and heat (renewable energy and high-efficiency cogeneration)		
Legal form	Any		Any		Cooperative		
Participation	**Structure**	**Actors**	**Structure**	**Actors**	**Structure**	**Actors**	
	Open & Voluntary	Any entity	Open & voluntary	Natural persons, local authorities and SMEs whose participation does not constitute their primary economic activity	N.S.	For-profit - Minimum 15 members (legal entities and 50%+1 individuals); - Minimum of 10 members (island municipalities with <3,100)	Not-for-profit - Minimum 5 members (legal entities and/or individuals); - Minimum 3 members (2 municipalities and/or legal entities or individuals ; - Minimum 2 members (island municipalities)
Control	**Structure**	**Actors**	**Structure**	**Actors**	**Structure**	**Actors**	
	'Effective' control	Natural persons, local authorities and small and micro-sized enterprises	'Effective' control & Autonomy	Natural persons, local authorities and SMEs whose participation does not constitute their primary economic activity	- 1 member 1 vote - one or more optional shares, with a maximum holding of 20%; - municipalities (OTAs) may participate in the capital up to 50% for first-degree island regions with a population bellow 3,100 or 40% for others - Minimum number of members	Idem	
Autonomy	Large energy companies cannot exercise any decision-making power		Explicitly mentioned		The transfer of a cooperative share to a member or to a third party shall be effected only upon the consent of the Board of Directors		
Geographical limitation	No		Those in control need to be located proximity of projects owned and developed by the community		At least 50%+1 members need to be located in the District of the headquarters		
Purpose	Social, economic and environmental benefits for members/shareholders or the local area in which it operates		Social, economic and environmental benefits for members/shareholders or the local area in which it operates		For-profit cooperative: surpluses can be distributed to the members or shareholders	Non-profit cooperative Surpluses remain within the community	
Activities	Generation, distribution, supply, consumption, sharing, aggregation and storage of electricity, energy-efficiency services, EV charging-services, other energy-related services (commercial)		Generation, distribution, consumption, storage, sale, aggregation, supply and sharing of renewable energy Energy-related services (commercial)		Energy innovation, energy poverty reduction and promoting energy sustainability, production, distribution, aggregation, sharing, storage, self-consumption, distribution and supply of energy, enhancing energy self-sufficiency and safety in island municipalities, as well as improving energy efficiency in end use locally and regionally Energy efficiency services, EV-related services and other energy-related services are allowed		

Rights, privileges and responsibilities	**EMD**	**RED II**	**Greek law**
General rights and privileges			
Provision of regulatory and capacity-building support provided to public authorities in relation to energy communities	YES	YES	YES
Identification/assessment of barriers		YES	Has started
Removal of unjustified regulatory and administrative barriers		YES	
Tools to facilitate access to finance and information		YES	No
Support scheme that takes into account the specificities of energy communities		YES	Exemption from bidding procedures for projects up to 6 MW for wind farms and 1 MW for PV; and a budget of 12,5 million euros managed by CRES
Type of support		YES	Operational and initial investment support
Production	Allowed	Allowed	Allowed
Rights			
Fair, proportionate, non-discriminatory and transparent production licensing and registration procedures	YES	YES	Priority consideration and exemption production license within Region where the energy communities' HQ is located
Transparent, non-discriminatory and cost-reflective production charges	YES	YES	Exemption from the obligation to pay the annual fee for retaining an electricity production license
Responsibilities			
Distribution	Discretion MS	N.S.	Allowed (restricted based on location)
Rights			
Own, establish, purchase, lease a private/public distribution network	YES		YES
Autonomously manage	YES		YES
An agreement with the DSO	YES		YES
Responsibilities			
Unbundling requirements	YES		Not specified
Regulated third party access	YES		
Negotiated third party access	Maybe by exception		YES
Supply	Allowed	Allowed	Allowed
Rights			
Fair, proportionate, non-discriminatory and transparent supply licensing and registration procedures	YES	YES	The same procedures apply
Transparent, non-discriminatory and cost-reflective supply charges	YES	YES	Minimum supply licensing capital is reduced to € 60,000
Responsibilities			
Respect the freedom to switch suppliers	YES	YES	YES
Financially responsible for imbalances	YES		YES (can be delegated)

Rights, privileges and responsibilities	**EMD**	**RED II**	**Greek law**
Sharing	Allowed (for the electricity produced by the production units owned by the community)	Allowed (for the electricity produced by the production units owned by the community)	Allowed (for the electricity produced by the production units owned by the community)
Rights			
Cooperation of the relevant DSO to facilitate transfers	YES	YES	YES
Subject to applicable network charges, tariffs and levies	YES	YES	Virtual net-metering
Collective self-consumption	Allowed	Allowed (building level)	Allowed (building level), but N.S.
Rights			
Cost reflective, transparent and non-discriminatory network charges	YES	YES	(Virtual) net-metering
Aggregation	Allowed	Allowed	Allowed (for the electricity produced by the production units owned by the community)
Storage	Allowed	Allowed	Allowed
Sale	Allowed	Allowed	Allowed
Rights			
Access to all electricity markets either directly or through aggregation in a non-discriminatory manner	YES	YES	YES (through aggregator)
Energy-efficiency services	Allowed	Allowed	Allowed
Other energy-related services	Allowed	Allowed	Allowed
EV charging services	Allowed	Allowed	Allowed