VPP4ISLANDS

Virtual Power Plant for Interoperable and Smart isLANDS

VPP4Islands

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GA 957852

Deliverable Report

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REVISION AND HISTORY CHART

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1.0	06/07/21	Robert Garner, Geert Jansen, Zahir Dehouche	Document reviewed by FTK and CU, with suggested changes made.

List of abbreviations and Acronyms

Abbreviation	Meaning
DER	Distributed Energy Resources
DT	Digital Twin
DLT	Digital Ledger Technologies
DSO	Distributed Service (System) Operator
EMS	Energy Management System
ESS	Energy Storage System
FIT	Feed in Tariff
GHG	Greenhouse Gases
NPV	Net Present Value
LIS	Laboratoire Informatique des Systèmes
IPR	Intellectual Property Rights
IRR	Internal Rate of Return
PPA	Power Purchase Agreement
PVM	Protisvalor Méditerranée
RES	Renewable Energy System
TSO	Transmission Service (System) Operator
VESS	Virtual Energy Storage System
VPP	Virtual Power Plant
CVPP	Commercial Virtual Power Plant
TVPP	Technical Virtual Power Plant
BRP	Balancing Responsible Party
BSP	Balancing Service Provider
LCA	Life Cycle Assessment
LCOE	Levelised Cost of Electricity

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List of Partners

Abbreviation	Meaning
ALWA	AlgoWatt
AMU	Aix-Marseille Université
BC2050	Blockchain2050
BORN	Bornholms Varme A/S
BoZI	Bozcaada Belediye Baskanligi
BUL	Brunel University London
CIVI	CIVIESCO srl
CSIC	Consejo Superior de Investigaciones Científicas
CU	Cardiff University
FORM	Consell Insular de Formentera
FTK	FTK Forschungsinstitut fur Telekommunikation und Kooperation EV
GRADO	Commune di Grado
IDEA	Ingenieria Y Diseno Estructural Avanzado
INAVITAS	INAVITAS Enerji AS
RDIUP	RDI'UP
REGENERA	REGENERA LEVANTE
SCHN	Schneider Electric
TROYA	TROYA CEVRE DERNEGI
UEDAS	Uludag Electric Dagitim

Nomenclature

Name	Symbol	Unit
Net cashflow during a single period $\boldsymbol{t}$	C_t	€
Discount rate of return targeted	R	%
Index number of time periods	t	years
Maximum number of time periods	n	years
Capital cost during a single time period $\boldsymbol{t}$	CC_t	€
Maintenance cost during a single time period $\boldsymbol{t}$	M_t	€
Fuel cost during a single time period $\boldsymbol{t}$	F_t	€
Energy generated during a single time period $\boldsymbol{t}$	E_t	kWh

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Executive Summary

The market for distributed Renewable Energy Systems (RES) has been increasing considerably in recent decades due to several economic and climate related factors. The vision of the VPP4ISLANDS project is to develop novel and advanced concepts for energy production, distribution, and monitoring on geographical islands, by promoting the use of RES. The Virtual Power Plant (VPP) would not be considered as a conventional power plant but as a modular green energy system that can store surplus energy and be explicitly controlled to support island growth and change in energy demand, climate, and electricity market. The define of a VPP is given below:

"A flexible and virtual portfolio of DERs connected through the use of communication technology to be represented as a single power entity. The system utilises advanced learning methods to accurately forecast the optimal operation based on environmental conditions, required grid services and performance objectives". [1]

This report builds upon existing knowledge of VPPs within literature and industry and their enabling technologies to define a novel VPP concept. A comprehensive diagram for the VPP concept architecture is presented, explaining the multilevel control and services strategy, and applying this to the lead islands of Gökçeada and Formentera with modelling system.

1.1. Project Motivation

The European Council for climate action set out a target of at least 27% share of renewable energy usage within the EU by the year 2030, and a total 40% domestic reduction in greenhouse gas emissions compared to 1990 [2]. These energy targets were agreed with the objectives of the 2015 Paris Agreement on Climate Change following the 21st Conference of the Parties to the United Nations Framework Convention on Climate Change. This agreement aims to prevent global average temperatures from rising by 1.5°C, with a contingency aim of keeping well under 2°C compared to pre-industrial levels [3].

One of the major strides that Europe has taken is in significantly increasing the capacity of Renewable Energy Systems (RES) into the energy grid with the aim to achieve the previously described international objectives and curb the worst effects of climate change. One commonly identified problem with increasing RES in the energy grid is the reduction in dispatchable generators to reduce the differences between supply and demand during times of high grid stress. The continued installation of RES without significant intervention from both technical industries and policy maker will exasperate these problems. A method of realising the added value that

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exporting clean energy can add to the grid system would need to be required in order to continue reducing the carbon emissions of energy generation towards national and international targets. The proposed VPP system within this report will be used to provide solutions to the energy grid problems on geographical islands, where they will be used as an experimental platform to assist in accelerating the European and global efforts to achieve a zero-carbon society.

The report presents the concept definition of the VPP4ISLANDs architecture, with all necessary components and systems to perform the target services and scenarios for the lead islands. The central objectives are to reduce the emissions impacts of these islands in a reliable way that does not impact the local energy costs for the end user. The architecture will be used by later tasks and deliverables and provide a foundation for system integration and management of services and scenarios.

1.2. Key Results

Virtual Power Plants Review

Highlighted and discussed the key outcomes of each system, system structure and provided services to the energy grid. Discussed the importance of a clear and concise business model for services provision to ensure the success of the VPP. Noted the challenges and shortcomings of some VPP models, including stakeholder communication and the requirement for field data collection. All critical outcomes including benefits and challenges of the various VPP systems were brought forward to inform decision making for the concept definition.

Analysis of Physical and Virtual Enablers

This section presents analysis of the identified enablers to be developed within the VPP4ISLANDS concept. There are a number of different RES and ESS with varying degrees of suitable of VPP applications, it was noted that a combination of ESS technologies may provide the most flexible solution. Flexible loads could play a vital role in the true energy demand reduction and decarbonisation of geographical islands, however, are more difficult to directly control and have lower available flexibility than ESS. The key virtual enablers of DLT, forecasting tools, digital twin can bring many benefits to the concept, such as decentralised communication and optimisation, which has the potential to significantly reduce running costs over a centralised approach. Challenges include ensure secure and tamperproof transfer of sensitive information, and the ensuring steady uptake of the relatively new technology.

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VPP4ISLANDS Concept Definition

The concept architecture is categorised into a three level VPP system consisting of the VPPIBox, VPPINode and VPPIPlatform as presented in Figure 26. The VPPIBox is an enhanced RTU and smart metering that is able to measure all required power generation consumption variables to be used in the system and can also control variable loads and provides the location for the DLT based P2P trades to take place. The VPPINode is the local level centralised location for the devised VPP4ISLAND services to take place. This level receives unified and homogenised data from the VPPIBox before storage in the node level database for use in processes such as local forecasting, balancing services provision, scheduling optimisation and Energy Management System (EMS) commitment engine. The VPPIPlatform is the cloud-based service for the VPP4ISLANDS system, which aggregates all known knowledge of the VPP installations and stores in the shared Knowledge Base (KB). This allows for additional data elaboration and secure sharing with VPP stakeholders and other parties. The cloud platform also contains the Digital Twin for enhanced system monitoring. The aim of the DT is also to be able to test new systems and components without the requirement for field testing, reducing risk and project costs. Identified performance improvements can be relayed back to the VPPINode level to be used in the system.

Energy System Concept Models

Presents an analysis for the application of VPP concepts to the two lead islands of Gökçeada and Formentera. The Formentera ‘energy communities’ concept is explored, with the optimised sizing of a hybrid hydrogen fuel cell and battery energy storage system. The proposed optimised energy system contains an energy mix of 90 kW Solar PV for primary power generation coupled to a 75kWh Li-Ion battery and a Regenerative Hydrogen Fuel Cell (consisting of a 20kW PEM Electrolyser, 1,000kWh Hydrogen Storage, and 5kW PEM Fuel Cell). Results show that the system is able to effectively reduce both the emissions intensity and energy cost of consumption by 54.8% and 10.8%, respectively. The average system efficiency over the simulation time (6 months) is approximately 56%. The hybrid energy system concept is also applied to Gokceada to balance a selected number of end users with the RES generation from wind turbines and VP solar. The results show the optimised system to consist of a 1,000kWh Lithium-Ion battery combined with a 10,000kWh hydrogen storage, which is charged using a 15kW electrolyser while electricity is regenerated by a 30kW fuel cell. Results shows that while successfully able to reduce the emissions impact by over 70%, a minimum increase in energy cost of 2% was observed. While additional optimisation and modifications can be made to the model, it could be used as a foundation for any additional development of energy storage field equipment within this project.

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1.3. Summary

This report presents an in-depth description of the process and methodology for formulating the proposed VPP4ISLANDS concept.

A VPP literature review is first adopted to inform the requirements for a novel concept, including the required inputs, physical and virtual enablers, services, and stakeholder interactions that drive a successful VPP. Also noted were some of the challenges to implementation which build upon those discussed in 'D2.2 Obstacles to Innovation' deliverable.

Identification and analysis of the required physical and virtual enablers is then utilised in the design decision making for the proposed VPP4ISLANDS concept. The devised three level architecture allows for maximum flexibility in services and scenarios and contains all the necessary components for a successful system. A high-level description of each component interaction is also included but is explored in more detail in the 'D2.5.1: VPP4ISLANDS Specifications' report.

Overall, it is hoped that this description of the VPP4ISLANDS concept may provide a useful design roadmap for the future development of the envisioned system, for the purposes of decarbonisation and increased energy security of geographical islands.

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2. Review of Virtual Power Plants within Literature and Industry

Before defining an appropriate VPP concept to be proposed for the lead island participants, it is important to first identify notable and successful VPP concepts and systems that have been implemented. Since the technology is in its early adoption stage, most examples within literature point to technical showcases that have been tested on a small scale in partnership with TSOs and DSOs of the host countries. The concepts often require fundamental modifications to the method in which energy generation is handled and value is redistributed among aggregators and participants.

The studied systems also range in the variety of services that are supported and is often based on stakeholder restrictions and regulatory challenges for the given host country. Table 1 details the key aspects of the VPPs in literature, including a summary, provided services, and stakeholder involvement. The list also includes a brief description of peer-to-peer trading based 'microgrids', which by definition are subtly different to VPPs. The P2P concept architecture, however, is important to analyse for the purposes of the concept definition.

Table 1: summary of VPP and peer-to-peer microgrid systems in literature

VPP/Microgrid	Location	Summary	Services	Stakeholders
Fenix (2005-2009) [4]	UK, Spain	One of the first VPPs to address increasing visibility by aggregating DER and pass information to the TSO to assist in planning infrastructure upgrades, transmissions and assessing congestion problems	-DERs can be made visible to network operators -Contribution of DERs to grid management activities -Optimal use of DER in ancillary services	-Network operators (DSO, TSO) -DER owners -Grid regulators -Energy spot market
TWENTIES (2010-2013) [5]	EU various	'Power Hub' proposed as part of the project to provide VPP style flexibility services from large scale offshore wind farms and other DERs	-Ancillary services (voltage and frequency control) -Optimise outputs from	-Network operators (DSO, TSO) -DER owners -Grid regulators

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			available resources -Provide cost reductions through increased energy security	-Energy spot market
Con Edison (2016-2017) [6]	New York, US	Aggregation of 1.8MW capacity DERs with energy output of 4MWh.	-Network resiliency (outage support) -Power delivery smoothing -Load shedding and shifting	-Network service providers -Prosumers -Green energy companies and retailers -Energy Retailers -Energy spot market
AGL VPP (2018-) [7]	South Australia	The creation of a 5MW from a combination of 1000 prosumer residents (PV solar and batteries, during trail period)	-Voltage control -Frequency balancing -Der visibility	-Network service providers -Prosumers -Retailers
Piclo (2018-) [8]	UK	Online energy trading platform for flexible capacity auctions for independent Der generators to participate, allowing small players to participate in the energy marketplace.	-Demand side response -System regulation -Energy marketplace (primary, secondary response) -DER visibility	-Network operators (DSO, TSO) -DER owners -Grid regulators -Spot market regulator -Energy regulator
Brooklyn MicroGrid (2016-) [9]	Brooklyn, NY	A peer-to-peer energy platform for a local energy market to support weak energy grid and produce value from DER	-peer-to-peer energy trades -Grid support	-Network operators (DSO, TSO) -Prosumers and consumers -Local market operator
SonnenCommunity (2017-) [10]	Germany, Austria	Sharing excess DER generation among over 10,000 end-	-peer-to-peer energy trading	-Network operators (DSO, TSO)

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		users. Energy value is traded for the mutual benefit of all those in the community	-mutual DER value increase -Shared Virtual Energy Storage System (VESS) -Optimal real time energy balance	-DER owners -Grid regulators

2.1. VPP Concept Summaries

FENIX (2005-2009)

It is well understood that the increase in penetration of DER into the traditional energy grid reduces the amount of visibility and therefore ability of network operators to be able to plan supply and demand balancing effectively. As one of the first ever VPP concepts to present pilot demonstrations, the 'FENIX Future' aimed to represent the increased system capabilities on DER whilst removing barriers and negative impacts. The project began in 2005 and consisted of 20 partners from research and industrial EU partners, largely from the UK and Spain, to meet the challenge of future DER integration.

As noted in [4], the objective of FENIX was to design and demonstrate both technical and commercial architectures that would increase the viability of increased DER in Europe as a solution for the approaching green energy future. The key aim, in alignment with the simple definition of a VPP to represent DER as a single system which both generators and consumes energy, as shown in Figure 1. The concept is categorised into a Technical Virtual Power Plant (TVPP) and a Commercial Virtual Power Plant (CVPP).

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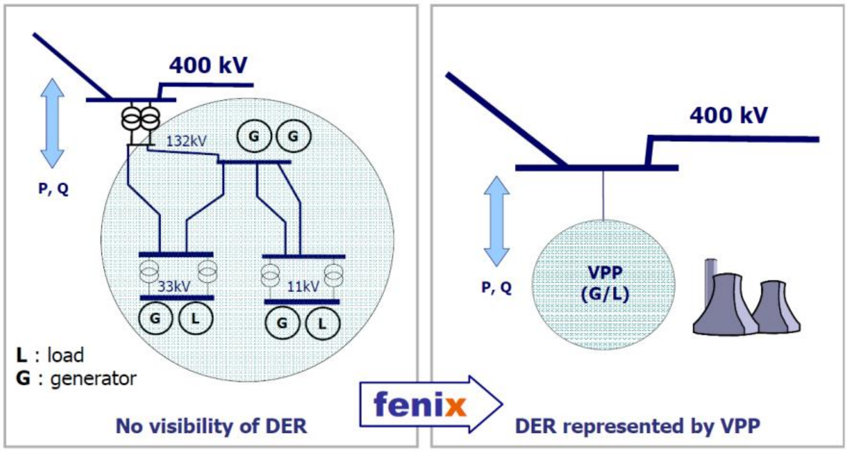

Figure 1: The FENIX VPP concept [11]

*TVPP***:** represents the physical DER as installed in the geographical location, including records of the real time influence of the aggregated system, as well as cost and operational characteristics. The main purpose is to allow of DER visibility, from which other functions include local grid system management and informed decision making for system balancing. In addition, the aggregation of many DER reduces the risk of unavailability from any one unit within the system, and therefore can smooth the output of the VPP. The operated could be the DSO but may face regulatory challenges as particularly in the UK, the DSO is not able to operate generation units [12].

*CVPP***:** represents the higher-level commercial services and function of the VPP portfolio, such as wholesale market participation and balancing services provision, and maximising the DER participation. It is known that these services face more stringent regulatory challenges due to the structure of the traditional energy market. The CVPP performs only commercial services and does not consider technical aspects.

Given that FENIX was one of the first VPP projects to present a pilot study, many of the technical requirements and enablers were first outlined within this project which could be built upon by others. It can be seen that the main architectural property was in separating the physical components such as generators, consumers, and storage from the virtual and commercial aspects of services support, data management and market participation with the TVPP and the CVPP. This is an important process in that it clearly highlights the challenge of combining these two domains using the VPP and can be more easily understood and engaged with. Although nomenclature can vary, this is a common conceptual structure of many later VPPs which go on to have successful pilot studies and commercial rollout.

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Edison

The Edison project was launched as part of the smart energy system drive on the island of Bornholm, Denmark. The project investigated how a large number of Electric Vehicles (EVs) could be integrated such that grid support can be offered for the mutual benefits of both the EV owners and grid operators. The motivation for the project was that with the projected rise in EVs in Europe will increase the demand on the grid during certainly times of the day, which could have an adverse effect on the reliability of the system when heavily loaded. Like the following WEB2ENERGY VPP, the Edison project builds upon the recommended set of IEC 61850 communication protocols and security measures.

The EVs connected within the Edison EVPP can be considered as a large power consumer which are also able to provide balancing at peak demand. This operates by modulating the rate of charge entering the EV such that the grid demand can be shifted to reduce stress. Like other projects, Edison uses a two-level environmental approach, with the 'electrical layer' consisting of physical components (EVs, DSO metering, generation) which can be represented with physical laws and constraints, and the 'electricity market' layer consisting of the commodity trading systems and various stakeholder involved in the clearing and billing processes.

The concept defined allows for two defined architectures to be presented. An integrated architecture approach requires an existing Balancing Responsible Party (BRP) such as power-generation or utility company to perform the interactions with the TSO and sport market on behalf of the EVPP, as shown in Figure 2. The BRP can use all the collected data from the systems metering and EV charging locations such as demand, generation, state-of-charge, and available flexibility to make decisions about when to perform the market interactions. By contrast, a standalone architecture absorbs the role of the BRP into the function of the EVPP such that it can interact with the market as an individual player. The EVPP would require additional intelligence to be able to make such scheduling decisions, and as discussed in within the previous 'D2.2 Obstacles to Innovation' report, will likely be met with additional policy and regulatory barriers when applying to bid on a national or international spot market [1]. Figure 2 below displays the similarities and differences in the two architectures.

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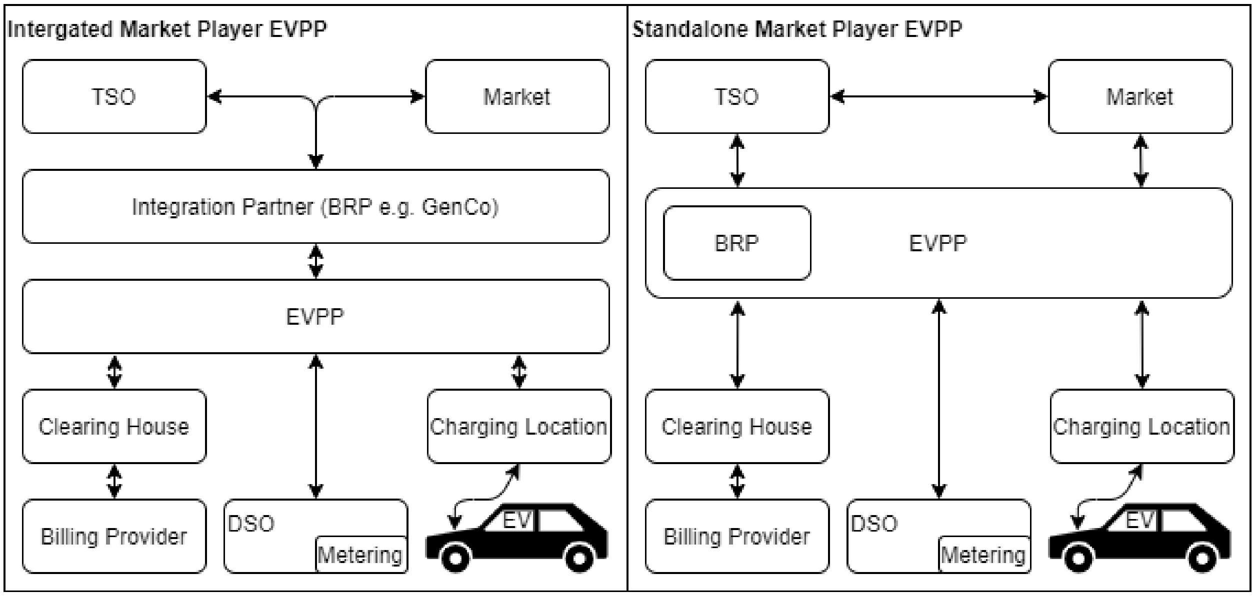

Figure 2: The integrated and standalone architectures presented as part of the Edison VPP (modified from [13])

There are advantages and disadvantages to both methods presented, however it would be more sustainable long term for the VPP to be able to act as a standalone entity for the purposes of cost saving and reducing the required stakeholder interaction. The project as in some ways ahead of its time as it anticipates the increase in future EV usage far before true widespread adoption. It is not known if the Edison VPP concept was successfully tested in field, likely due to lack of requirement at the time of research, and other regulatory challenges. Continued research into an EV based fleet VPP system was still ongoing in Denmark as of 2018 [14].

WEB2ENERGY

Web2Energy is a European project started in 2008 with the objective of implementing what is described as the three main pillars of 'Smart Distribution'. These three pillars are described as follows [15]:

*Smart Metering***:** the project implemented hundreds of consumer smart meters in the field to provide a number of innovative functions, including management of price signals, interruptions and failures, loads, generation, and demand profiles. This would allow the other two pillars to function.

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Smart Energy Management: Following the definition of a VPP, this pillar requires a large number of small independent DERs which are cooperatively controlled such that scheduled power can be manipulated for the given requirement in real time. In the Web2Energy, over one hundred smart meters were connected in five locations, with non-dispatchable generators such as wind turbines and PV solar connected to dispatched generators including CHP, pumped hydro storage, and controllable industrial loads. The generators can be scheduled for greater overall dispatch efficiency and reduce power losses within the system.

Smart Distribution Automation: The web2Energy project implements automatic grid support to reduce the probability of outages and increase overall reliability within the low and medium voltage levels (distribution side).

The project consisted of 5 CHP plants, 12 storage batteries (12x100kWh), 12 PV solar farms, 3 wind farms, 2 hydro plants, 3 large industrial loads, and involved 200 residential consumers in a 1-year Demand Side Management (DSM) study. Outcomes of the project highlighted the requirement of a standardised communication system for the smart systems to interact effectively, as well as the restrictions and market regulations that, like other VPP projects, hinder the realisation of many revenue streams that would otherwise be available. The project was also one of the first studies to explore the requirements of a commercially viable VPP system and was able to identify many components that are vital for future VPPs and the VPP4ISLANDS concept, including communication tools, energy management, and smart distributed generation.

TWENTIES

The aim of the EU TWENTIES project was to advance new technologies that would assist in integrating the ever-increasing penetration of onshore and offshore wind generation. Specifically, the demonstration project 2 invested a large-scale integration of a VPP ‘Power Hub’ to reliability deliver ancillary services such of voltage control and frequency balancing through intelligent control of the wind farms. The Power Hub was able to optimise the outputs of the different wind turbine units to provide the highest value of energy generation. The results from this project also indicate that the introduction of biomass and heat pumps could reduce the CO_2 emissions by 3.46% in comparison the main German power system (2013) [5]. Figure 3 below shows the VPP concept as visualised in the TWENTIES project, showing the variety of potential assets that could be implemented.

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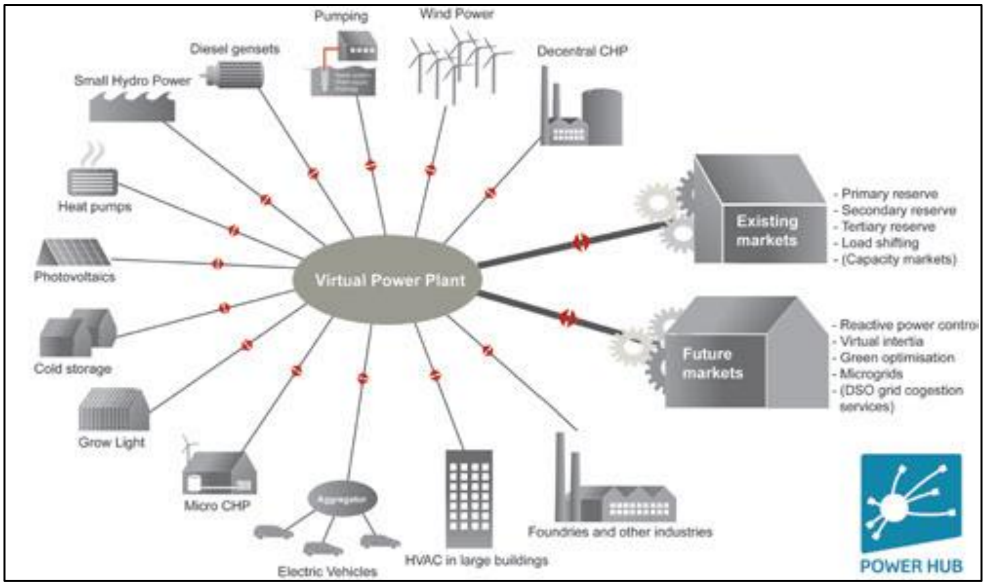

Figure 3: The VPP concepts developed as part of the TWENTIES project [5]

The main findings for the project were that the field tested ‘Power Hub’ was able to reliably deliver ancillary services such as voltage control and continuous reserves, as well as provide an optimised output to maximise value to all included generator units. Although the results were economically feasible, technical challenges were also identified. One of the challenges is the initial incentivisation for generator and industrial units to take part in the scheme and expand the size of the VPP. Another key challenge was in scaling up the VPP commercially due to the market and regulatory design in the test countries of Denmark, Germany, and Spain. The latter is certainly a common barrier that has been identified by multiple other VPP projects.

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Con Edison (2016-2017)

The Consolidated Edison Company of New York, Inc ('Con Edison') VPP was a project to create an aggregated RES platform created in partnership with SunPower for managing and dispatching distributed generation in the most efficient and cost-effective way. The motivation of the pilot project was to demonstrate a method in which combining PV battery systems in hundreds of homes could be reliably and remotely operated to fully realise the monetisable benefits. The project plan in [6] highlights the areas of New York that experience peak demand during the day and during the night. It is clear from the map in figure that as most of the high demand occurs at night, the PV solar generation should be shifted through the use of battery storage.

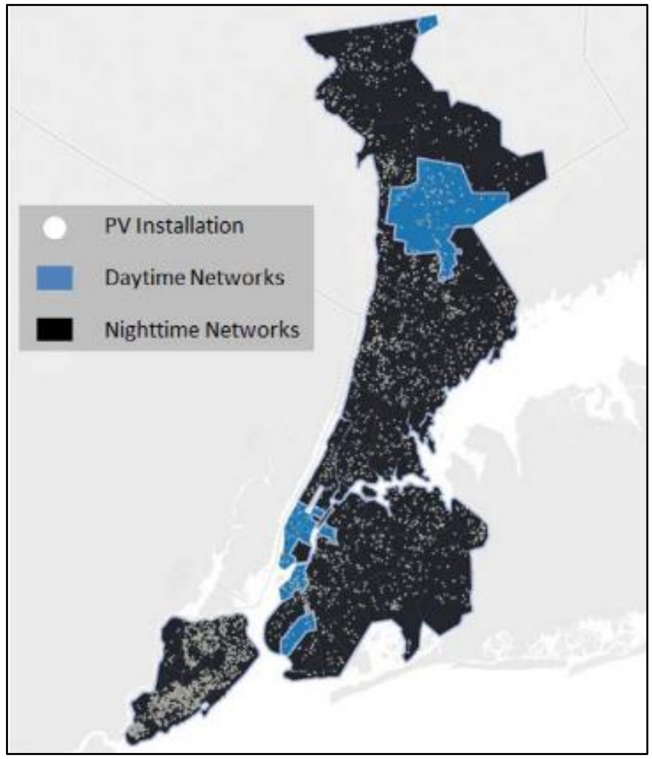

Figure 4: The Con Edison VPP location with PV installations and indication of peak demand time of day [6]

The pilot was categorised into three consecutive phases that each build upon the successes of the previous steps: customer adoption of resiliency services, VPP integration, and market participation.

Phase 1: Customer Adoption of Resiliency Services

This phase consisted of SunPower presenting an inclusive PV and storage package to residential customers to expand the capacity of the VPP. The chosen economic model stipulated that no upfront cost would be imposed on the customer, instead returns would be made back over the usage life of the system. The project estimated that with a market firm capacity value of $20 per kW per month, the inclusion of resilience fees would bring the Internal Rate of Return (IRR) to approximately 3 years before profit generation, as shown in Figure 5. These values were based on 2014 storage system costs, the report suggested that in the current year (2021) the system would be economically viable.

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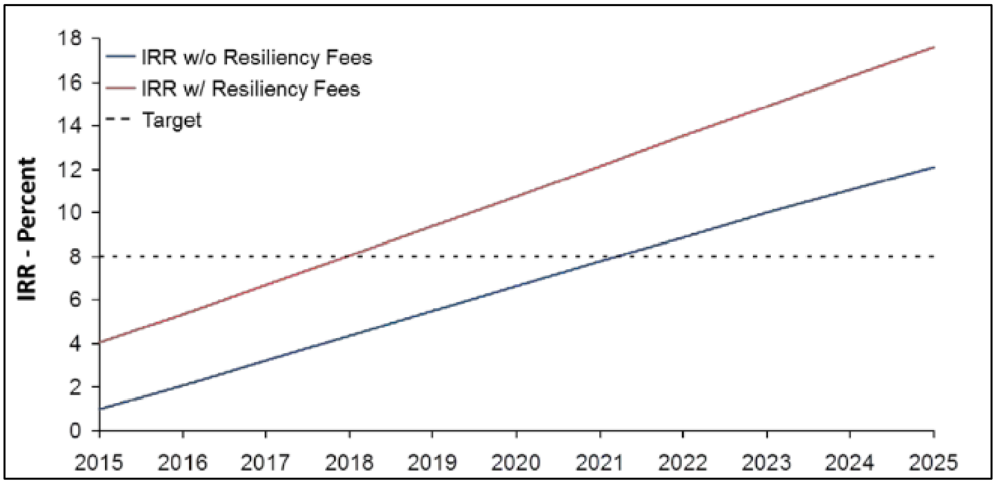

Figure 5: IRR of the hybrid VPP fleet based on value of firm capacity value [16]

Phase 2: Virtual Power Plant Integration

After the initial customer installations phase, the project would then move to produce a communication network of each end user's PV storage system. This process required upgrading Con Edison's existing SCADA system with smart meters so that services and control requirements can be communicated effectively. The system could also be performance tested to check the VPP response to certain operation inputs so that risk can be analysed before entering the capacity and spot markets.

Phase 3: Market Participation and Rate Design

Once the VPP integration with Con Edison's SCADA system is successful, the energy company would then explore method of market participation, although it was noted at the time of planning that there were currently no methods to do so given the regulatory barriers. In addition, alternative residential rate design such as Time of Use (TOU) cost was to be explored in order to incentivise participants in the VPP to maximise their flexible for the aggregated system [6].

The project has a promising background of stakeholders, including the DSO Con Edison and two large renewable energy companies SunPower and Sunverge. Unfortunately, significant challenges arose when seeking approval from local regulatory and community bodies to have access to and install the conceptual equipment in the required buildings. It is believed that the complexities of the installation, uncertainties and risk associated with the untested design meant that it was unfavourable with end users. The delay caused the termination of lead industrial

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partner SunPower's contract, and the project has been on hold since Q1 2017 [16]. This highlights one of the fundamental barriers that affects many VPP pilot studies and commercial rollouts.

AGL VPP

The AGL VPP is a large-scale distributed PV solar and battery hybrid system which has been in successful commercial operation in Australia since its trial period in 2018. The system consisted of 1000 end users from residential, commercial, and industrial sectors, and are now expanding to cover 50,000 households as of 2019 to produce 250MW of flexible demand, which is approximately 20% of the demand of South Australia [7]. The installation of the PV battery hybrid system in both AC and DC coupled modes are shown in Figure 6.
The main service of the VPP is to provide balancing services to the grid that would otherwise be provided by traditional synchronous generators. In partnership with Tesla, installed wall batteries can be remotely operated to inject, hold, or absorb energy to keep a balance between supply and demand. Results showed that the VPP could react to dispatch 'events' such as frequency fluctuations in as little as 6 seconds, theoretically allowing participation in Australia's contingency Frequency Control Ancillary Services (FCAS) market [7]. The map in figure shows the distributions of VPP PV battery sales in terms of citizen demographics.

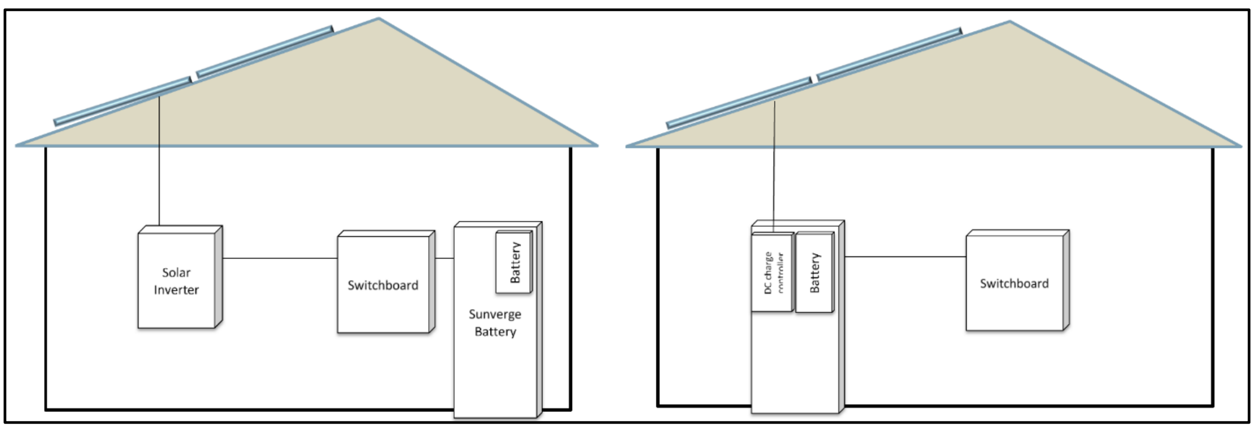

Figure 6: AGL hybrid end user system with AC coupled (left) and DC coupled (right) modes [17]

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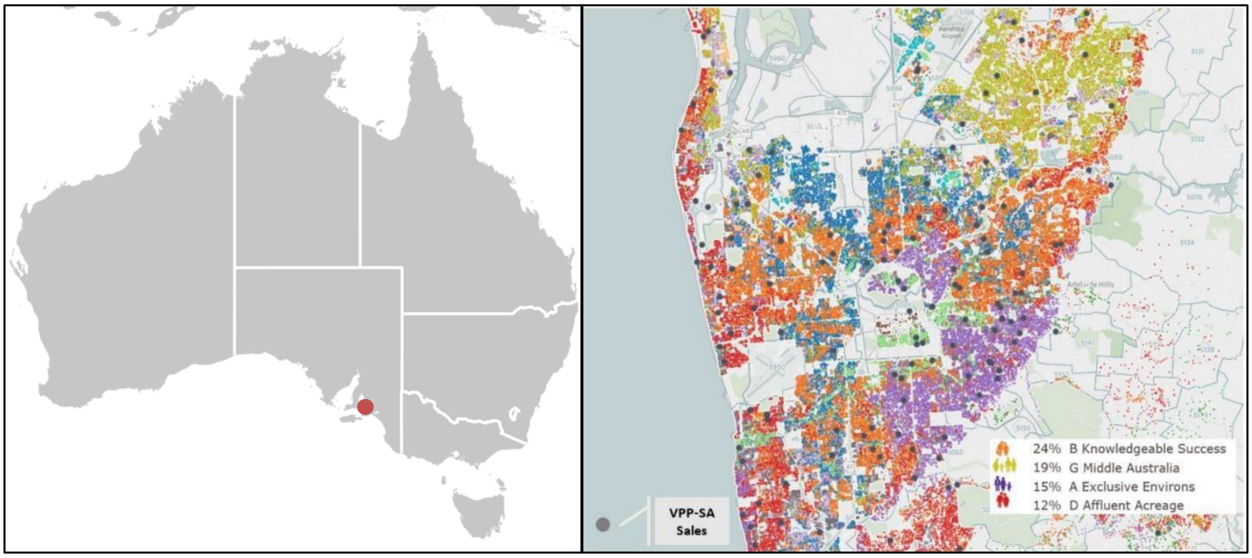

Figure 7: Location of VPP in Australia (left) and Distribution of VPP sales map of Adelaide (right) [17]

During the trial phase, the VPP showed successful ability to track the required power dispatch during a simulation frequency fluctuation event. In the example shown in Figure 8, the system power response from battery storage is displayed and compared with the target power output on a 6 second time frame. It can be seen that even on a modulation scale as small as this that the system is successfully able to track the required output.

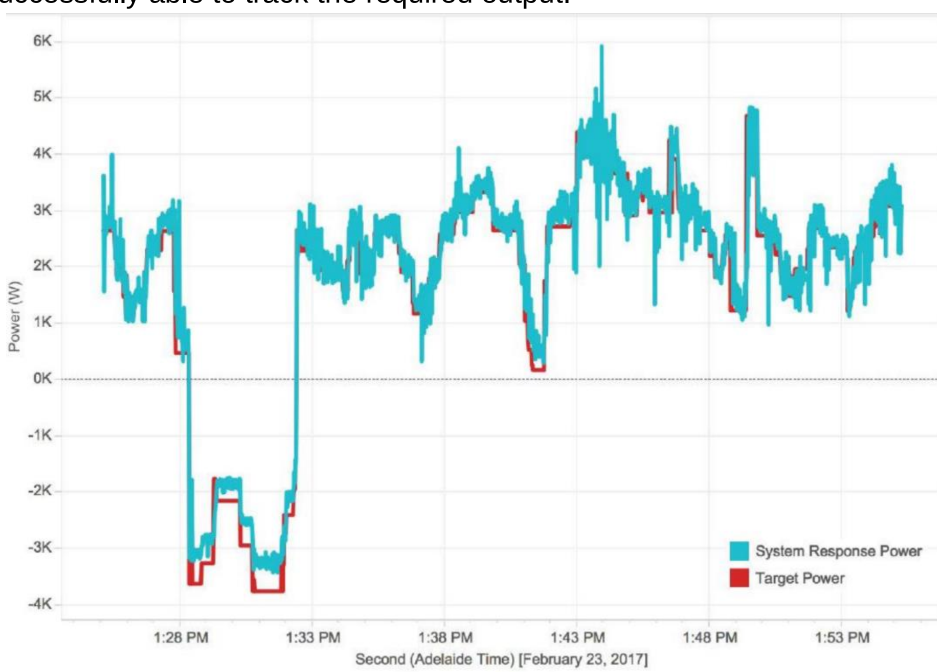

Figure 8: Example dispatch response from the VPP battery fleet compared to the target response [17]

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A major advantage of this type of VPP design is that it unlocks several lucrative value streams, such as increasing solar self-consumption, utilising back up power during an interruption, network support during peak power, frequency control services, and the potential energy arbitrage opportunities on the spot market. Additionally, the VPP project is overseen and managed by an established energy utility company, which assists in setting up the correct stakeholder communication pathways, including end users, field installers, DSO, TSO, regulators, and the spot market. Through the dislocation of the required traditional balancing generators, the system can also be seen to significantly cut the carbon impact of energy usage. A specific challenge that will need to be addressed in the VPP4islands concept is how to interact effectively with these stakeholder entities.

2.2. VPP Concepts Analysis

This section presents a review of the state-of-the-art VPP systems within literature. It can be seen from the research presented that VPP system design can vary significantly depending on a number of environmental factors and constraints.

The Fenix VPP system is unique as the first true concept to be explored and have real pilot studies conducted. One of the first key differentiating characteristics is in the distinction between the TVPP which handles the technical control and scheduling processes, and the CVPP which handles commercial and market interactions with stakeholders. Communication and integration between these two architectures is vital to the smooth operation of the VPP. Research presented on the Danish Edison VPP highlights the potential market interaction designs that could be integrated into the VPP4ISLANDS concept. It has been noted that the available services and commercial success of a VPP depends heavily on the market regulation and policies of the local region. The availability of a standalone BSP to aggregate services into a single energy flow schedule would significantly benefit the commercial operation of the VPP and allow for additional streams of revenue.

The commercially successful VPP concepts including the Australian AGL VPP have been able to display the economic viability of this type of technology. The AGL VPP itself is relatively simple in principle and only had a few couple output services that are delivered. The first key service is demand and supply balancing for the FRR market in Australia, and the second is the available of emergency energy storage of thousands of energy customers with the required PV solar and battery system installed. The success of the system is due in part to the management of the project by the DSO, AGL. It is therefore more reasonable to be able to access the appropriate

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technical measurement data and market pathways to integrate the VPP into the traditional energy grid.

Overall, this review presents a good foundation for the design decisions made within the VPP4ISLANDS concept architecture.

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3. CONCEPT ENABLERS

Concept enablers defined the group of technologies and components required for the VPP4ISLANDS concept to function as intended and provide the necessary output services in a multi-stakeholder environment. A complete understanding of the definition, uses, advantages and disadvantages of each concept enabler is crucial in integrating each component at the concept design stage. The following section contains examples from literature of the enablers that will be considered in the final concept and can be approximately separated into two key categories as displayed in Figure 9.

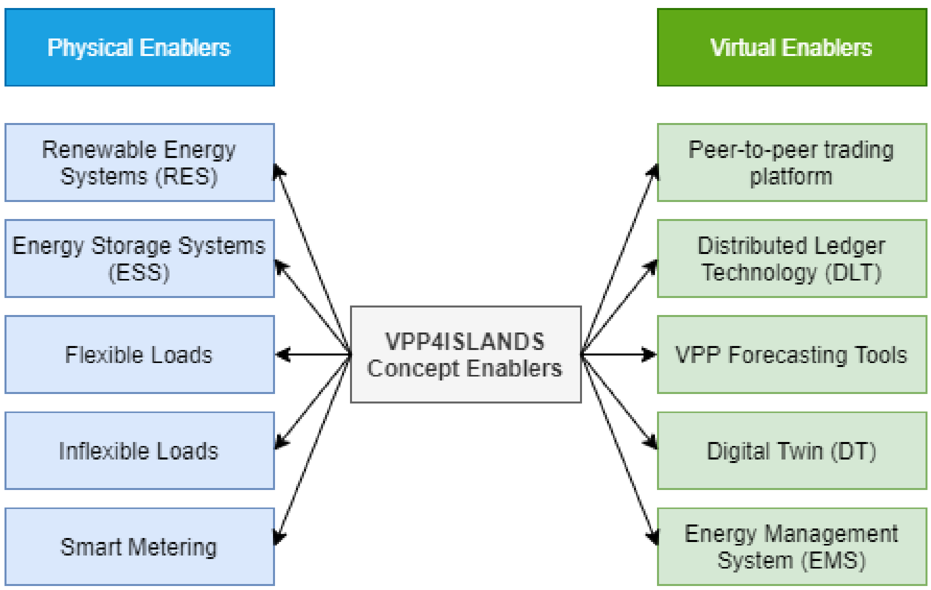

Figure 9: VPP4ISLANDS Concept Enablers

3.1. PHYSICAL ENABLERS

The physical enablers are defined as any component that physically exists as an asset in the field which can be integrated into the VPP. Similar to the 'electric layer' defined in the Edison VPP and TVPP within the FENIX VPP, these enablers can all be described with physical laws and constraints that dictate their operation. Understanding of the function and availability of these components is key to formulating the concept definition of the VPP as they will dictate the performance and flexibility of services that can be described. The following section presents a summary of the physical enablers, including their capabilities, benefits, and challenges to integration into the VPP.

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Renewable Energy Systems (RES)

RES describes a category of low carbon lifespan energy generating technologies which can be distinguished over their traditional power generator counterparts with their advantages of sustainability, low pollution, and long-term economic benefits [18]. Some examples of RES include the following:

- Photovoltaic (PV) solar
- Wind generation
- Hydropower (pumped storage and run-on-water)
- Tidal and wave power
- Biomass

Many RES exists as large 'farms' to take advantage of areas with high natural resources and minimise installation costs, however, many exist as smaller DER for domestic and commercial usage. 'Domestic RES' installed on buildings can also be consumed directly by the owner, or injected back into the grid, whereas 'Public RES' installations are generators only, and thus are limited in flexibility. It is important to make this distinction for the purposes of the concept design as there are not only technical variations between the two categories including voltage level and controllability, but regulatory and ownership. The original distinction was made in [19] and has been built upon for the purposes of this report.

Public RES: A generation unit or series of generation units connected and owned by an energy utility company with the primary aim of providing power to the grid. The units to not have directly connect consumers but is instead sold through the energy market or by Power Purchase Agreement (PPA) which is then bought by energy sales companies and sold to consumers. Due to the higher power capacity, these RES are usually connected directly to the medium voltage distribution or high voltage transmission grid.

Domestic RES: a generation unit that is owned privately by a single or group of prosumers, who can be a mix of residential, commercial, and industrial. The aim of the domestic RES owners is to increase energy independency, as well as reduce the environmental emissions and cost of their energy usage. The excess energy generated is injected into the grid and the owner may receive renumeration in the form of a Feed-in-Tariff (FIT). A disadvantage of domestic RES is that the owners do not have access to the energy market, so are limited in terms of their monetary exploitation of the system.

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Many of the common RES types including PV solar and wind generation are stochastic in nature [20], and are therefore coined as non-dispatchable, as opposed to dispatched generators such as biomass and pumped hydro plants. As the generation capacity of non-dispatchable units directly correlate to the local weather conditions, advanced forecasting techniques can be used to predict with a degree of certainty the power generation in advance. The capabilities of forecasting tools is discussed in depth in the later section.

To summarise, the major advantage of RES is the significant reduction in societal carbon emissions [21]. The VPP must maximise the usage of RES in the most efficient manner by avoiding losses and generation curtailment. RES can be categorised into domestic and public generators, both at different levels of grid integration and usually owned by different stakeholders with varying system objectives. This could have a major impact on the observability and controllability of the generation unit.

Energy Storage Systems (ESS)

The rapid growth of RES is a great benefit to the decarbonisation of energy generation and a requirement to meeting international targets [22]. To continue this trend, the VPP concept will integrate ESS into the system to increase system flexibility and the number of services that can be provided. ESS achieves this by injecting or absorbing energy from the grid and thus can perform temporal shifts in the energy usage habits of the consumer. Many different types of ESS exist for grid-scale applications, including pumped hydro storage, compressed air, batteries, and hydrogen fuel cells [23]. Figure 10 below shows the variety of grid storage technologies available.

Successful VPP concepts within literature almost always include ESS as a vital asset to increase flexibility of services and balancing the generation of RES in the grid. This provides a major advantage for increasing revenue streams for the VPP and reassumes industry stakeholders such as the DSO/TSO and regulatory bodies that the VPP will not adversely affect the current grid energy structure. There are, however, barriers and obstacles to the inclusion of ESS within the VPP concept, which have been explored at length in '*D2.4 Obstacles to Innovation in Islands'* report. There were several key outcomes relating to the use of ESS, including EU ownership and operation regulations, how a Time of Use (TOU) tariff or related cost be devised, and the definition of the services procurement.

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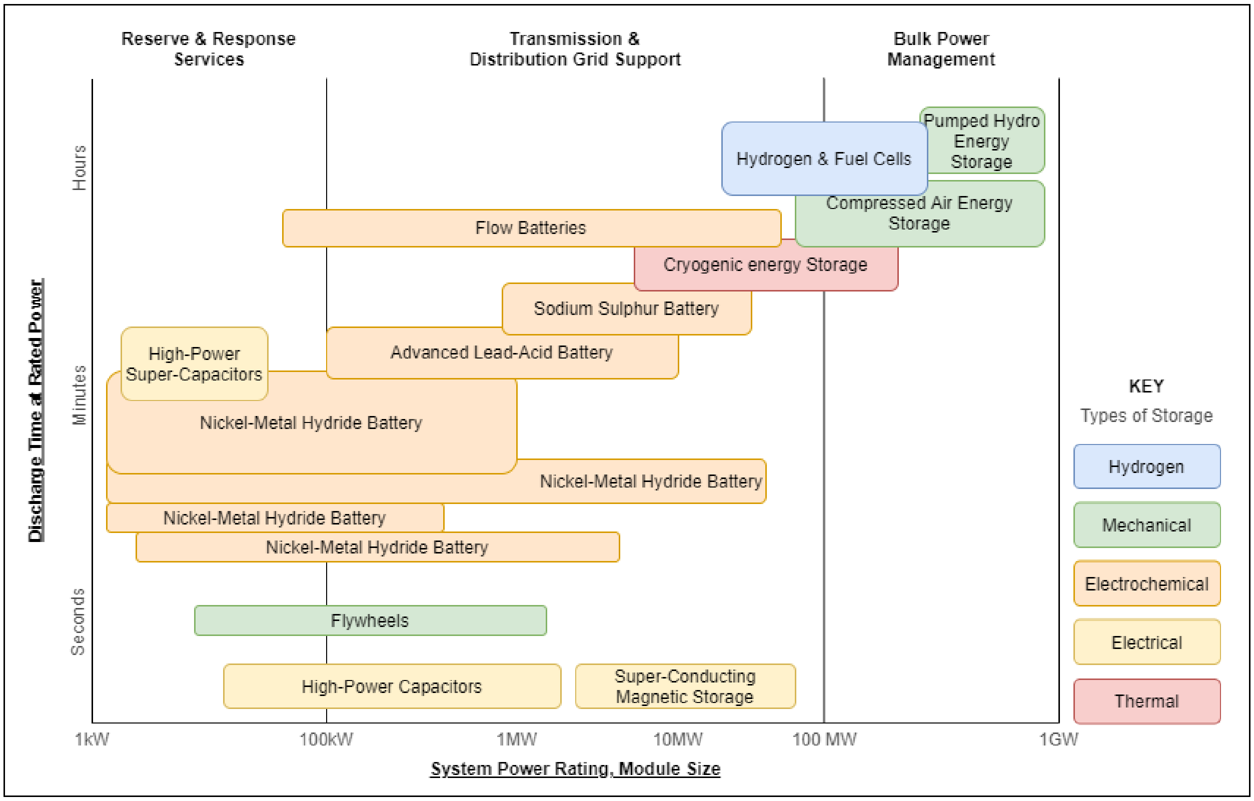

Figure 10: Comparison of ESS in terms of storage capacity and discharge duration (modified from [24])

Flexible and Inflexible Loads

The efficient integration of RES generation calls for not only the addition of ESS systems, but also an understanding of any flexible Demand Side Management (DSM) opportunities [25]. The VPP concept like other smart grid technologies aims to improve the efficient use of energy and actively engage passive customers [26] to participate in emissions reduction strategies. The level of engagement can be categorised into the type of loads available at the end user: *flexible and inflexible.* Inflexible loads are simply the classical end user loads that fluctuate naturally throughout the day, of which it is the task of the energy system operators to management the balancing between supply and demand. Flexible loads, however, are a more complex entry but add a number of advantages to the VPP system.

Flexible Loads

Flexible loads are typically a selection of loads that able to make adjustments to their usual usage habits in response to grid signals and incentive payments [27]. Current flexible loads identified with the energy grid are largely limited to direct load of industrial customers [26], which in small

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geographical island locations within this project is uncommon. TOU tariff structures are also used to incentivise end users to modify their usage habits [28]. In island settings, explicit control of Heating, Ventilation and Air Conditioning (HVAC) could be a suitable alternative to control of flexible industrial loads. Particularly on the island of Formentera, who's economic activity relies heavily on tourism and hospitality sectors, control of HVAC could play a major role within the VPP4ISLANDS concept. The World Tourism Organisation (WTO) suggests that approximately 40% of energy usage in in the hotel industry comes directly from air conditioning [29]. Not only hotels are being considered for the inclusions in the energy communities concept, but this HVAC flexible control concept could also be applied to community and residential buildings where HVAC is present. A number of studies including [30] and [31] have explored the use of flexible HVAC control in buildings to maximise peak load reductions and not only reduce grid stress but also reduce environmental emissions. The control of flexible loads for other appliance loads as well as HVAC must also consider any comfort sacrifices that are acceptable to the building occupants [32].

Not only the practical feasibility of connecting various flexible loads to the VPP concept, but also the dispatch mechanism and market environment into which the loads would operate. The cost and carbon reduction optimisation strategy would need to be balanced within the constraints of end user comfort requirements – which would be the task of the optimal energy dispatch engine. These dispatch requirements would then need to be transformed into incentive-based signals (TOU) so to promote change in the end users usage habits.

Smart Metering

All physical enablers will require a degree of observability so that the VPP system is able to process the grid activity and perform the correct output services. To complete the selection of physical enablers or the TVPP as defined in [4] the monitoring and handling of on-site issues is handled with the use of smart metering equipment. Therefore, one of the most important roles of smart metering is to gather all the required measurement values from the field's remote measurement devices and integrate into the complex Energy Management System (EMS) through unification and homogenisation of data [33].

Reliable access to high quality measurement data in the correct timesteps and data format will be crucial to the smooth delivery of a number of VPP services, such as demand response, frequency balancing, and other local ancillary services. For the smart meter to work effectively, a number of factors need to be considered [34]:

- Basic functionality of the measuring equipment

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- ‘Smart’ or other intelligent systems (redundant control, DLT in the case of peer-to-peer capabilities, local data storage)
- Extended functions (UI, online monitoring)
- Remote communications (communication protocols, data bandwidth, latency and response time)

The smart meter should also be ‘future-proofed’ to an extent such that it is able to provide service not yet required in the field, and thus extend its useful life and Return on Investment (ROI).

Benefits to Application

The benefits of increasing the number of smart metering technologies within an energy grid an numerous. A standard architecture of a smart meter communication system is shown in Figure 11. Firstly, there is increased awareness of energy consumption habits at the end user, partly if a flexible TOU tariff is adopted. If the customer is made aware of these peak hours, they may their deferrable loads such as large household appliances and electric vehicle charging [35]. Smart metering data can also be encrypted and anonymised before being sent to a secure database [36]. On the operator side, smart metering requirement allows for remote access to accurate and reliability machine data, which can then be combined with a Digital Twin to perform continuous improvements and fault detection. Improving grid visibility with the increase in distributed generation is a priority of network operators, so data can also be gathered to understand more about load flows and potential grid congestion. Smart meters can be combined with hybrid energy storage systems to provide information about the most efficient operating conditions to minimise environmental impact and maximise cost savings.

Challenges to Application

In addition to the benefits, there are some challenges to the application of smart meters for end users. One of the technical challenges may occur when operating smart meters form different manufacturers as the measurement timesteps and communication protocols could be different. A method of harmonisation, unification and homogenisation would be crucial to the usability of the output machine data. The added system complexity and remote communication could also add other security vulnerabilities including weak authentication, quality of software, error handling and weak protocols [37]. The implementation of large-scale smart meter systems in the grid network also requires significant investment [37], which would need to be clearly justified through a thorough business model and comprehensive value proposition. Smart meter system ownership must also be considered, more specifically whether the end user owns or is able to access and potentially temper with the smart meter operations. Allowing end user access might allow for manipulation and security breaches, therefore a sealed system me be more appropriate for the concept. The VPP4ISLANDS project aims to better unlock the potential value from smart meter

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installation with the addition of local and national energy trading, as well as linking to a Digital Twin for advanced system management. The system must also uphold the security requirements such that measured data cannot be manipulated.

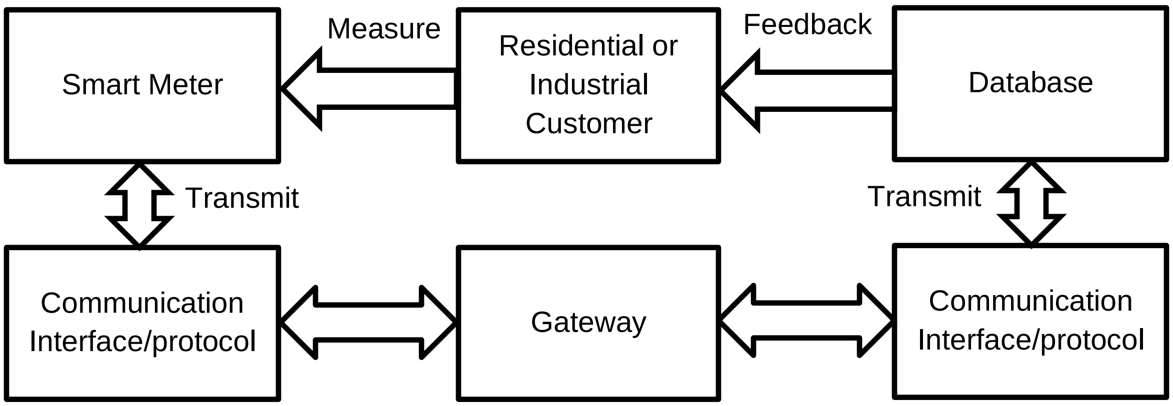

Figure 11: Metering architecture of a smart meter (modified from [37])

3.2. Virtual Enablers

Distributed Ledge Technology (DLT), Blockchain, and Smart Contracts, and Peer-to-Peer

With smarter components and advanced connected sensors such as smart meters and flexible loads, the electricity market is moving toward the Internet of Energy (IoE). In the IoE, smart sensors and intelligent real-time monitoring & control techniques collect information about the energy system from edge components and grid participants, and shares this information within grid components to obtain knowledge regarding power demands, energy usage, forecasting future demands, etc. IoE is the realisation of IoT, Big Data, Artificial Intelligence and computing capabilities in distributed and decentralised energy management systems with an aim to optimise the efficiency of the existing energy infrastructure. [38]

IoE allows for ease of collaboration of among others renewable energy sources, consumers, Electric Vehicle charging and discharging and control centre, which improves the efficiency, flexibility and supportability. Hence, the IoE technology helps toward the shift from the centralised, producer concentrated, one-way electric framework to a distributed on-demand, two-way energy supply management system [38].

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Power monitoring, demand side energy management, growth of renewable energy integration, reduced wastage of electricity, reduced blackouts, self-organisation, resource management are important benefits of IoE. IoE, however, opens up security and privacy issues in the network and as IoE market increases, its connections, communication, infrastructure and malicious attacks will also continue to increase. Hence, innovative technologies and techniques are required to ensure safety for all participants and components of the system.

Distributed Ledger Technology (DLT) has the potential to allow for security of data and resilience against malicious attacks. DLT is a decentralised database managed by multiple participants, across multiple nodes. Blockchain is a specific type of DLT where transactions are recorded with an immutable cryptographic signature called a hash. The transactions are then grouped in blocks and each new block includes a hash of the previous one, chaining them together, hence why distributed ledgers are often called blockchains. In relation to Blockchain, DLT is the fundamental framework that supports it [39].

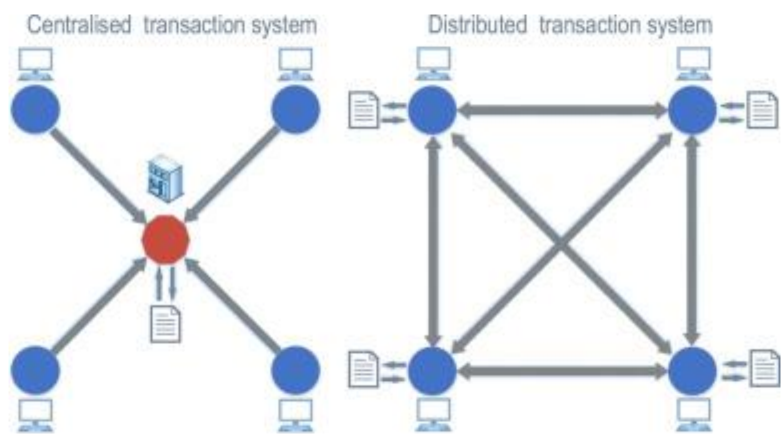

Figure 12: Centralised and distributed transactional platforms: a single trusted authority manages the ledger as opposed to every member holding a copy of the ledger [40]

In the blockchain, each peer in the network holds his own copy of the ledger and can access it in the open cloud. Hence, every member can see the historic log of the transaction and verify the validity, enabling a high level of transparency. When the central authority is removed, however, an efficient way to consolidate and synchronise multiple copies of the ledger needs to be found. Consensus between the different members and their version of the ledger is found through validation mechanism known as distributed consensus algorithms. [40]. When the consensus is reached, the transaction data are stored into a block and added to the chain. This addition of new blocks is called mining. A cryptographic hash function links any two adjacent blocks in the blockchain with the hash of the previous block stored in the current block [41]. Several consensus algorithms are in use, and more are being developed. The Proof-of-Work algorithm that was first

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introduced on the Bitcoin blockchain but is energy-intensive and time-consuming, hence lighter consensus algorithms are developed, such as the popular Proof-of-Stake and hybrid Proof-of-Authority, which enable faster mining with less computational power requirements.

As described in *D2.7- 'Smart Contract Specifications'*, the VPP4ISLANDS project takes into account the energy issues and aims to implement the smart contract and blockchain DLT on the Ethereum blockchain, given the development and deployment of the Ethereum 2.0 is successful. Ethereum 2.0 refers to Ethereum's transition from PoW consensus to PoS. Ethereum 2.0 is an upgrade to its existing blockchain. It aims to increase the speed, efficiency, and scalability of the Ethereum network, enabling it to address the bottlenecks and increase the number of transactions [39].

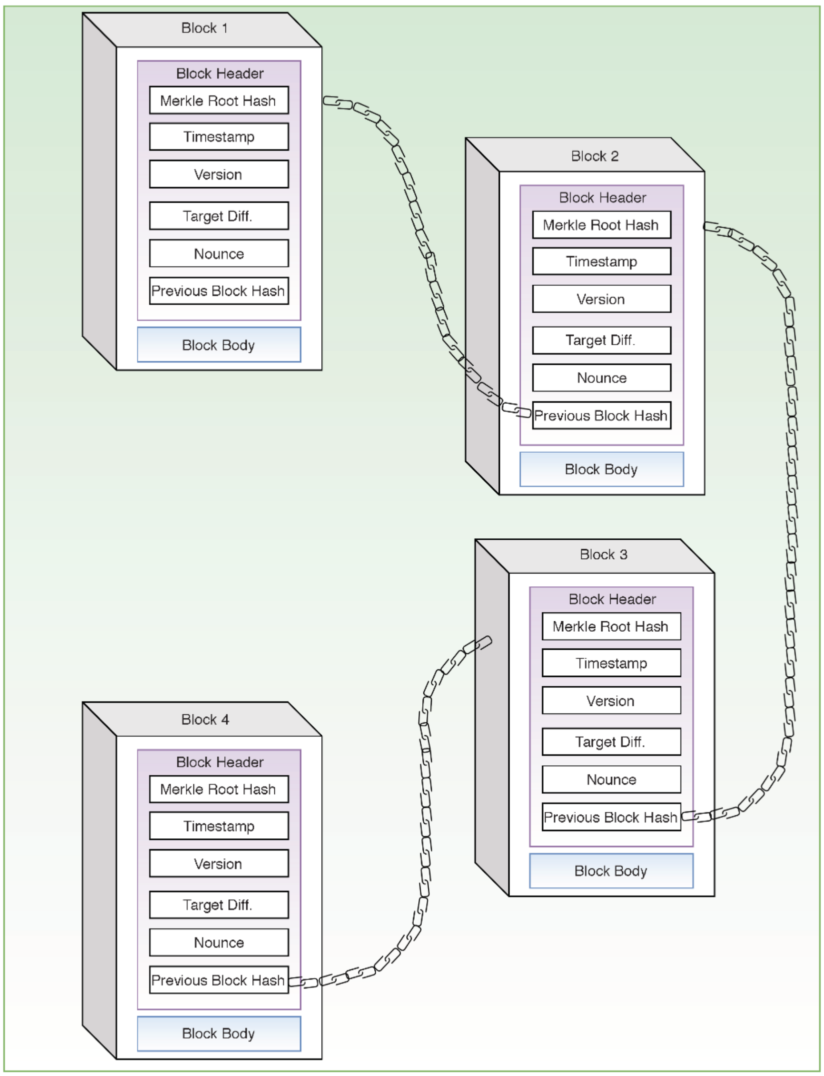

Figure 13: Blockchain structure [41]

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Each block in the blockchain comprises of a block header and block body. The block header contains various fields such as the previous block's hash, timestamp, version, etc. The Merkle root is the digital fingerprint of the transactions stored in a particular block and is generated by iteratively hashing pairs of transactions until only one hash value is left. The block body comprises of the transaction information related to the block and can be divided into two parts: the information of the transaction (amount, date, time, etc.), and information on the participants of the transaction.

It is impossible to modify a field in the block without modifying the hash, and since the hash of the current block is stored in the previous block, to modify a block the rest of the blocks in the chain needs to be modified one-by-one. Furthermore, the attacker has to ensure no new block is added to the chain while modifying a block, hence a much higher processing and hashing capability is required on the attacker's end compared to the combined capability of all the miners in the network. Therefore, tampering data in a blockchain is technically and economically quite infeasible. Additionally, since a copy of the blockchain is available with each participating node in the network, any tampering or other malpractice is easy to detect [41].

Benefits to Application

Blockchain can bring benefits to several actors in the electricity system, including operators and end-consumers. For example, renewable energy producers can issue a Renewable Energy Certificate per kWh/MWh or electricity produced and delivered to the grid. These certificates can then be sold to electricity consumers who can offset their carbon emissions in this way. Such efforts offer real-time guarantees to customers that the power they use really comes from renewable sources. Existing systems now take weeks or even months to provide a confirmation of certification because they are centrally managed through a third party. Blockchain promises to eliminate the third party, and greatly speed the transaction, allowing the customer to track the energy it purchases and ensure it meets sustainable goals.

Additionally, P2P energy trading scenarios for IoE involve trading among smart buildings, homes with solar and wind installations, electric vehicles and power grids to balance load peaks, EV to EV, renewable sources to grid, etc. The current energy trading market involves manual processing by third-party auditors which result in high time complexity and lower reliability. When the population increases, the IoE scenario becomes complex. If a centralised organisation collapses due to heavy load, it can lead to high operational costs. As an example of implication, this architecture is implemented in the Ethereum blockchain [42] which consists of full nodes and light nodes. The market operator operates the full nodes to manage the trading platform by offering computing power for block mining and verification. Prosumers and microgrid traders operate light nodes to store header chain and verify their related transactions.

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In an IoE network, electricity distribution among nodes involves payment bills of electricity usage which is further used for services such as load prediction, dynamic price prediction and optimal scheduling energy usage. Payments for energy trading in smart grid or distributed energy resources should be negotiated between electric utilities who are involved in the process of buying and selling. Existing payment methods may share accounts information on other parties without user's consent. Additionally, sharing of payment information among nodes may cause a privacy concern regarding the pattern of usage of electricity, identity, and location threat.
Smart Contracts can overcome these threats, as they are executable programs that make changes in the ledger and can be triggered automatically if a certain condition is met, such as if an agreement between the transacting parties is honoured [40]. The construction of a smart contract based on blockchain includes three steps [43]:

1) Construction of smart contract; multiple users in the blockchain participate in formulating the contract.
2) Storage of smart contracts; smart contract is stored on each node via a DLT database throughout the P2P network.
3) Execution of smart contract; when a specific data or command occurs, the deployed smart contract is being triggered automatically on the blockchain network and the actions in this contract are followed.

The benefits of smart contracts are a high efficiency in contract formulation, low contract maintenance costs, and high contract execution accuracy [43].

Challenges to Application

Despite the benefits of blockchain technology, there are also challenges to the implementation and adoption of this technology. First and foremost, blockchain needs to prove that it can offer scalability, speed and security required for the proposed use case. This aligns with the explicit challenge for early adopters of blockchain technology to select the right consensus mechanism and system architecture, without having a clear picture of the long-term pros and cons of this technology. Thereby, security breaches are still likely while the technology is maturing, which could delay the progress and further development of the technology, as well as influence the public opinion. Another important challenge is the high development costs of blockchain. Blockchain systems may require new ICT equipment and software, the cost of which can be high in the early stages [40].

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Peer-to-Peer Energy Trading

Inspired by the concept of sharing economy, peer-to-peer energy trading enables energy prosumers (both the producers and consumers) to directly trade electricity and other services, e.g. demand side management and frequency response, and carbon credits. The peer-to-peer energy trading is able to facilitate the local energy balance, bring revenue for prosumers, reduce power losses caused by long-distance transmission, and support the operation of bulk energy systems.

With respect to the platform design for peer-to-peer energy trading, both the centralised trading platforms, e.g. the 'ElecBay' [44], and decentralised trading platforms, e.g. those in [45] [46] [47] [48], were designed.

With respect to the power infrastructure in supporting the peer-to-peer energy trading, a number of studies have been carried out in recent research, e.g. using the distribution locational marginal pricing to determine the trading prices, as proposed by research in [49] [50] [51]. With respect to the communication infrastructure, Zhang et al. [44] studied the requirements for communications between the bidding systems and control systems to realise the peer-to-peer energy trading. Jogunola et al. [52] analysed the peer-to-peer communication architectures in achieving the peer-to-peer energy trading, under both structured and unstructured protocols.

With respect to the regulations, Diestelmeier et al. [53] identified regulatory implications for the electricity laws in EU, considering the transition of the role of electricity consumers with the support of blockchain technology, which is closely related and widely applicable to the peer-to-peer energy trading.

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Architecture of Peer-to-Peer Energy Trading

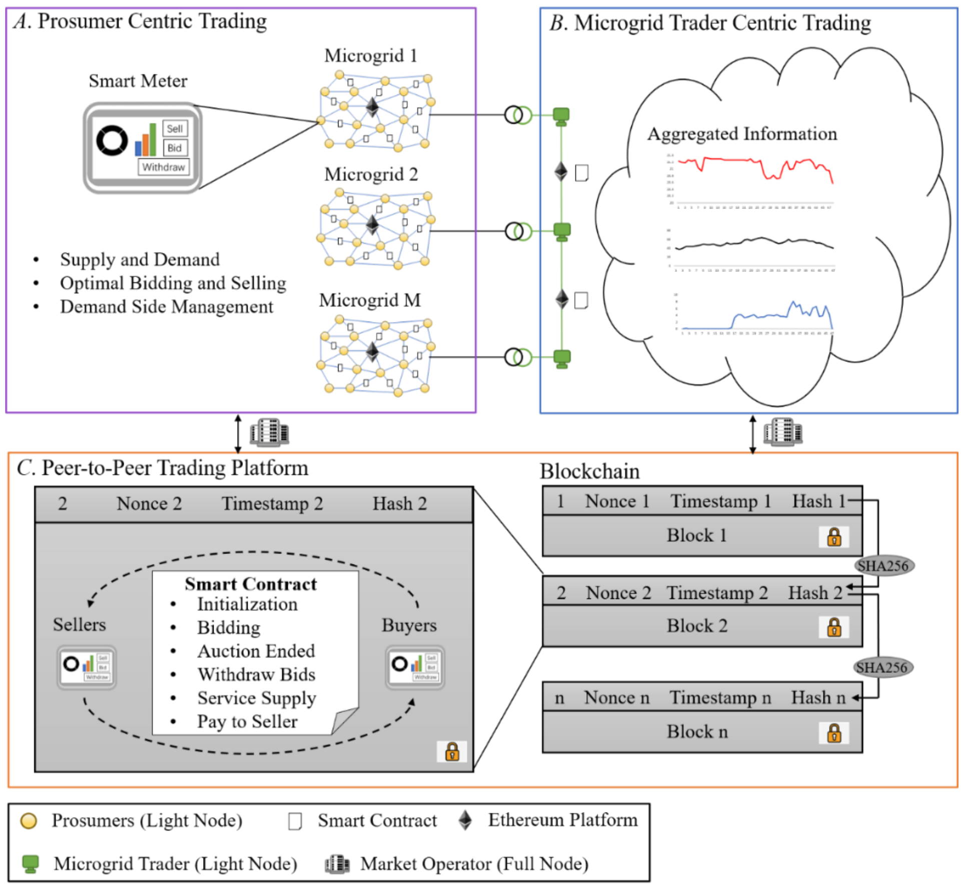

Figure 14: Proposed architecture of the peer-to-peer energy trading. (A) prosumers trade energy at the layer of prosumer-centric trading. (B) The residual supply and demand from an ensemble of prosumers within the same microgrid are aggregated and traded by microgrid traders at the layer of microgrid trader centric trading. (C) The trading of energy is realised at the layer of the peer-to-peer trading platform.

To facilitate the commercial relations between microgrids and local energy markets, a virtual entity, microgrid trader is used to manage the energy trading of microgrids. The architecture is hierarchically categorised into three layers: prosumer-centric trading, microgrid trader-centric trading, and peer-to-peer trading platform. Fig. 1 illustrates the information exchange of these three layers. The proposed architecture can be implemented in the day-ahead market to schedule energy and conduct trading for the next day. The prosumers seek for minimising their costs by participating in peer-to-peer energy trading. The detailed design of each layer is given as follows.

Prosumer-Centric Trading

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At the layer of prosumer-centric trading, individual prosumers make optimal decisions of energy scheduling and trading, based on the collected metering data. The decisions are obtained by solving their optimisation problems with the objective of minimising the costs of energy buyers or maximising the profits of energy sellers. The optimal decisions of energy scheduling are implemented by controllers, and the optimal trading decisions are sent to smart contract for auctions. For local energy balance and minimising the transmission losses, prosumer-centric trading only applies for the prosumers geographically in the same microgrid. The advantages of the prosumer-centric trading are that the scheduling decisions are directly incentivised by prosumers' buying or selling prices, instead of retailers or suppliers.

Microgrid Trader Centric Trading

An ensemble of geographically connected prosumers is managed by a microgrid trader. On the layer of microgrid trader centric trading, microgrid trader aggregates the residual energy supply and demand to trade with other microgrid traders and utility grids. The optimal trading decisions are also yielded by solving its optimisation problems with the same objectives as prosumer centric trading. The purpose of the microgrid trader centric trading is to help its prosumers balance residual energy.

Peer-to-Peer Trading Platform

At the layer of the peer-to-peer trading platform, a standardised negotiation and self-enforcing settlement platform is provided, such that energy buyers and sellers can conduct the energy trading. The trading functions are achieved by the blockchain smart contracts. A general form of smart contracts is '*if an event A happens, buyer B pays the currency to the seller C in a self-enforcing manner*' [54]. In the context of this research, the event is the energy delivery which is self-enforced after querying smart meters of prosumers.

The executing procedures of the smart contract at the peer-to-peer trading platform include *a)* initialising, *b)* matching sellers and buyers, *c)* bidding, *d)* selecting winner, and *e)* assets ownership exchange. The seller firstly initialises its smart contracts with specified conditions. Buyers who satisfy the conditions will be matched to the sellers' contracts and are able to deposit their bids for auction. After the auction ends, the buyer with the highest bidding price wins this auction. The rest unsuccessful buyers would withdraw their deposits from smart contracts. In order to ensure that agreed energy is delivered by the seller at the agreed time, smart contracts need to verify with smart meters before transferring the deposited bid from the buyer to the seller. All the transactions are managed, validated, and stored by the full nodes to ensure the authenticity and security. These validated transactions are structured in and chronologically chained with each other, forming a blockchain. The validation is collectively achieved through reaching a consensus using the proof-of-work [55]. The proof-of-work uses SHA-256 with inputs of block number, nonce, timestamp, and hash output of previous block, and outputs of a fixed-length digest which is a unique identity of a block. This uniqueness of the digest is guaranteed by finding the nonce. Therefore, the chaining feature of the blockchain and the difficulty of mining the nonce ensure transactions to be verifiable, traceable, and tempering resistance.

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In the layer of the peer-to-peer trading platform, the designed blockchain based auction mechanism is applicable for both prosumers level and microgrid traders level, under the standardised negotiation and self-enforcing settlement of smart contracts. Each step is conducted by a function of smart contracts. Detailed steps of executing the smart contracts are described as:

Step 1: Each seller calls the initialisation function in smart contracts to specify the conditions of the seller address, seller type (either prosumer or microgrid trader), microgrid serial number, selling volume, minimum accepted buying price, the currently highest bid, and the auction ended time. The blockchain stores and updates all the initialised offers from sellers.

Step 2: In the proposed auction mechanism, each buyer is required to bid with a price higher than the currently highest bid. The matching function aims to help buyers automatically match the optimal combination of offers, according to the principles of: *1)* satisfying the energy demand; *2)* the selected optimal combination of offers have the minimum summation of the currently highest bidding prices, which allows buyers to bid with minimum bidding prices.

Step 3: The bidding function enables buyers who meet the conditions to submit their bids after confirming that: 1) the auction is not ended; 2) the microgrid serial number matches; 3) buyer has enough balance to bid. After a buyer successfully submits a bid, the highest bidding price is updated. Until the auction is ended, all the bids are frozen by smart contracts, which means that not any buyer is able to withdraw their bids back to their account.

Step 4: Once the auction is ended, the buyer with the highest bid wins the auction. The rest unsuccessful buyers withdraw their submitted bids by calling the withdrawal function.

Step 5: After the smart contracts confirm the energy delivery with the smart meters of buyers, the deposited bid is transferred to the seller's account by the pay-to-seller function.

Case Study

The following case study is discussed in [56], which contains similar components as those in the VPP4Islands case studies, e.g. solar PVs, flexible loads, and wind turbines. The case study is based on the modified IEEE 37-bus test feeder as shown in Fig. 2. The solar generation data is obtained from the U.K. rooftop solar generation of endpoint consumers [57], and the generation of diesel, wind, and biomass are scaled down by 2.5×10^7 times from the GB power systems. The load data is collected from residents in England. The scheduling interval is set as 0.5 hour, according to the Great Britain energy market settlement period. The data of retail electricity prices is obtained from the GB electricity retail market [58]. These retail electricity prices are set as the minimum accepted bidding prices, so that buyers can provide higher prices than the retail prices. Such design encourages prosumers to participate in the peer-to-peer trading and thus reduces the energy import from the utility grid. The smart contracts were written by the Solidity language and executed on the Ethereum virtual machine. The optimisation algorithms for prosumers to schedule energy and determine selling/buying prices are developed by using the MATLAB and solved by the artificial immune algorithm.

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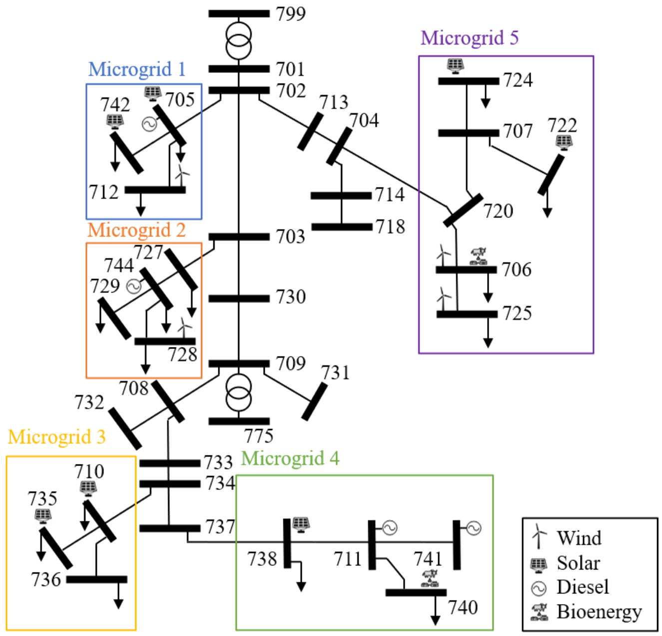

Figure 15: Modified IEEE 37-bus distribution system. The network is separated into 5 microgrids. Each bus represents a prosumer.

Benchmark

To demonstrate the efficiency of the proposed peer-to-peer trading architecture, the proposed scheme was compared with the schemes of the centralised energy trading and aggregator-based energy trading as shown in Table 1. For the centralised trading scheme, the energy is only traded on the retail markets at the retail electricity prices. For the aggregator-based trading, an aggregator is in charge of an ensemble of its prosumers, with the same objectives of minimising electricity bills for energy buyers or maximising profits for energy sellers. Aggregators then pay their prosumers the monetary compensation for the energy dispatch.

Table 2: Comparison of electricity trading schemes used in case studies.

	Centralised trading	Aggregator-based trading	Peer-to-peer trading
Pricing	Retail electricity pricing	Buying/Selling pricing determined by aggregators	Buying/Selling pricing determined by prosumers
Stakeholders	Retailers, prosumers, and consumers	Aggregators, prosumers, and consumers	Prosumers and consumers

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Impacts of Peer-to-Peer Energy Trading on Regional Energy Balance

Figure 16 presents the daily power balance of the distribution network. The positive value indicates the total generation is greater than the total demand. The negative value indicates the total generation is less than the total demand, and in this case electricity has to be imported from the higher-level utility grid. Through the proposed peer-to-peer energy trading scheme, the total daily net import energy is 0.99kWh, which indicates a better energy balance, compared to -4.50kWh in the aggregator-based energy trading scheme and -46.44kWh in the centralised energy trading scheme.

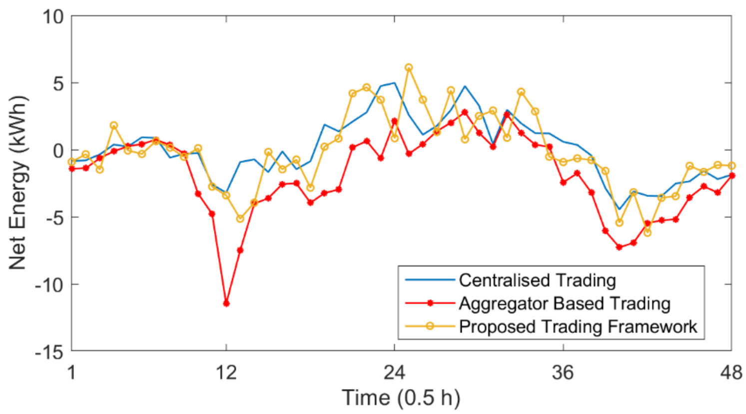

Figure 16: Power balance of the distribution network. The positive value indicates the total generation is greater than the total demand. The negative value indicates the total generation is less than the total demand.

Interactions Between Scheduling and Smart Contract

The optimal scheduling and trading decisions for each microgrid trader are shown in Figure 17, compared to the case without the energy scheduling, i.e. the original generation and consumption. For the microgrid which cannot generate surplus energy to trade, there is no energy seller and corresponding buying price. It can be seen that during the peak demand periods, the generation is scheduled to increase and the consumption is scheduled to decrease. When the microgrids experience high power consumption and low generation, the buying prices are stabilised at around 10 pence/kWh. This can prevent extreme high or low prices to avoid negative profits or high electricity bills for individual prosumers.

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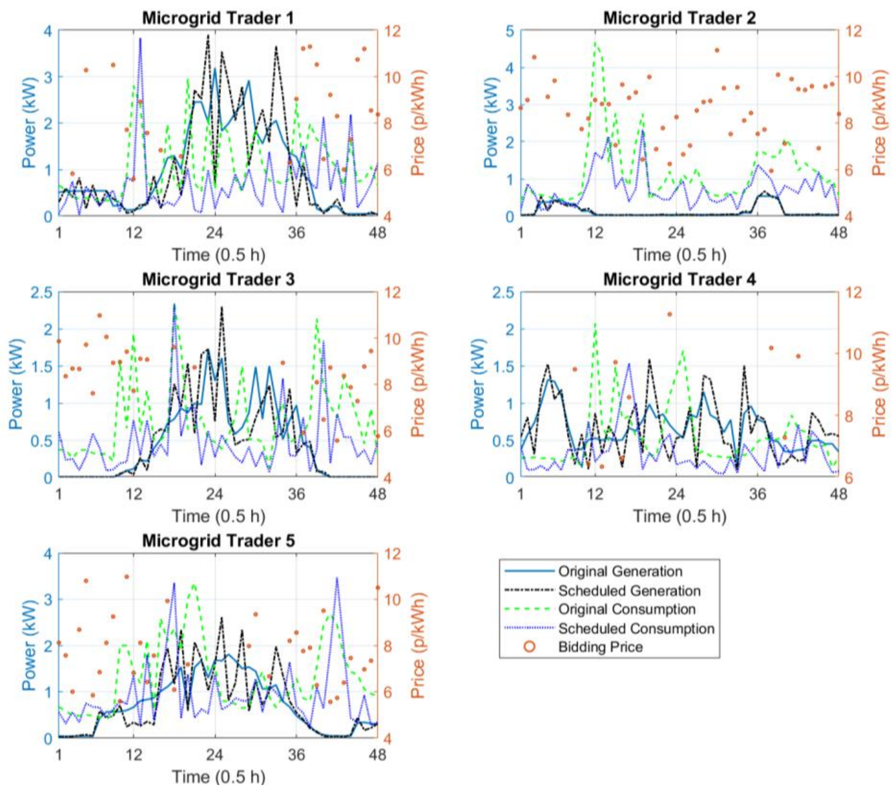

Figure 17: Energy scheduling and trading decisions obtained by microgrid trader centric algorithm. The left y axes indicate the power of microgrids, and the right y axes indicate the bidding prices. The x axes indicate the scheduling time of day.

The interactions between scheduling and trading decisions are shown in Figure 18. Through solving the optimisation problems of prosumers, the optimal buying prices of energy buyers (indicated by the colour bar) are sent to smart contracts for auction. The highest buying prices are accepted by sellers. It can be seen from Figure 18 that the auctions happen in every time slot at microgrid 4, whereas only happen at a few time slots at microgrid 2. This is because the generation capacity at microgrid 2 cannot meet its own demand, so it needs to import the energy from other microgrid traders. Through the proposed peer-to-peer trading, the selling prices are stabilised between 6 pence/kWh and 10 pence/kWh, which prevents extreme high or low prices in local energy markets so as to avoid negative profits or high electricity bills for individual prosumers.

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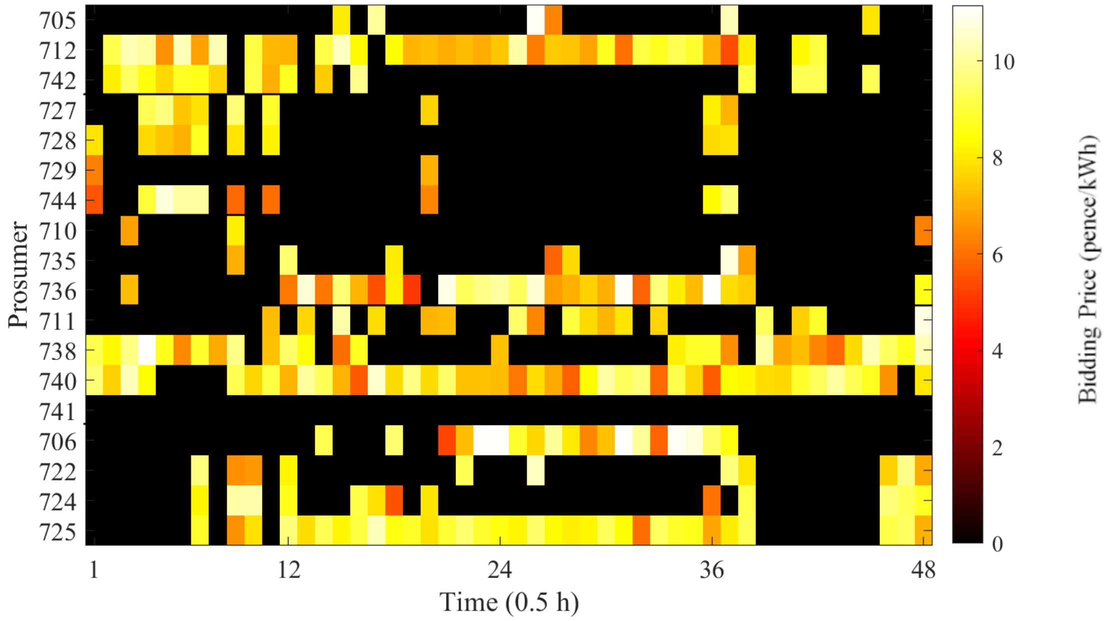

Figure 18: Optimal bidding prices of energy buyers. The *y*-axis indicates the bus number of prosumers. The *x*-axis indicates the scheduling time of the day. The colour bar indicates the optimal bidding prices from each prosumer.

Forecasting Tools

According to the concept definition of the VPP4ISLANDS, three forecasting modules are required at the level of node and platform.

- Weather
- Electricity production and consumption
- Market price

The goal of these modules focuses on the exhibition of the wind and solar energy production forecasting tools. The first task consists of choosing and designing a model. Once this step is performed, the model will need to be trained by adjusting the optimisation parameters. For this reason, there will be architecture to be defined to allow both the model training and the optimisation of the model hyperparameters based on optimisation algorithms such as the Particle Swarm Optimisation (PSO) algorithm. Learning and optimisation are two interconnected tasks that are generally completed by satisfying cost functions or key performance indicators. All these mentioned points need input data. Pre-processing will need to be carried out so that the data is

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adapted to the model. For the output data, it is vital to ensure via the model prediction of the future value(s) for the target variable with estimation of its confidence intervals.

Weather

For the prediction or forecasting of energy production, it is required to predict meteorological variables such as wind speed for wind power and solar irradiation for photovoltaics.

This type of prediction is unique as all variables will be ordered within a temporal time interval, known within literature as *time series* variables. Time series data consists of a sequence taken at successive equally spaced points in time.

Market Prices

The development of the electricity price prediction algorithm can be divided in three phases: **phase 1:** Creation of a Data Base which stores data that can affect to the electricity price such as rains, wind, solar radiation and air temperature data. **Phase 2:** Development of the algorithm for electricity price prediction, which is the main step of the subtask 4.1.2. **Phase 3:** Computation of the algorithm. In this phase, the algorithm developed will be fed with real-time data obtained from the Data Base.

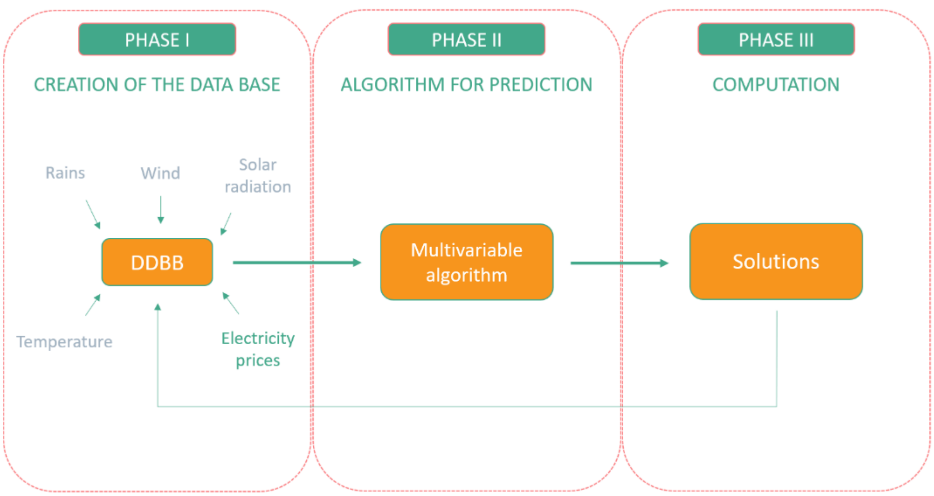

Figure 19: Three phases of the development of market price forecasting tool based on weather and historic energy price.

Data from different sources as weather stations or electricity market platforms will be integrated in a database that will be continuously updated. All of the data will be stored as time series in order to allow the identification of the effect of the variation of each parameter in the electricity price.

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Energy Consumption
For consumption forecasts, Machine Learning/ Artificial Intelligence models will be used. General structure for the forecast process is given at the picture below.

As it can be seen, procedure starts by the inputs. Then, we will process them via ML/AI algorithms. Then, results of algorithms will be sent into the overall system via APIs. Figure 20 displays the generalised structure of the energy consumption forecasting method, starting with the required input data, choosing the correct predictive model, and outputting the data in the appropriate time interval.

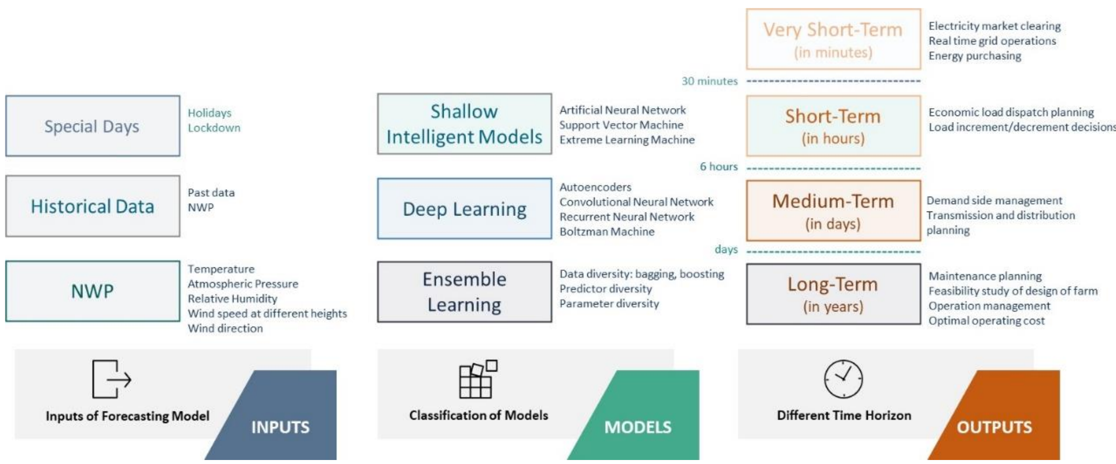

Figure 20: General structure of the consumption forecasting tool.

Prediction methodology

Input data pre-processing
The general design of the tool will be a box (model) that needs input data. This box will then generate output data. Input data pre-processing is needed so that the input data become suitable for the model. Data pre-processing includes cleaning, resampling, instance selection, normalisation, transformation, homogenisation, anonymisation, feature extraction and selection, etc. The product of data pre-processing is the final training set.

Forecasting / prediction model concept
Machine learning methods can be used for classification and forecasting on time series problems. In the machine learning field, the prediction task of numeric values for a given variable was called regression. Many methods have been proposed to perform this goal. In other words, we have to

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design a model using these methods in order to predict or forecasting. Indeed, we distinguish three categories of methods in the literature.

Classical machine learning regression methods
This category of methods does not need to respect the chronological and temporal aspects in the variables. A non-exhaustive list of the category methods include Linear Regression, Logistic Regression, Ridge Regression, Bayesian Linear Regression, Decision Tree Regression, Random Forest, K Nearest Neighbours, and Support Vector Machines.

Classical time series forecasting methods
Classical time series forecasting methods may be focused on linear relationships, nevertheless, they are sophisticated and perform well on a wide range of problems, assuming that the data is suitably prepared, and the method is well configured. Examples include the following methods: Autoregression, Moving Average, Autoregressive Moving Average, Autoregressive Integrated Moving Average, and Vector Autoregression …

Deep learning regression methods
Much of the success of modern Neural Networks comes from their ability to exploit the compositional nature of the problem. This is, in perception problems such as image or audio analysis, features have an order (spatial or temporal) and local patterns aggregate to form higher level concepts and objects (e.g., a picture of a car is made of wheels and other parts, which are made of lower-level visual features, which are made of basic shapes like edges, circles and lines, etc.). Modern Neural Networks take advantage of this by learning increasingly abstract features in the deeper layers. The following are some deep learning methods: Convolutional Neural Network, Recurrent Neural Network, LSTM, GRU, Bidirectional LSTM, and Convolutional LSTM Network … We focused in this report on only the last method category which is based on the principle of neural networks.

Learning, optimisation and forecasting architectures

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Once the method is chosen and the model is designed, we must train it and optimise the model learning. The diagram in Figure 21 displays the Particle Swarm Optimisation (PSO) algorithm learning model with hyper-parameterisation, and Figure 22 without.

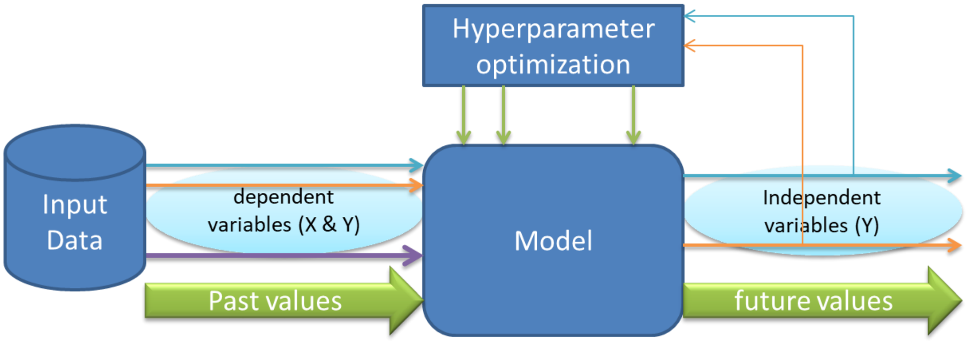

Figure 21: Architecture of forecaster Using PSO algorithm for model learning and the optimisation of the model hyperparameters.

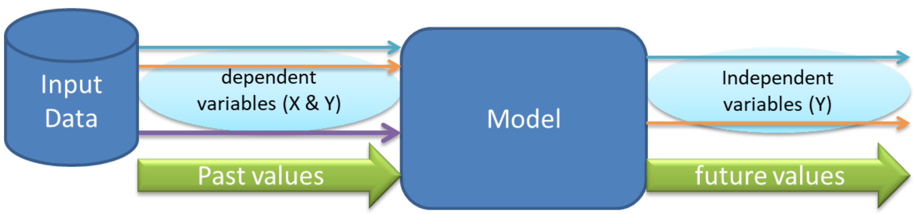

Figure 22: Architecture of the forecaster with model learning and without hyperparameter optimisation.

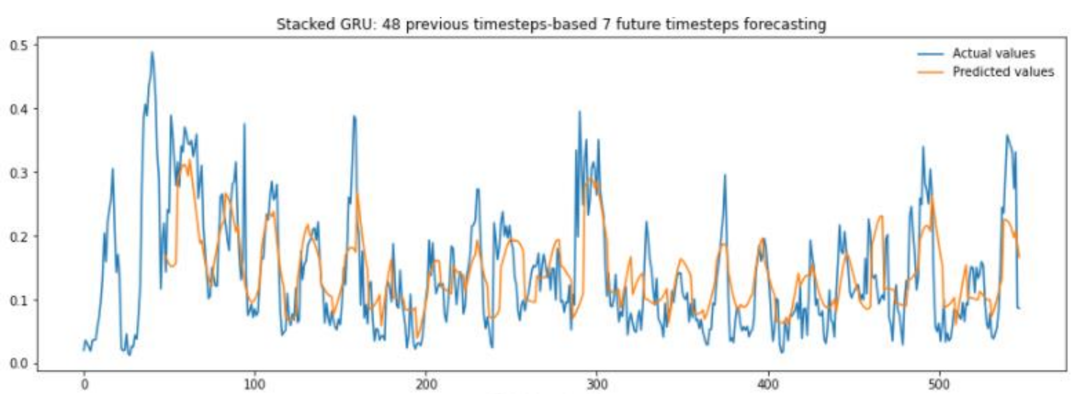

Figure 23: The results of forecasting in comparison to the actual values

Figure 23 displays an example output prediction for a given timeseries input. It can be noted the predicted data values based on the actual values for the same time interval.

Forecasting Performance Indicators

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The learning stage is ensured by satisfying some cost functions which are generally called evaluation metrics. In regression model, the most known evaluation metrics include:

R-squared (R2)
R2 is the proportion of variation in the outcome that is explained by the predictor variables. In multiple regression models, R2 corresponds to the squared correlation between the observed outcome values and the predicted values by the model. The higher the R-squared, the better the model.

Root Mean Squared Error (RMSE)
RMSE measures the average error performed by the model in predicting the outcome for an observation. Mathematically, the RMSE is the square root of the mean squared error (MSE), which is the average squared difference between the observed actual outcome values and the values predicted by the model. The lower the RMSE, the better the model.

Residual Standard Error (RSE)
RSE, also known as the model sigma, is a variant of the RMSE adjusted for the number of predictors in the model. The lower the RSE, the better the model. In practice, the difference between RMSE and RSE is very small, particularly for large multivariate data.

Mean Absolute Error (MAE)
Like the RMSE, the MAE measures the prediction error. Mathematically, it is the average absolute difference between observed and predicted outcomes. MAE is less sensitive to outliers compared to RMSE.

Digital Twin (DT)

Cyber physical systems have allowed for an ever-increasing quantity of machine generated measurements and data [59]. The machine generated data can be used for a variety of purposes, including data analytics to improve the performance of the product or process. These performance improvements can be of great benefit to the system owner or operator, such as cost reduction, reliability enhancements and continuous improvement. The concept of a Digital Twin takes this idea a step further by using this machine generated data to produce a virtually augmented version of the product or process. The connected and synchronised replica of the physical assets can be used to represent both the elements and the dynamics of how the system operates within its environment. Within the VPP4ISLANDS project, the DT will have to ability to provide a ‘near real-time’ closed loop version of the physical system, as well as a ‘mixed reality’ approach where the current system can be continuously improved upon [60]. In addition, one of the key services that

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will be offered is the ability to simulate potential new services or physical system components before applying to the field. The aim is to significantly reduce development costs and potential risks associated with real system testing.

The design process for DT development has been covered in detail in [61], in which an ontological model is combined with a digital single line diagram of the energy system, master and loading measurement data, and a mathematical model. The diagram of the proposed process is shown in Figure 24.

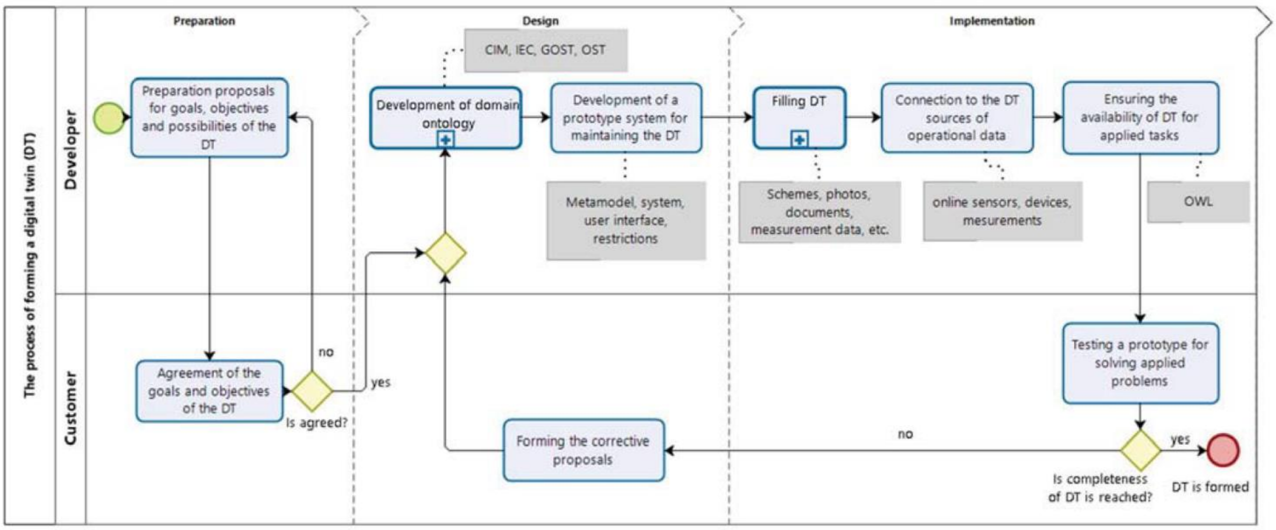

Figure 24: Proposed process for forming a Digital Twin (DT) [61]

This work highlights the importance of selecting an appropriate field test location for the system, whether this is laboratory based (hardware-in-the-loop) or a real energy system such as a building or grouped microgrid. Critical criteria include the location of the energy system in relation to the development group, availability of smart meter measurement readings, timestep and accuracy of machine data, and the local policies for installing additional systems and equipment as required. These points raised will form important factors when the system is to be integrated into the island Living Labs.

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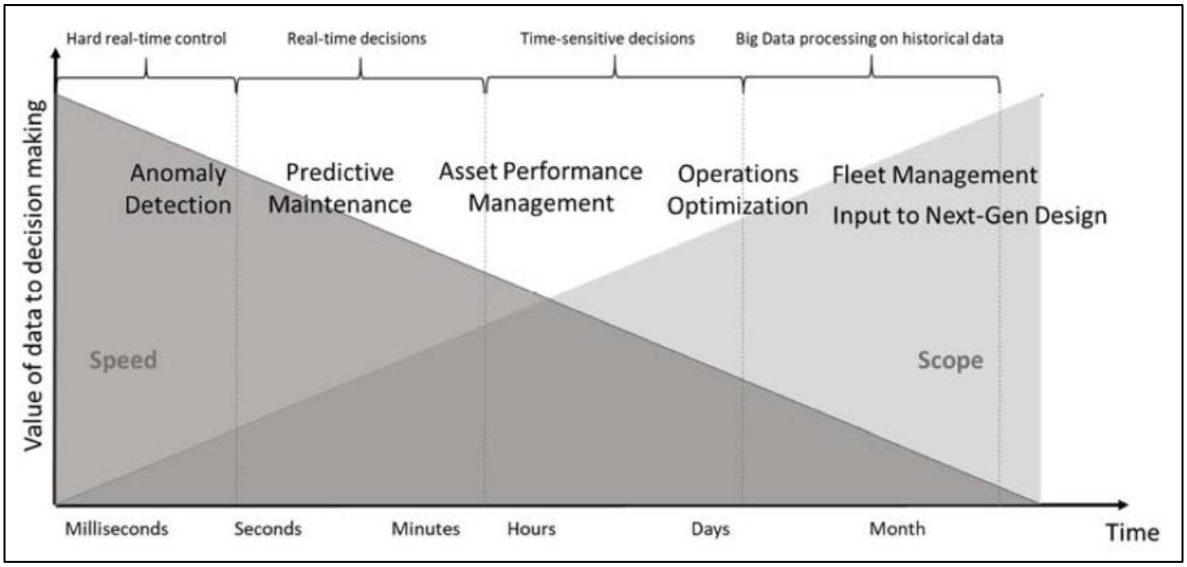

Figure 25: DT simulation step size in relation to actionable outcomes [62]

The DT model is a dynamic system with constantly changing control states and measurements that will develop over time, so the simulation step size will be critical to the availability of certain system phenomena to be observable. The graph in Figure 25 shows the ability to provide different levels of analysis based on the simulation time steps. It can be seen from the graph that in order to capture system level Electromagnetic Transient (EMT) anomalies which may include inverter or rectifier faults, a timestep size on the millisecond scale would be required. On the other hand, to perform asset management performance analysis and optimisation, a larger timestep at the level of hours to days can be used. Ideally the Dt would be able to observe the entire range of system phenomena, but will be naturally limited by the data quality, communication latency, and scale of available computation [63].

Benefits of Application

It is clear that there are numerous benefits to the development of a DT to an engineering problem such as is presented in the VPP4ISLANDS project. The key enhancements presented in [64] provide great insight into the potential capabilities of DTs within future energy grids. Firstly, Advanced modelling and observation of current and future situations can be vital to future planning of control actions. Additionally, observable machine data could be used to estimated the behaviour of unobservable system states, increasing system reliability. System stresses, security threats, and model failures can all be theoretically detected within an appropriate model timestep.

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Modelling of future scenarios and the ability to modify services and component characteristics would also be a powerful tool in assessing these scenarios and minimising exposure to risk [63]. The virtual management of buildings and assets would also allow operators to benchmark the system performance for a given timestep [65], which can then be used as an objective function to optimise the VPP for later scenarios. Crucial to the aims and objectives of the VPP4ISLANDS project, a DT would also be able to simulation future services and components without the need to install and test in the field, significantly reducing project cost and risk for the operator and customer.

Challenges of Application

Challenges (access to appropriate machine data, timestep requirements, modelling accuracy, predictive behaviour accuracy, management of large sets of data, data security, data latency and losses, real time computational requirements, interaction and control of physical assets, big data structures, data interfaces).

The challenges to implementing a complex cyber physical system such as a DT should also be clearly laid out so that they can be acted on appropriately during the development stages. The commercial challenges identified by *Siemens Digital Industries Software* have been well defined in [66]. One of the most important factors identified was that the DT needs to be well-defined ahead of the design and architectural stage, and have clear advantages in product development, operation, and after delivery service. A DT that is also able to keep up with changes in the industry and market to continually develop is also crucial to long term success.

Other challenges to the implementation of the DT include effective management of large quantities of machine data, real-time communication requirements, model realism, ensuring data security, continuous DT updates, and limits of available computational power [63].

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4. Concept Definition

The key deliverable from this report is in defining the high-level conceptual architecture for the VPP4ISLANDS system that will serve as a guide for all future developments within this project. The central methodology for defining the architectural 'taxonomy' was to perform a in depth literature of the state-of-the-art physical and virtual enabling technologies as presented in the previous section. This process in combination with the analysis of current VPP and microgrid system allowed for the aggregation of the various enablers to define a novel architecture. This section presents the system and provides an explanation for each VPP component within the defined three-level architecture consisting of the VPPIBox, VPPINode, and VPPIPlatform.

4.1. Architecture Overview

The structure of the proposed VPP4ISLANDS concept is presented in Figure 26. The concept consists of a physical energy system in combination with a three-layer virtual world to enable the VPP. The VPP consists of a VPPI-Box which collects operational data and enables communication of information between the physical energy system component and the flexibility aggregator. The flexibility aggregator within the VPP4ISLANDS is the VPPI-Node, which receives information from the distributed VPPI-Boxes to optimise the operation of the energy system considering the wider environment and neighbouring energy grid. Finally, the VPPI-Platform aggregates signals from the (multiple) VPPI-Node(s) to plan the generation and consumption capacity and optimise the cost of energy while minimising the environmental impact. Each of the layers and its functionalities are discussed in detail in sections 4.2 – 4.4.

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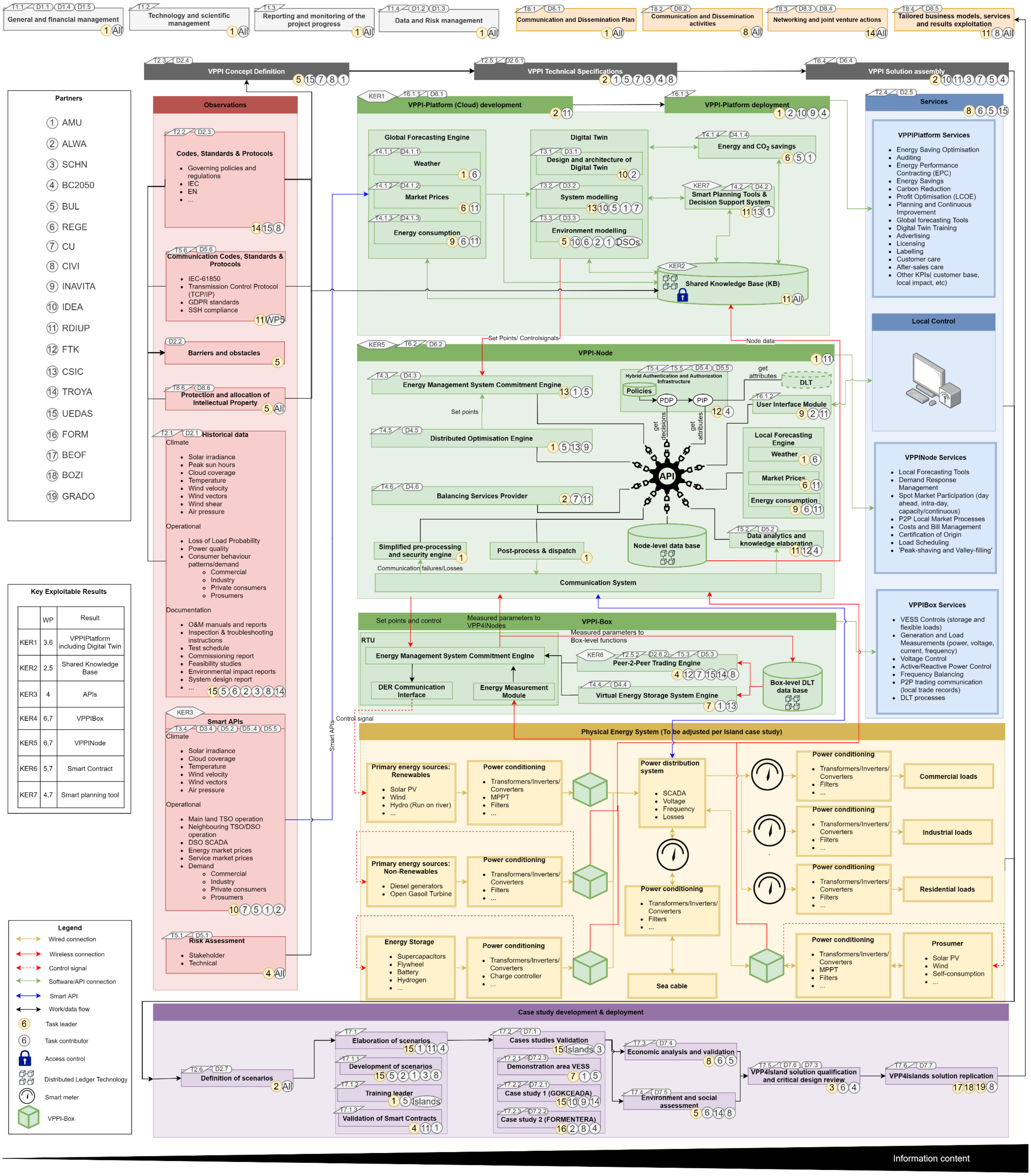

Figure 26: VPP4Islands concept architecture diagram

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4.2. VPP4IBox

The VPP4IBox is the required hardware with embedded software at each consumer/prosumer location that enables communication of information between the energy system of each consumer/prosumer and the flexibility aggregators (VPP4INode) [60].

Building upon this original description, the VPPIBox will have to perform a number of additional local level services and operation. The Virtual Energy Storage System (VESS) aggregates the flexibility parameters of connected ESS to be passed onto the communication gateway and onto be utilised for services and scenarios. The VESS will therefore form a vital part of the data collection and processing at the VPPIBox level. In addition, a DLT-based peer-to-peer energy trading energy utilises the measurements taken by the RTU, VESS operations, and forecasting inputs to set up smart contracts for energy transactions between producers, consumers and prosumers. The structure of the VPPI-Box, showing the interaction of the components and functionalities, is presented in Figure 27.

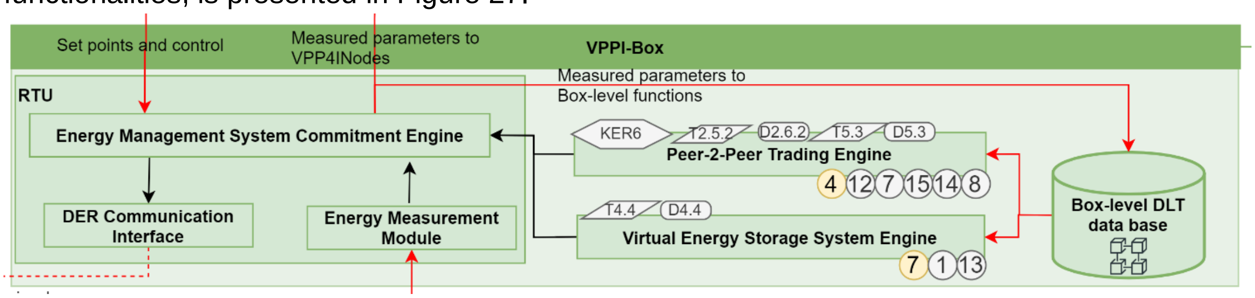

Figure 27: VPPIBox concept architecture diagram

Smart Meter/Remote Terminal Unit (RTU)

The pivotal component in collecting and monitoring data measurements from the field is the proposed Remote Terminal Unit (RTU). The RTU is essentially a smart meter with enhanced capabilities to go beyond the standard smart meter technology and allow for the additional requirements of the VPPIBox concept. This section outlines the high-level functionality of the RTU with an emphasis on required communication and data that will be sent to other system modules.

Firstly, the RTU will require a timeseries based communication protocol such that successive data measurements can be collected and transferred to the EMS. The integrated EMS can then ensure that data sent and received is correct and of the appropriate quality before sending on the VPPINode and VPPIPlatform. For this process to perform correctly, a registry-based system has been proposed.

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A data registry within the RTU will be used to store incoming data, tagging the correct variable for traceability. The variable data can then be read and sent to the corresponding registry within the VPPINode database. The RTU can contain a number of registries for record a variety of datasets from the field, but all must be mapped appropriated onto a single registry at the VPPINode level, which would need to be indicated in the communication protocol, for example, through the use of IP addresses. IEC 60870 could be used to give accurate time stamps to the incoming data and can be discretised into any given timestep (10 minutes, 1 hours, etc).

To perform all the necessary system operations, the RTU contains the energy and data measurement module for taking direct readings from the RES including active and reactive power, frequency, voltage, current, and SOC in the case of an ESS. This information is passed to the EMS commitment engine to check the validity of the data and map to the correct registry. At this point the data may also require unification and homogenisation if multiple data types are being used. The EMS can then pass data to the communication interface for transmission to the VPPINode. Measured parameters and box level functions are also saved in the VPPIBox level DLT data base. A more in-depth technical specification of the RTU is available in the *D2.6.1 Technical Specification for VPP4ISLANDS* deliverable report.

SCHN wis providing their expertise and IPR to the design of the VPPIBox with the following:
Hardware/Software/Algorithms (Trademark), Control device for the monitoring of control of electric infrastructure, RTU are part of the VPP4I-Box, providing communication, processing and control capabilities, RTU are physical devices. Schneider Electric will provide RTU for the VPP4Islands project purposes. The RTU are based on Linux OS and may require ISaGRAF licenses for some advanced logic implementation.

Virtual Energy Storage System (VESS)

The VESS technology will be used to provide an enhanced and cost-effective flexibility provision through the aggregation of various energy storage types, and by forming a vital component in the smart management of flexible energy at the VPPIBox system level. As mentioned in the previous section 3.1, ESS can take the form of many technologies including batteries, fuel cells, and flexible loads.

The key performance measurements for each system will be collected from the RTU and analysed within the VESS module to determine the level of available energy to be delivered for a given

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timestep. This information can then be delivered to the EMS commitment engine to schedule the best usage for the aggregated flexibility for the given scenario.

An independent VESS control method will also be developed to coordinate the operation of the ESS components at the VPPIBox level. This local coordination combined with communication pathways to the EMS, VPPINode, and VPPIPlatform (as can be seen in the concept architecture) will allow for the optimisation of VESS operation and ultimately increase the efficiency of the overall system performance.

CU will be bringing their knowledge and expertise with software and algorithms to estimate the Virtual State of Charge (VSOC) to inform the optimal operation VESS.

Peer-2-Peer Trading Engine

Energy trading between peers within distributed energy communities is powered by the peer-2-peer trading engine. In the layer of the P2P trading engine, the designed blockchain based auction mechanism is applicable for all connected consumers, producers and prosumers. The VPP4Island energy community consists of up to 50 smart meters, 10 VPPI-Box and 10 selected households for additional solar PV installation. Energy trading within the energy community is performed as described in section 3.2.

The P2P trading engine is located in the VPPI-Box since this allows for local monitoring and control of individual loads and equipment. Thereby, this places the required hardware with embedded software at each consumer/prosumer location that enables communication of information, such as setpoints of the remote units, between the energy system of each consumer/prosumer and the flexibility aggregators (VPP4INode).

As energy trading within a P2P network brings challenges to the data security and privacy of participants, the P2P trading engine utilises blockchain based DLT database and smart contracts to ensure trust and safety. Smart contracts are automatically triggered when certain condition(s) are met, such as if an agreement between the transacting parties is honoured. Thereby, the use of a DLT database at each node in the P2P network makes the whole process transparent to all participants without needing trusted central authorities.

Partners BC2050 have expertise in the field of blockchain smart contract technology, so will be developing and contributing to the P2P trading engine, software and algorithms for blockchain process evaluation, and other smart contract utility models.

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DLT Remote Database

The overall goal of smart contracts for P2P energy trading is to minimise the use of centralised databases that reside on host servers to provide encryption, and hence secure transmission of data between parties in the VPP4I-Platform.

The application of a blockchain based DLT database for decentralised energy trading within the energy communities will allow the assurance of high reliability and decentralised operations by implementing trackable and tamperproof transactions between all the actors involved in the P2P network.

The VPP4ISland adopts a blockchain based DLT for capturing transaction data, including the state, address/ID, and functions that can change the state during the operation and eventually emits output events, e.g. to charge or discharge an energy storage device with a certain quantity of power over a specified duration of time for an agreed upon cost. This is enabled by identity management approaches as well as storing and assessing the contracted services that have been activated in the platform securely. So, to that end the architecture requires robustness, high availability, and scalability thus the development of the Blockchain DLT will take all these design principles into account so as to meet the VPP4Island’s demanding applications and services.

The blockchain based DLT will be used to ensure the security and trust of the energy information exchange within the platform, enabling both energy data traceability, eliminating at the same time the need for intermediaries or central authorities, and secure access for the stakeholders using relevant security standards and state of the art security and privacy algorithms.

4.3. VPP4INode

The VPPINode is the level of the VPP4ISLANDS system that performs the centralised local operations. Field measurements are received from the VPPIBox via the communication system and are processed via the security engine and pre-processing system. The central modules including the BSP, distributed optimisation engine, local forecasting engine, and EMS commitment engine are used to make service scheduling decisions based on the measurements received. The VPPINode also contains a UI module for stakeholders to be able to access relevant operational data about the system, which is provided via the authorisation and access control interface. All data is stored in the local database, with copies relayed to the shared KB within the VPPIPlatform level. The diagram in Figure 28 displays the architecture of the VPPINode system with all required components arranged to illustrate interaction and transfer of data.

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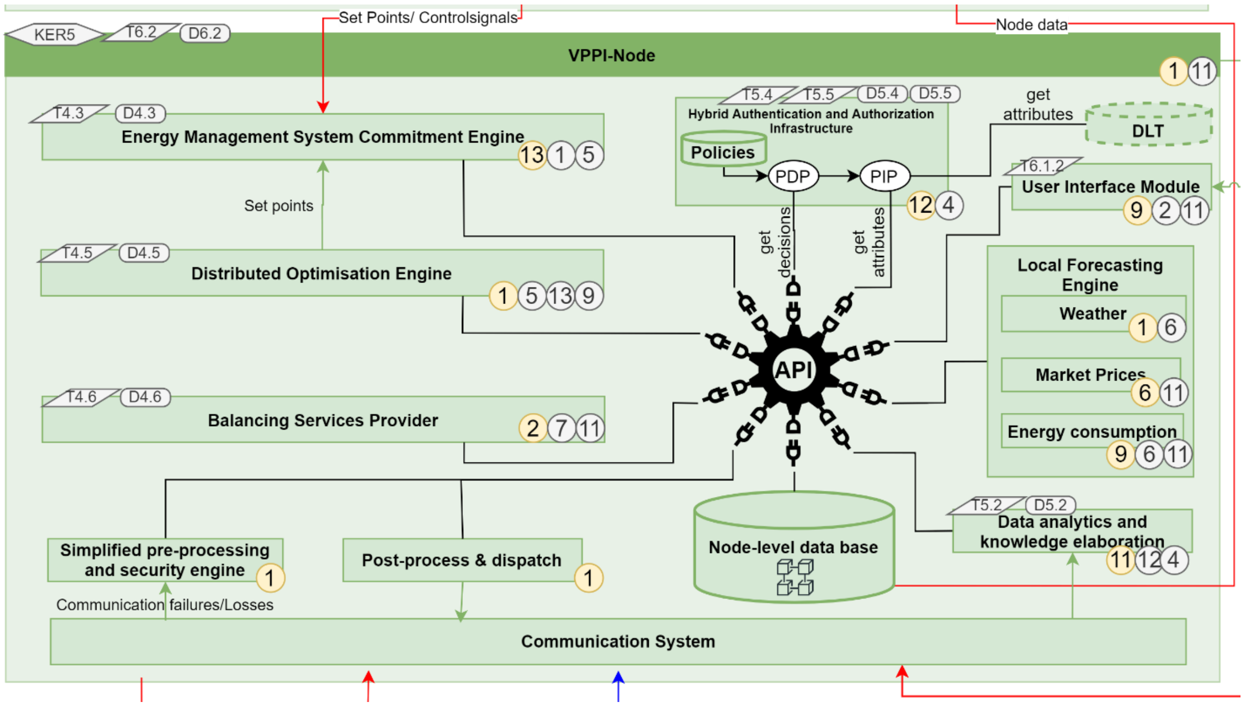

Figure 28: VPP4INode taxonomy diagram

Energy Management System (EMS) Commitment Engine

The VPPINode is the central local hub for communication, control, and authority for the VPP4ISLANDS system. Central to this concept is the EMS commitment engine. As can be seen in the diagram in Figure 28, the EMS receives data and inputs from all ancillary components within the system that relate to the delivery of services and scenarios for stakeholders and end users, including the distributed optimisation engine, hybrid authentication and authorisation infrastructure, and Balancing Service Provider.

The EMS will also contain distributed and shared control methods including Model Predictive Control (MPC), adaptive control, and PID based systems. These will be used to define the control authority and signals to be sent to variable loads and generators connected to the VPPIBox on the field. Control schedule tracking and record keeping will also be a key factor in traceability and security during operation of variable ESS or flexible loads. This means that the component will need to have controls access authorisation through the authorisation engine, as can be seen in the diagram.

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Distributed Optimisation Engine

A closely related concept of the EMS commitment engine is the distributed optimisation engine being developed by AMU. The two components work together to ensure the optimal scheduling and dispatch of control signals to the field. This methodology is based on a 'two-level' optimisation approach which takes into account both the physical and network constraints of the system. Using this method, the optimisation engine can be used to solve scheduling conflicts and assist in routing services and scenarios. The key outcome of this process is to identify the optimal operating strategy for the local VPP4ISLANDS system based on the available resources and required scenarios.

The optimisation requires inputs from other modules located within the VPPINode, including the BSP, local forecasting engine, and the access control/authorisation module. The system interacts with these modules through the proposed Mongo API system in which data is stored and accessed from the node level database.

IPR relating to this module will be delivered by AMU, including a software copyright for optimal scheduling of different assets regarding the upstream spot market interaction.

Balancing Services Provider

The definition of the Balancing Service Provider (BSP) is a *'new market participant with reserve providing units/generators able to provide balancing services to the TSO and ensure optimal network operating strategy'* [60]. This definition indicates that the BSP is the centralise authority for procuring and enabling the VPP services and scenarios, and interfacing with external stakeholders such as the DSO, TSO, and local community. The BSP will consist of Production and Load Aggregators (PLA) which will be supported by the other VPPINode components to enable continuous monitoring and management of energy flows. Given the requirements laid out, the BSP will also have the ability to handle energy dispatch requests from the aforementioned stakeholders and prioritise based on optimal performance signals from the optimisation and EMS commitment engines.

The BSP will activate at a time interval of approximately 2 hours, but this depends on the particular market structure of the country of region. The predicted values from the local forecasting engine are used to provide day ahead and intra-day forecasting information for the system to participate in these markets. The standard day ahead market time intervals are 1 hours, and intraday is set

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at 15 minutes. The BSP can also receive an updated forecast for every timestep that new data is available, which will again be at 15-minute intervals.

For the completion of the BSP module, the Balancing Service Provision Platform (ER-LIBRA) software application from ALWA can be used for demonstration/validation purposes. The definition of this application is as follows:
"ER-Libra is a scalable and modular platform for the management of operational processes of Balancing Service Provider (field measurements, communication with TSO, modulation of loads/production, offers on MSD market, accounting). End-to-end solution for the entire operational process (measurement, communication with Terna, implementation of provisions, monitoring of actions, offers on the MSD/MB market, integration with company business process). An end-to-end solution for the entire operational process (measurement, communication with Terna, implementation of provisions, monitoring of actions, offers on the MSD / MB market, integration with business process)." [67]

User Interface (UI) Module

The proposed UI module will allow a variety of VPP4ISLANDS stakeholders to access their desired system information in near real-time. End users, for example, will be able to view energy flows and related costing information for each service timestep (30 mins, 1 hours, 6 hours, etc). The relevant performance measures will also be available via the access control and authorisation system, such that stakeholders can be exposed to selected data in a secure manner. Data can also be anonymised for operational analysis or sharing with third parties to open up potential revenue streams. Different exposure levels can be defined based on the stakeholder requirements and access rights.

Related IP will be bought into the project as the User Interfaces of Inavitas, registered as a Trademark with the Turkish Trademark Office (2019 113777) [68]

Local Forecasting Engine

The focus of the local forecasting engine is to employ the use AI training and optimisation algorithms to predict future system inputs. The key predictions as described in section 3.2 are of the local weather conditions, energy production and consumption, and energy market price values. The key algorithms used include classic ARIMA methods, Neural Networks (NN), and other machine learning techniques, with additional methods described in section 3.2.

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The data required for this predictive methodology varies depending on the target prediction data set. For example, the prediction of PV solar generation will have a strong dependence on the solar irradiance, as well as the air temperature, with less dependence on parameters like wind speed and air pressure. The key data sources include:

- Meteorological (available through local weather station or third-party API)
    - Air temperature
    - Wind speed
    - Air pressure
    - Solar irradiance
- Market prices (available through market regulator API)
    - Day ahead
    - Intra-day
    - Continuous markets
    - End user energy price
- Energy measurements (smart meters and VPPIBox)
    - Power consumption (active/reactive)
    - Power production (active/reactive)
    - Frequency
    - Voltage
    - Pre/post meter power flows

The local forecasting engine will be connected to the local VPPINode database so that it can receive the required timeseries data sets to perform the predictions. These predictions can then be passed to the optimisation engine and on to the EMS commitment engine to guide decision making about VPP operations. For forecasting engine must also be able to provide analysis of prediction accuracy by means of RMS or residual error, and identify the sources of potential inaccuracy through correlation analysis and statistical significance.

The partners bringing IPR to this area are REGE and AMU, which are listed below:

- REGE: Forecasting engine (Market prices considering weather conditions) Software – AI algorithm, Patent or utility model.
- AMU: Weather forecasting engine Software - the weather forecasting engine is very important, and its absence may affect the VPP flexibility and reduce improve the effectiveness of the optimisation scheduling, copyright.

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Pre/Post Processing and Unification of Datasets

Data acquired from a variety of resources including smart meters, VPPIBox RTU, third party APIs, models and simulations will all inevitability have different data formats and standards. The data will have to be unified and homogenised before it is able to be used by the VPP4ISLAND components and system. The unified data can then be stored in the local database or the shared Knowledge Base (KB).

The unification of data from multiple resources can be a challenging task but can be achieved with specialised data acquisition and unification software such as OMNIO. These tools can enable the communication and management of third-party assets if required to streamline to acquisition and storage of required data. It will also be important to synchronise time series data to the chosen timesteps for other VPPINode components to function.

Data will also be homogenised by sorting into timestamped JSON files containing all static and dynamic data sets for the system so that all components can easily accessed and understood, which will be stored in the Node Level Database. AMU will also be providing a pseudo-anonymisation software engine to guarantee data protection requirements are enforced for all stakeholders.

Hybrid Authentication and Authorisation Infrastructure

The VPPINode architecture relies on the ability of different processing modules to be able to perform actions such as access data or perform actions on a protected data resource, such as reading and editing datasets. The Streaming Attribute Policy Language (SAPL) is a method for expressing access control policies as well as a publish/subscribe protocol based on JSON [69].

This policy language has several internal protocols and services that allow it to be applicable to a number of scenarios where secure access control as required when reading and subscribing to data is required. A high-level explanation is that the given policies contain rules that govern the type of access that is available, then these rules are applied to an attribute-based structure consisting of the standard subject-action-resource layout.

Within the VPPINode, this SAPL will be used to ensure data access individuality requirements between different stakeholders, particularly when requesting access through the UI module. This allows the interface to implement any necessary cyber security requirements between the internal

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components and external stakeholders, APIs, and third-parties. Streaming data can also be anonymised to protect sensitive user information from being revealed to malicious entities.

The use of smart contracts in combination with the SAPL will also provide a secure and distributed method for negotiating sharing policies, potential new uses and business cases involving the physical energy system. It will be possible to securely share and anonymise any data with third parties using the subscription-based protocols, which can also limit access time for streaming data. This could allow for a licensing or subscription-based service for parties to access VPP4ISLANDS data and expand potential involvement or improve the functionality of their product or service.

4.4. VPP4IPLATFORM

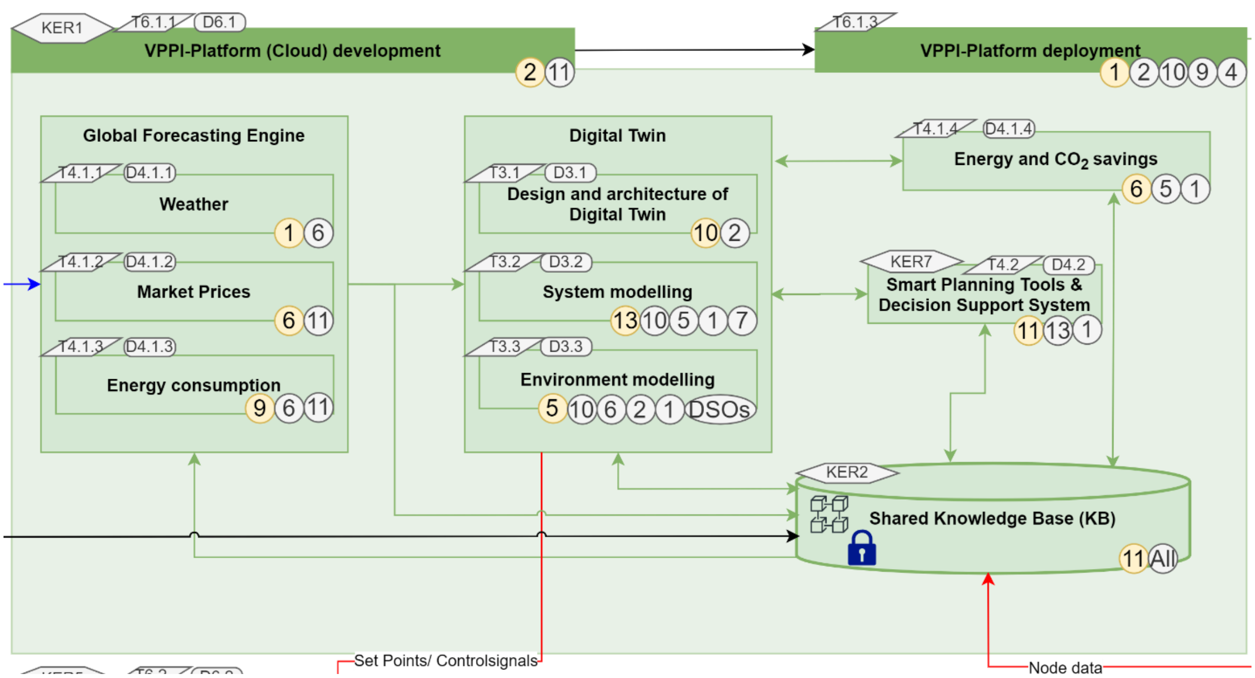

Figure 29: VPP4IPlatform concept architecture diagram

Global Forecasting Engine

The global forecasting engine will be similar to that of the local library of predictive tools but will be less involved with the real time management and control of system assets. Instead, the global

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forecasting tools will be used to supplement the modelling and analysis performed by the Digital Twin. The forecasted parameters can be directly compared with numerically modelled and actual data to detect system faults and sub-optimal processes. The system model will receive the predicted consumption and generation values from the global engine to compare to the historical operation data and identify inconsistencies.

In addition, the market price predictions from multiple installations can be used to provide additional data analytics and expand the knowledge base across locations, improving forecasting and learning accuracy. The global forecasting engine will perform more medium to long term forecasting, as opposed to the local forecasting engine which will conduct short term predictions to be directly fed back into the local decision-making logic. The frequency suggested for local short-term forecasting is approximately 15 minutes, whereas data received at the VPPIPlatform level will resolve at larger timesteps in the range of several hours to days.

Similarly to the local forecasting engine, the global engine can also provide statistical analysis of correlation and regression between different hyperparameters, and identify sources of error and inaccuracy to offer potential prediction improvements.

Digital Twin

As discussed in the previous section, the Digital Twin is used to provide a virtual model of the VPP to compare performance parametrises and to test new services and scenarios before installation in the field. Data will be received from the VPPINode in longer timesteps in the range of 6 hours to one day, so the DT primary services is to provide a retrospective view of the actual system to inform future predictions of performance and outcomes. A high-level description of the DT concept definition is given below:

Systems Model
A full power system dynamic simulation of the VPP energy system, including generators, consumption loads, and interconnection lines. The simulation can output voltage, perform load flow analysis, and frequency deviation with the swing equation. The system model will also have the capability to exchange components and system design to test new components and services, providing analysis of system stability and reliability.

Environmental Model
The environmental model will handle the modelling and simulation of all other VPP process surrounding the physical system. These processes include the activation and management of services, markets participation, and environmental impacts assessment (LCA). The

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environmental model may also be able to test out new services and scenarios in parallel with the systems model to determine with service activation will be beneficial to the related stakeholders and analyse the effects on performance.

The DT requires inputs from the VPPINode but can be requested in relatively long timesteps compared to the local level system components (VPPINode and VPPIBox), including the RTU measurement data, market prices, BSP activities and EMS commitment engine control signals. The DT will then provide modelling outputs of these variables for comparison and further optimisation. Outputs will be sent to the *Energy and CO2 Savings* module, as well as the *Smart Planning Tools and Decision Support System.* All outputted data will also be sent to the shared KB where it can be organised for later analysis or shared with external stakeholders.

Below is a summary of the foreground and background IPs that will be integrated into the DT development:
Background: IDEA, BIM digital Twin V02 is focused on the integration between data sources and the BIM model. Software, Trademark: BIM Digital Twin.
Foreground: IDEA, Development of a pluggable API that supports those modules and data traffic - Simulation and validation of the different models and resources needed by the VPP4IShadow to represent appropriately the real VPP4INode.

Energy and CO2 Savings

Outputs from the DT in combination of analysis of the actual energy system in the field is used to derive reports on energy consumption reduction, cost savings, Life Cycle Analyses (LCA), and the development of the VPP4ISLANDS services portfolio. These outcomes are then used to inform control and processes changes handled by the distributed optimisation and EMS commitment engine. All data outputted will again be stored in the shared KB so that it can be made available to the appropriate systems.

Smart Planning Tools and Decision Support System

The concept of the *Smart Planning and Decision Support System* Is closely related to the outcomes of the *Energy and CO2 Savings* module. As mentioned, all outcomes from the latter will be stored in the KB, where it will then be accessible for this component.

The smart planning and DSS consists of a AI-based open framework. The module will collate performance variables (cost saving, reliability benefits, emissions impacts) into a defined multi-objective trade-off model to allow for further optimal decision-making suggestions for the

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VPPINode. Other dependencies include outcomes from the DT, data mining and forecasting modules. Other outcomes include ROI and economic assessments, LCA, DR and service capabilities, and analysis of VPP participation over time. Key exploitable outcomes can also be used in other VPPINodes located in different regions to build and elaborate upon the local knowledge.

Shared Knowledge Base (KB)

The vision of the shared KB is that all collected, produced and mined data should be collated and stored to produce a foundation of experiences and technical information. This information can be both shared internally to different VPP4ISLAND components and processes, as well as externally to end users, operational stakeholders, and third parties. The access control and authentication system can be employed to ensure data security and privacy is upheld whilst allowing multi-system and stakeholder access. Stored data will include static grid information for all installed VPP4ISLAND systems, timestamped and dynamically collected datasets, control strategies and operational developments over time, and all outputted performance metrics. The shared KB therefore should be accessible to all modules within the VPP4ISLANDS system at all levels.

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5. Initial Concept Models

The first sub task within this deliverable report was to adapt and improve proposed concept components brought into the project by various partners (forecasting tools, DLT, DT, VESS, etc) to produce a novel VPP4ISLANDS concept architecture. It can be seen in the previous section that this objective has been achieved with the presentation of the novel concept architecture that will be used to guide design and integration decisions as the system progresses. The second part of this deliverable is concerned with producing a real system concept for the two lead islands of Gökçeada and Formentera. Within these models, systems have been designed and optimised to significantly reduce the carbon impact of the islands by implementing a lifecycle-based sustainability definition and minimise the impact on energy costs for the end user. In this way, social and environmental factors are both considered for the novel concept design with a comparison to the reference system.

The aim with this work is that it will provide on initial vision and methodology for implementing a true decarbonising energy system that can be operated using the novel VPP4ISLANDS concept architecture. Further optimisations can be performed as more information is known about the system processes and services that will need to be provided.

5.1. Formentera: Energy Community

Energy System Model

The concept design for the island of Formentera centres around the proposed energy communities concept. Within this definition, multiple smart buildings can be virtually connected such that they are able to act as a single energy prosumer, and trade excess energy between peers for the mutual benefit of all energy parties. It has been established that Formentera contains seven communities PV solar installations that could be implemented into this concept.
In this concept, the energy community consists of these seven community PV solar installations each equipped with a VPP4I-Box, as well as a selected number of commercial, industrial, and residential consumers with smart metering equipment installed. Up to 10 additional residential buildings are planned to have PV solar installed to be part of this energy community. This configuration allows for energy trading between the prosumer buildings and consumer buildings. The buildings in the energy community remain connected to the DSO, hence, for energy trading within the community, DSO network is used for the exchange of energy. Additionally, this requires communication with the VPPI-Node and VPPI-Platform for the evaluation of actions in the energy

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community and its effects on the DSO grid, e.g., by use of the digital twin or forecasting engine. Furthermore, this allows the energy community to provide auxiliary services to the DSO or TSO through energy storage and/or flexible loads. A hybrid Lithium-Ion/Hydrogen energy storage system is proposed to be used within the system. The lithium-ion battery is perfectly suitable for short duration (<4hours discharge time) and fast response. The hydrogen energy storage's strength is the long-duration storage (days to months). Hybridising these energy storage solutions by finding the synergy between them increases the economic viability, reduces operational stresses to maximise component's lifetimes, and provides additional redundancy to increase system resilience.

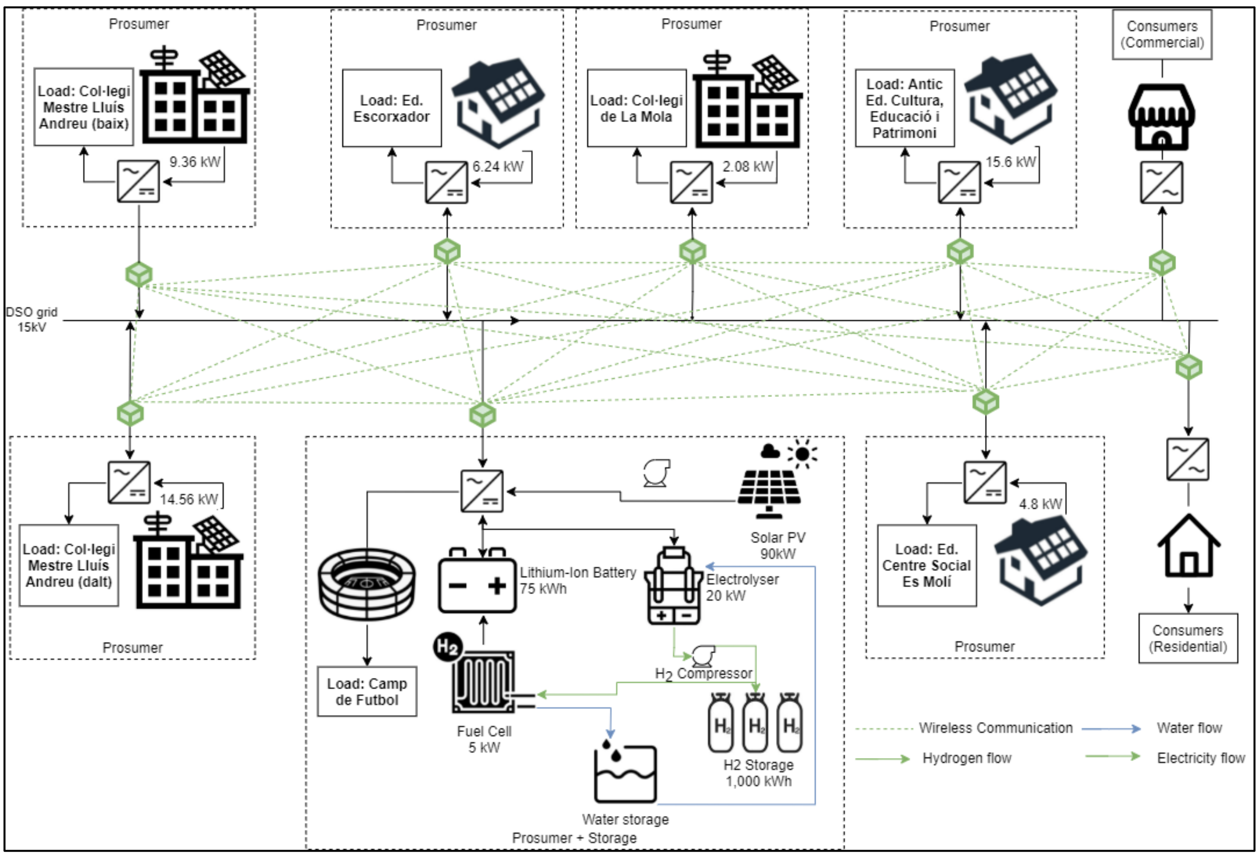

Figure 30: Formentera energy communities concept diagram

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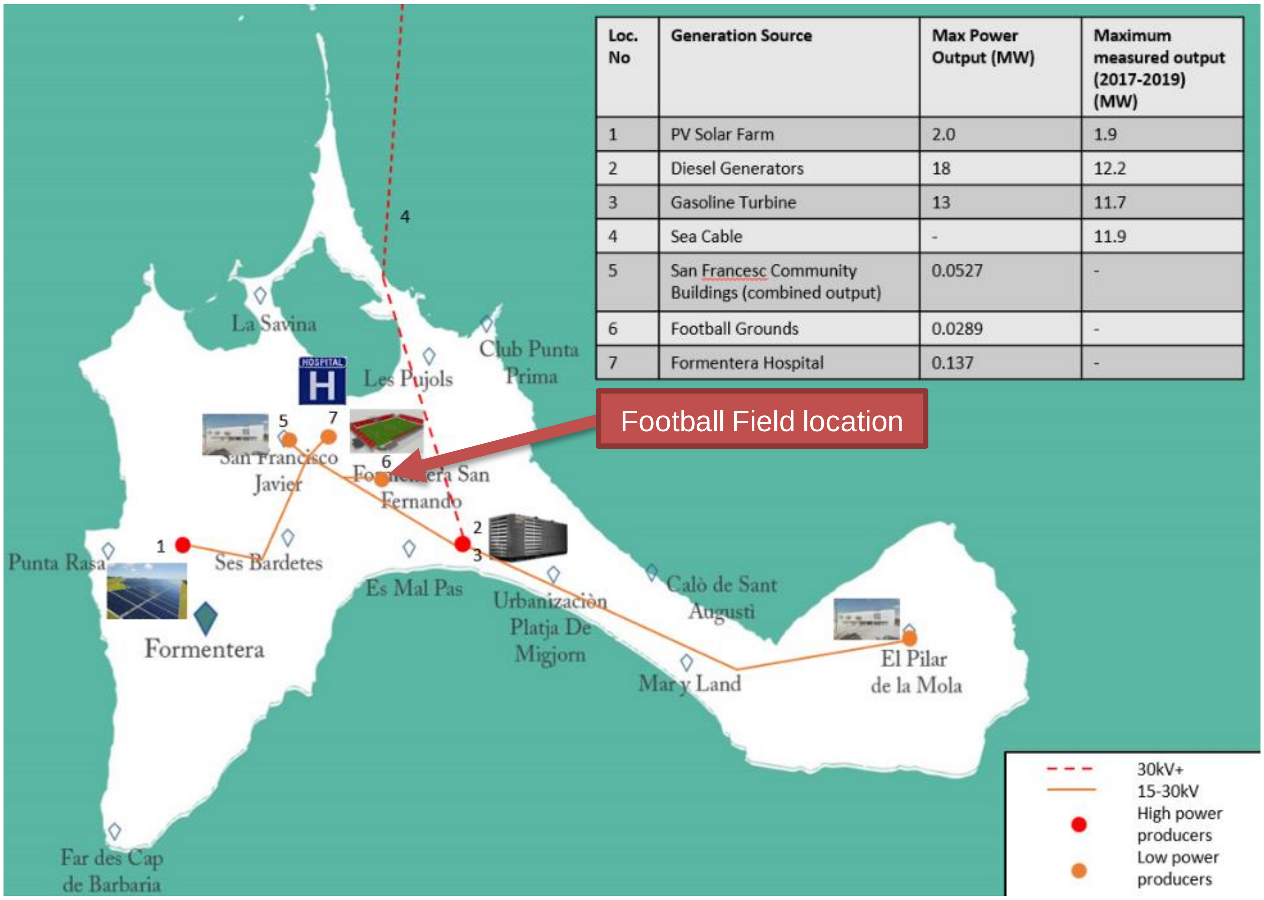

Loc. No	Generation Source	Max Power Output (MW)	Maximum measured output (2017-2019) (MW)
1	PV Solar Farm	2.0	1.9
2	Diesel Generators	18	12.2
3	Gasoline Turbine	13	11.7
4	Sea Cable	-	11.9
5	San Francesc Community Buildings (combined output)	0.0527	-
6	Football Grounds	0.0289	-
7	Formentera Hospital	0.137	-

Figure 31: Map of Formentera with Location of the Football Field

For the purposes of this analysis, one building is used for the conceptual study with the view of expanding to the other buildings once the system functionality has been proven. The building chosen is the Football Field located on the island, as shown in the map in Figure 31. An average day energy consumption curve is also shown in Figure 32. It can be seen in the graph that the building has a base level consumption of approximately 5kW which increases slightly during daylight hours. The current PV solar system has a nominal power of 29kWp and is able to produce a good amount of excess power generation during this time, which will be vital for increasing energy flexibility and allowing for additional services. It can also be observed in the graph that there is a substantial increase in energy consumption in the evening, likely due to the use of flood lighting to light the Football Field during games. This peak also coincides with the peak power consumption of the island, so will likely add to increased grid stress and energy costs during this

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time. The ability to reduce this peak power consumption will be vital to improving emissions, energy costs, and reliability.

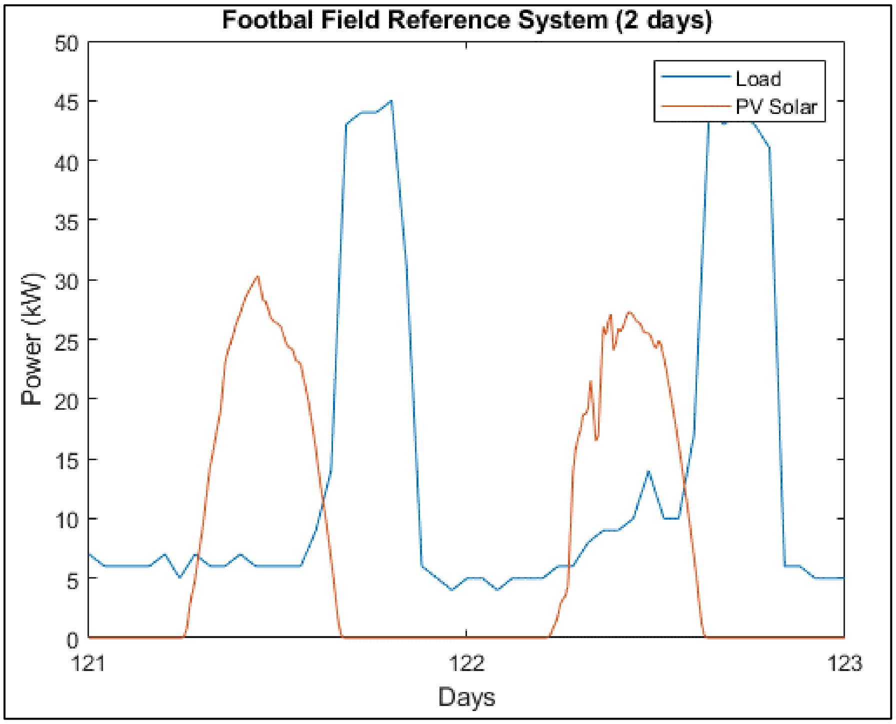

Figure 32: Football Field reference system with building load and PV solar generation (April 2019)

The system proposed is an integrated hybrid Regenerative Fuel Cell (RFC) and battery energy storage system to store the excess PV solar when available and release the energy again in a temporal shift to improve system performance [70]. For this, the system parameters were optimised to reduce the LCOE and ensure that the hydrogen state of charge does not excess operational limits. Also, the system must be able to limit energy imported from the grid so that the building relies on the new integrated energy system to reduce costs. A diagram of the proposed system is shown in

Figure 30. The control logic for the system is also shown in Figure 33.

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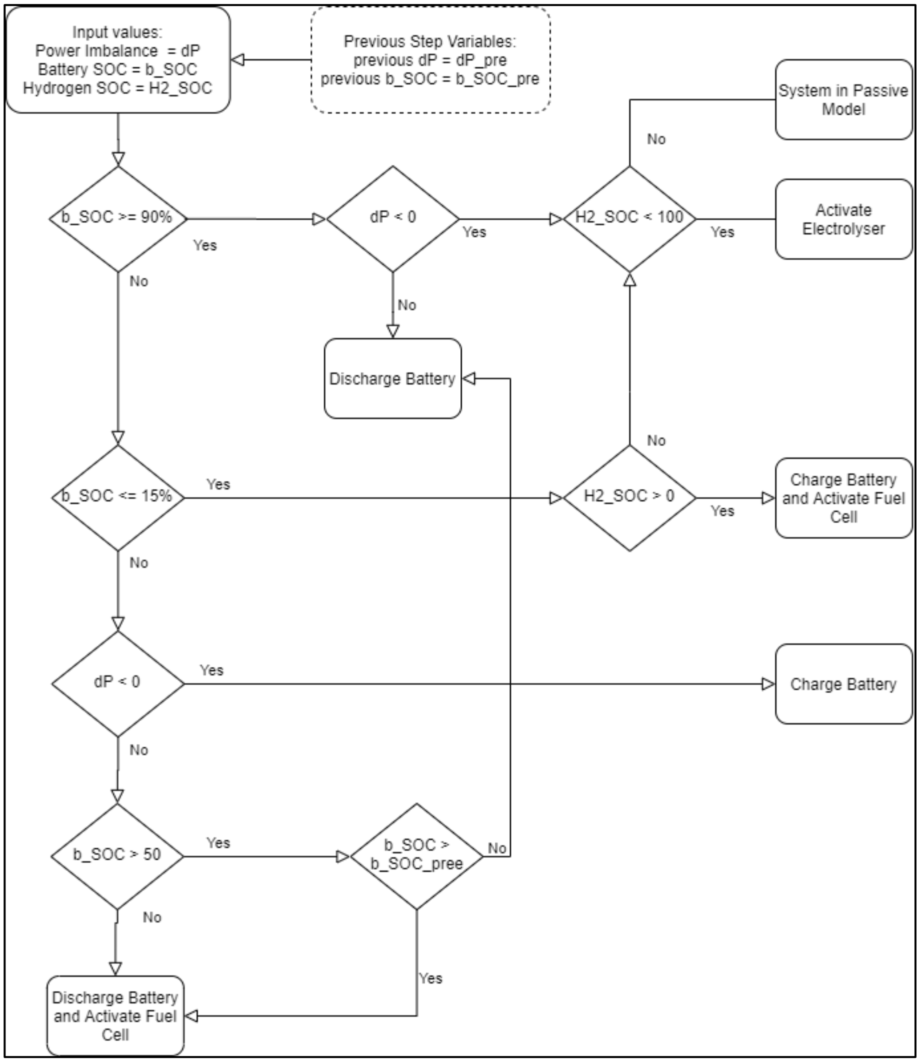

Figure 33: Integrated hybrid energy system control logic (simulation performed with Simulink Stateflow)

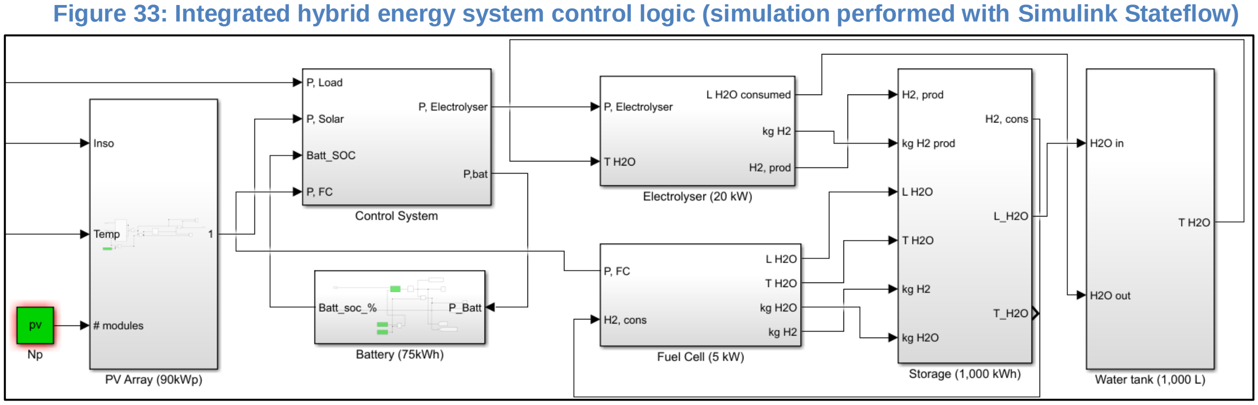

Figure 34: Integrated hybrid energy system simulation model in MATLAB/Simulink

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The methodology for appropriately sizing the integrated hybrid system centres around a multi-objective design optimisation process within the commercially available MATLAB/Simulink software. As mentioned, the key performance measures of this system are the LCOE, hydrogen storage capacity, and the minimisation of grid energy import to the building. The scalarised cost function can therefore be described as the following:

$$Minimise\ f(x) = \min_{x} \sum_{i=1}^{3} w_i x_i$$

Where:
$x_1 = \sum_{i=1}^{n} (E_n * LCOE_n)\ / E_n$
$x_2 = SOC_{start} - SOC_{end}$
$x_3 = E_{import}$
$w_i = 1$; ie. all functions are equally weighted.

$E_n = Energy\ from\ given\ energy\ source\ n$
$LCOE_n = Levelised\ Cost\ of\ Electricity\ from\ given\ energy\ source\ n$
$SOC_{start} = hydrogen\ state\ of\ charge\ at\ beginning\ of\ year$
$SOC_{end} = hydrigen\ state\ of\ charge\ at\ end\ of\ year$
$E_{import} = total\ energy\ imported\ from\ the\ grid$

The design variables for this concept are the sizes of the PV solar, battery, fuel cell, and electrolyser. The Pattern Search optimisation process within MATLAB was used to resolve the minimisation procedure to the global minima within the design search space. The levelised costs used for the LCOE calculation are shown in Table 3 below.

Table 3: LCOE of the component systems

Energy Source	Energy costs (€cent/kWh)
Grid energy	28.9 [71]
PV solar	6.5
Battery	11.96
Hydrogen system (FC and electrolyser)	15 [72]

For the purpose of the financial analysis, the capital expenditure (CAPEX), operational expenditure (OPEX), and system degradation & lifetime data are taken into account. These data are presented in Table 4-Table 6.

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Table 4: Capital expenditure (CAPEX) of the component systems

Energy Source	CAPEX	Reference
PV solar	€ 700.00/kWp	[73]
Battery	€ 280.00/kWh	[74]
Hydrogen system (Electrolyser)	€ 1,200.00/kW	[75]
Hydrogen system (Pressurised Storage)	€ 10.66/kWh	[76]
Hydrogen system (Fuel Cell)	€ 2,500.00/kW	[77]

Table 5: Operational expenditure (OPEX) of the component systems

Energy Source	OPEX	Reference
PV solar	€ 9.50/kWp-yr	[73]
Battery	1.5 % of CAPEX/yr	[78]
Hydrogen system (Electrolyser)	2 % of CAPEX/yr	[79]
Hydrogen system (Pressurised Storage)	0.5 % of CAPEX/yr	
Hydrogen system (Fuel Cell)	2 % of CAPEX/yr	[79]

Table 6: Lifetime of the component systems

Energy Source	Lifetime	Reference
PV solar	20 years	[80]
Battery	3,500 cycles	[81]
Hydrogen system (Electrolyser)	60,000 hours	[75]
Hydrogen system (Pressurised Storage)	20 years	
Hydrogen system (Fuel Cell)	20,000 hours	[77]

The financial analysis is performed to assess the economic viability and compare the investment opportunity on a like-for-like basis. For a fair assessment of the investment opportunity, the most effective method discounts future net cash inflows, and further capital outflows back to their equivalent Net Present Value (NPV). The NPV represents the value or contribution of an investment to the business. If the NPV is positive, the investment is potentially worthwhile [82, 70]. The NPV is calculated by the following equation, where the system lifetime (n) is assumed to be 20 years.

$$\mathrm{NPV} = \sum_{t=1}^{n} \frac{C_t}{(1+R)^t}$$

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The Internal Rate of Return (IRR) uses discounted cash flows to calculate a percentage rate of return on an investment as per the equation below. It is the annual return that makes the NPV equal to zero. The IRR can be more conceptually benchmarked against other investment returns as compared to the NPV [82, 70].

$$\mathrm{NPV} = \sum_{t=1}^{n} \frac{C_t}{(1+IRR)^t} = 0$$

The LCOE is an important financial parameter to measure cost-effectiveness of energy generating technologies. Although LCOE calculations are sensitive to the underlying data, it offers a comparison between projects and technologies. LCOE aims to provide comparisons of different technologies with different project size, lifetime, different capital cost, return, risk, and capacities. It is an economic assessment of the total cost to build and operate a power-generating asset over its lifetime divided by the total energy output of the asset over that lifetime. The LCOE is calculated by [82, 70]:

$$LCOE\ (\frac{€}{kWh}) = \frac{\sum_{t=1}^{n} CC_t + M_t + F_t\ \ (€)}{\sum_{t=1}^{n} E_t\ \ (kWh)}$$

Which covers the whole lifetime of the energy system from year 1 ($t = 1$) to end of life ($t = n$). Where, C_t is the CAPEX, M_t is the OPEX, F_t is the fuel cost, and E_t is the electricity generated by the system.

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Results

The graph in Figure 35 below shows the progression of the multi-objective function as it approaches the global minimum. The cost function begins at a value of approximately 60 before sharply dropping and eventually tending towards a final value of around 15. This shows that the devised objective function is able to actively search the design space and tend towards a real, non-constrained set of design variables. The data in Table 7 also displays the initial and final system sizing parameters inputted and outputted from the optimisation procedure, rounded to the nearest 5kW set to the size of the FC.

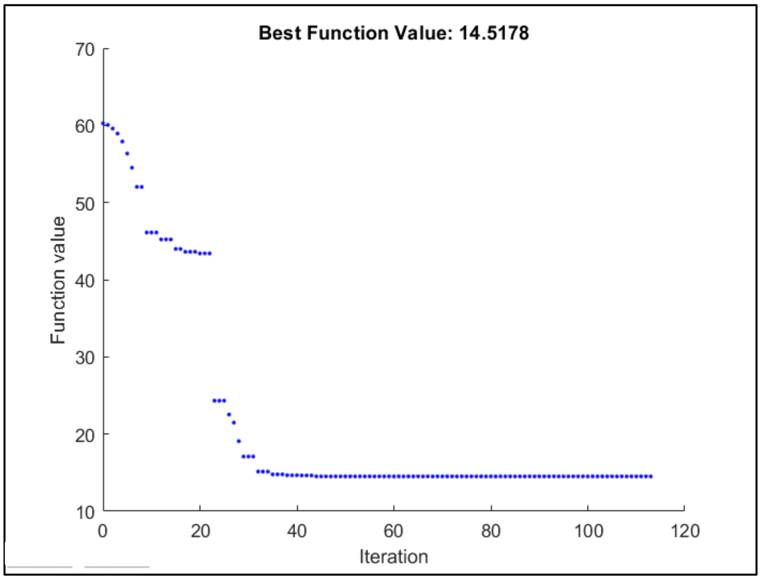

Figure 35: Cost function reduction outputted from the optimisation procedure

Table 7: Optimal sizing of system parameters

System component	Original system size	Optimised size
PV solar	29 kW	90kW
Battery	0 kWh	75 kWh
Fuel cell	0 kW	5kW
Electrolyser	0 kW	20kW

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The graphs in Figure 36 display the output performance of the proposed hybrid system. Unfortunately, due to data collection limitation only 6 months of consumption data from July to December 2019 was available for this building, so has been presented in (a). The system follows the control logic laid out in the methodology. Graph (b) shows the interaction between the various system components in line with the control logic laid out in the previous section. It can be observed that at the beginning of the day, the FC is being used to supplement the battery power to the load to ensure that no grid import is required, and thus reducing cost and environmental impact. Once PV solar is available in excess the battery begins to charge and the electrolyser is also activated to produce hydrogen. An assumption made in this scenario is that any excess PV solar that is not used for one of these purposes can be traded with other energy community 'peers' within the VPP. Once PV solar is no longer available, the battery is discharged and supplemented by the fuel cell until it is empty, from which point a small amount of grid import may be required. The building load then returns to the base level and the battery and fuel cell work together to supply the requirement.

Graph (c) shows the 6-month variation in state of charge of the battery and hydrogen storage. While the battery generally performs a full charge cycle once a day, the hydrogen storage is able to provide support for seasonal variability. The hydrogen storage starts at 70% SOC and steadily climbs during the summer months before declining in the autumn to approximately 30%. The assumption made in model is that for the remainder of the year the electrolyser can make the SOC back up to 70% for the following July. The two main reasons for seasonal variability are the reduced number of sun peak hours for the PV solar panels to be effective, and the increased usage of the Football Field flood lights during the darker evenings in the autumn and winter.

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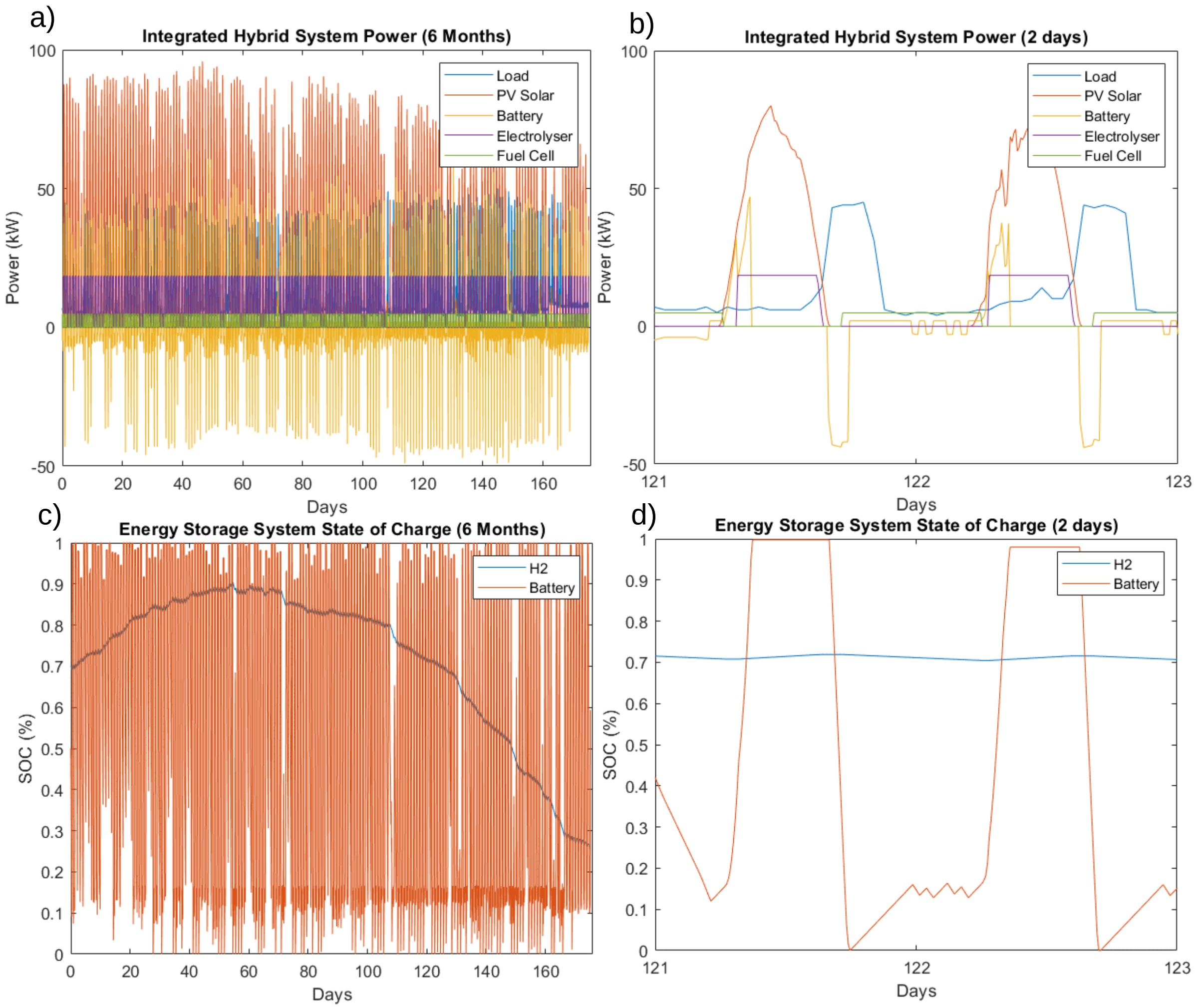

Figure 36: (a): Power production and consumption from the hybrid system during 6 month simulation (summary to winter), (b) power production and consumption two day example (April 2019), (c) energy storage system state of charge 6 months, (d) state of charge two day sample (April 2019)

Graph (d) shows the 2-day variation in the system SOC. The battery generally charges and discharges in a single day to temporally shift the available excess PV solar to when it is required. The data in Table 8 displays the improvements in LCOE and emissions intensity in line with the social and sustainability definitions.

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Table 8: Performance parameters improvement through implementation of the hybrid system

Parameter	Current system	Hybrid system	Percentage improvement
LCOE (€cent/kWh)	17.68	15.77	10.8%
Emissions Intensity (gCO2e/kWh)	276	126	54.3%
Grid energy cost (€cent/kWh) (2019)	28.9		

The optimised energy system

The proposed optimised energy system contains an energy mix of 90 kW Solar PV for primary power generation coupled to a 75kWh Li-Ion battery and an Regenerative Hydrogen Fuel Cell (consisting of a 20kW PEM Electrolyser, 1,000kWh Hydrogen Storage, and 5kW PEM Fuel Cell). The results show an enhanced cost-effectiveness of the synergised system, resulting in an LCOE of 15.77 €cent/kWh compared to 17.68 €cent/kWh for the conventional electricity grid over the 20-year system lifetime. With a Net Present Value of €129,060 and Internal Rate of Return of 11.5%, the investment has commercial viability. Therefore, as shown in Figure 37, the initial high capital cost is recovered with an 8-year payback time to become valuable investment through reduced operational expenditures reducing the energy cost in the long term, as well as increasing energy security, equity, and sustainability.

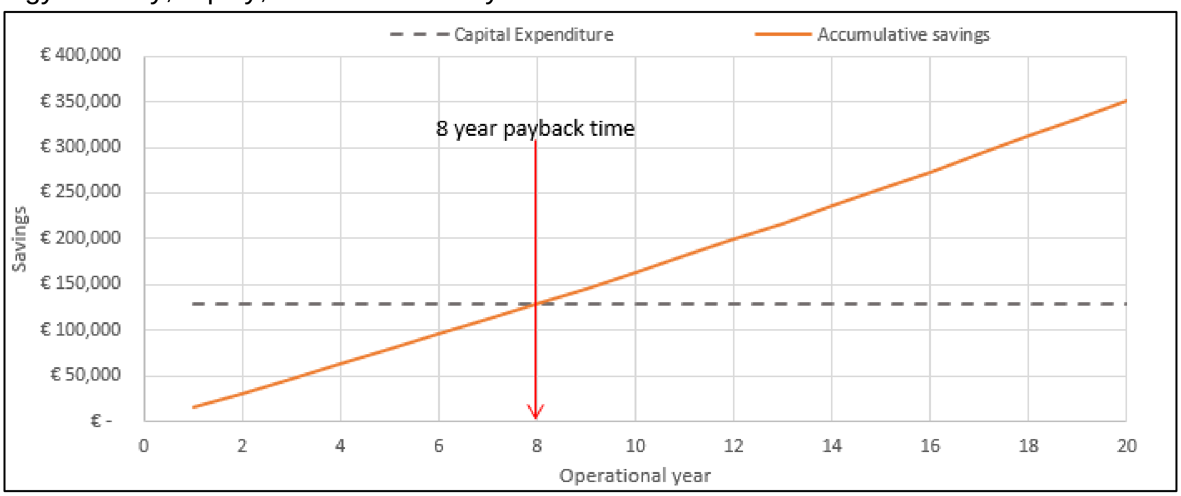

Figure 37: Payback time calculation for the Formentera football stadium solar PV + energy storage system

Summary

This section presented the proposed hybrid energy storage and delivery system of the island of Formentera. Due to limitations with the data collection, a single building was used as a proof of concept for the design. The Football Field was chosen due to the availability of data and the

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measurable excess PV solar above that of the building load. The initial system has a 29kWp solar panel installation, with scope to increase in size.

A multi-objective optimisation process was used to appropriated size a hybrid integration system to reduce cost and carbon emissions. The pattern search optimisation procedure was successful in achieving these objectives. The new concept was able to reduce the LCOE by 10.8% and the emissions intensity by 54.8% over the original system, resulting in an LCOE of 15.77 €cent/kWh compared to 17.68 €cent/kWh for the conventional electricity grid over the 20-year system lifetime. With a Net Present Value of €129,060 and Internal Rate of Return of 11.5%, the investment has commercial viability.

Due to data collection limitations, a number of assumptions have been made about the system in order to conduct the design process. Further optimisations could also be made to include additional grid services over the current load following employed in this preliminary design. The capital cost of the system is also high when compared to the overall budget for the installation, so may have to factor in financial feasibility for later iterations.

5.2. Gökçeada: End User Support

Energy System Concept Model

The initial concept design for the island of Gökçeada is similar to that of Formentera. The aim of this system is to balance the energy flow to several end users such that the only energy received is from either renewable energy resources (wind and solar) or stored energy from the integrated hybrid system. the single line diagram in Figure 38 shows the connections between all generation and storage components, as well as the industrial, commercial, and residential consumers.

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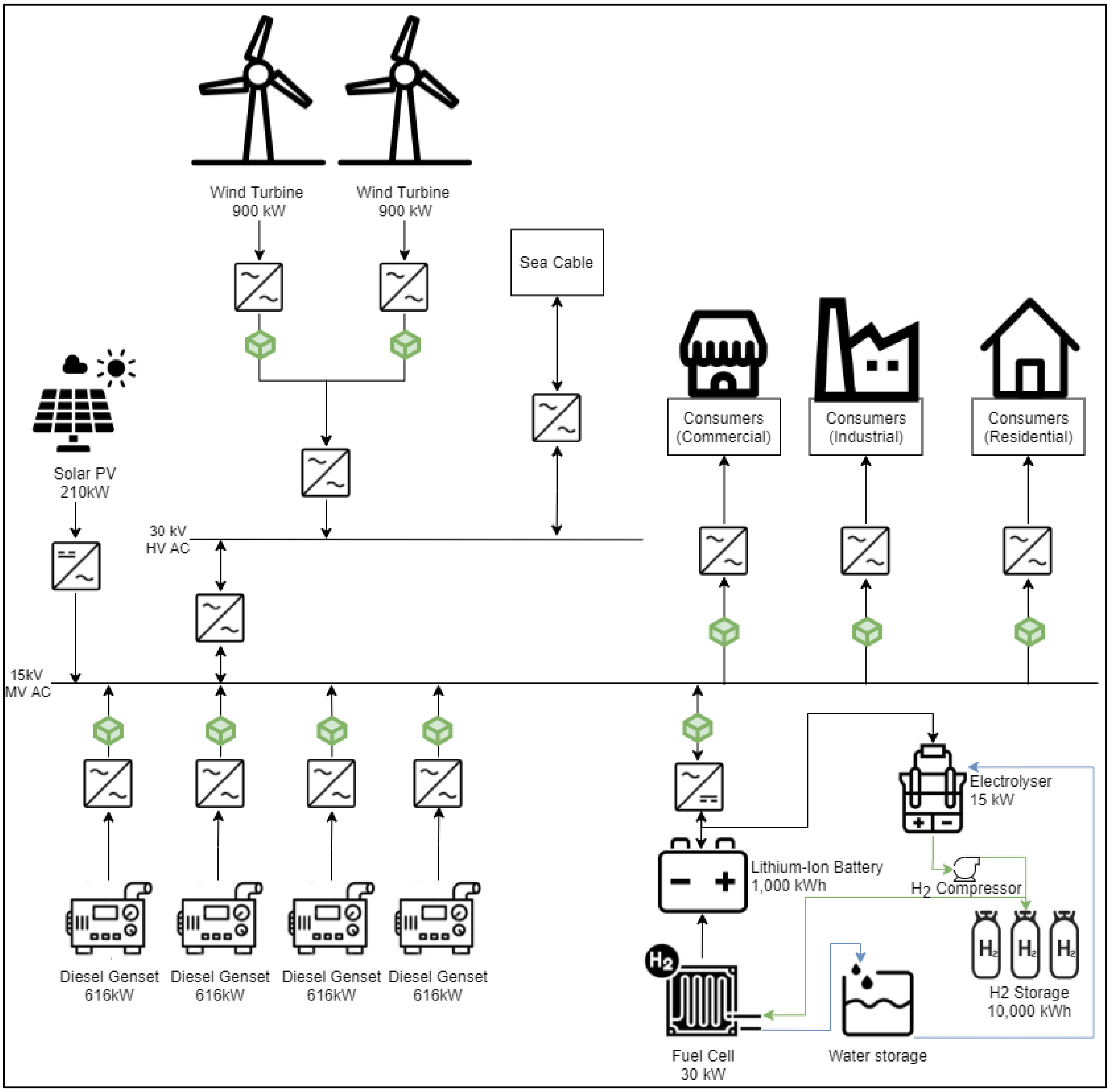

Figure 38: Gökçeada island single line grid diagram with integrated hybrid storage system
For the purposes of this concept analysis, a sample of data collected from 94 different commercial and industrial loads measured with currently installed smart meters. The total end user loads were reduced to 30 to ensure that the concept design is relatively small in size, before expanding as more information is available. The data in

Figure 39 shows the total end user load and the renewable generation from wind and PV solar, respectively.

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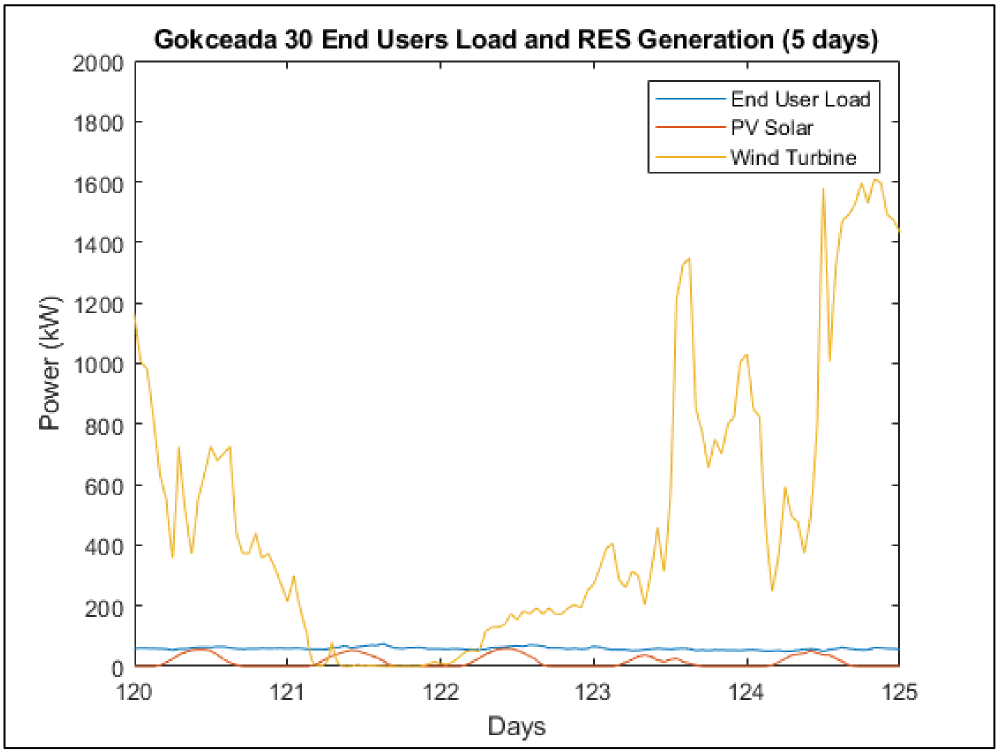

Figure 39: Gökçeada 30 chosen end users load and renewable energy generation 5 day sample (April 2019)

Similar to the Formentera concept, the system proposed for Gökçeada will be sized to cover the energy requirements whilst renewable energy generation is unavailable and limiting the requirement for energy to be imported from the sea cable interconnector as it comes at a higher cost and higher environmental impact. The hybrid energy system uses the same control schematic displays in Figure 33, and the pattern search optimisation procedure used with the devised multi-objective function was employed. The grid energy cost was set to 10.45 €cent/kWh based in data from [71].

Simulation Validation: Wind Turbine Generation

Simulated power generation from the wind turbines can be validated using the real energy measurements received from the local grid system. The graph in Figure 40 below shows a sample of the actual measured power output from the two installed wind 900kW turbines in one hour time intervals. The red dashed line displays the performance of the simulation wind turbine and that it very closely follows the characteristics of the true components. The validation was performed for one year and showed an overall model accuracy of 95.95% and 95.48% when compared to wind turbine 1 and wind turbine 2, respectively.

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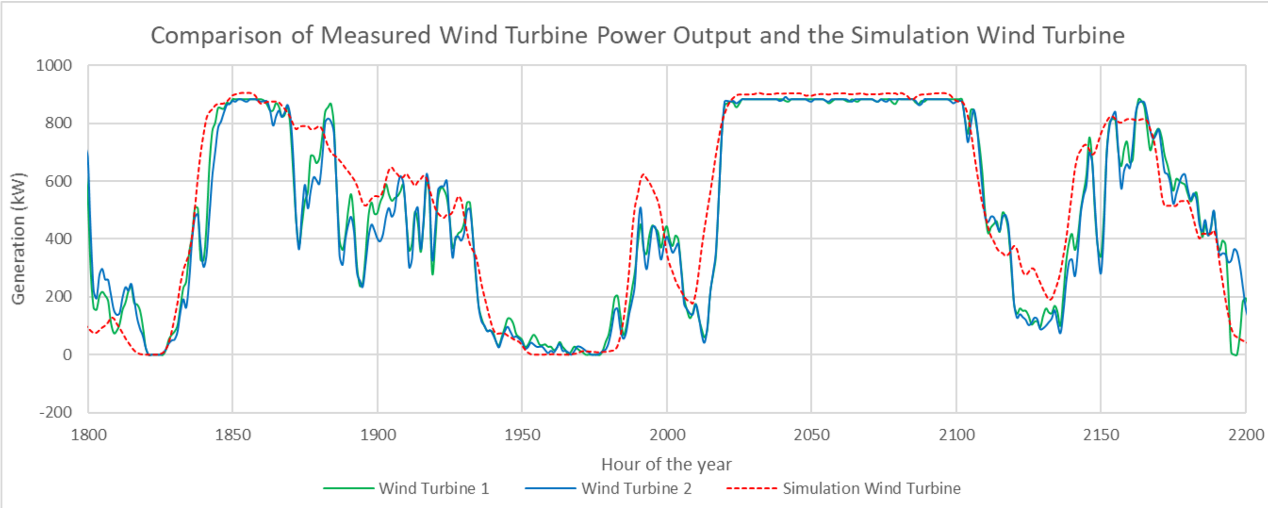

Figure 40: Wind turbine model validation comparison with measured data

Results

The data in Table 9 below gives the initial and optimised energy system sizing outputted from the optimisation process. It was assumed that since no energy community is to be established on the island that the RES could not be modified. This means that the wind turbine quantity and PV solar installation size could not be adjusted during optimisation.

Table 9: Gökçeada concept system optimised sizing

System component	Original size	Optimised size
PV solar	210 kW	210 kW
Wind turbines	1800 kW	1800 kW
Battery	0 kWh	1000 kWh
Fuel cell	0 kW	30 kW
Electrolyser	0 kW	15 kW
Hydrogen storage size	0 MWh	10 MWh

The graphs in Figure 41 display the output performance of the proposed hybrid system. The system was able to be simulated for one year due to the increased availability of data compared with Formentera. It can be observed from the data in graph (b) that the system is successful able to react to the scenario when the RES generation drops below the demand of the selected end users. In this instance, the battery is the first to react by following the load requirement for this period. The FC is also used to supplement power so that the battery SOC does not drop to a

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critical level. Once the RES generation is restored, the battery can be recharged with excess RES and the electrolyser comes online to replenish the quantity of hydrogen lost. Graph (c) shows that the hydrogen storage SOC varies significantly based on the wind conditions on the island for a given time of year. The high winds in the early months allow for a large amount of hydrogen to be stored, whereas the spring and early summary months bring lower wind speeds, so the storage level drops significantly. The optimisation process ensures that over the course of the year the same amount of hydrogen is used and consumed, hence the level returns to 50% SOC by the end of the year. Finally, graph (d) shows that SOC variation over the sample 5-day period, in that when required the battery SOC drops which triggers the FC to come online, using a small percentage of the seasonal hydrogen storage available. The battery is then recharged immediately once RES is available again and the electrolyser also begins producing hydrogen.

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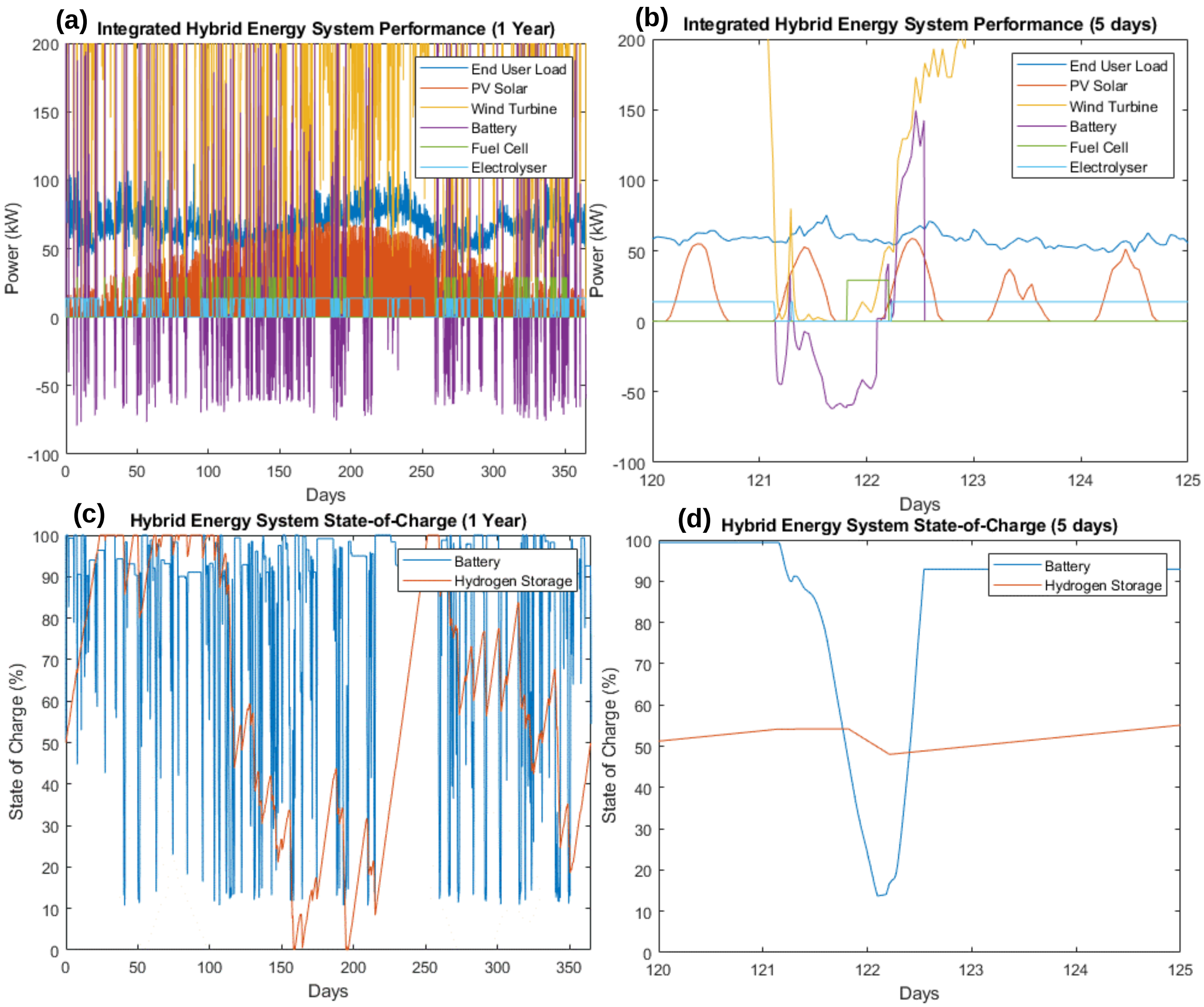

Figure 41: (a) Power production and consumption from the hybrid system during one year simulation, (b) power production and consumption five day example (April 2019), (c) energy storage system state of charge one year, (d) state of charge five day example (April 2019)

Table 10: Gökçeada system cost and emissions changes with new concept system

Parameter	Original value	Hybrid system value	Percentage improvement
LCOE (€cent/kWh)	6.20 (wind value)	10.68	-2.2% (relative difference with the actual energy cost)
Emissions Intensity (gCO2e/kWh)	348.6	100.9	71.1%

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Energy cost (€cent/kWh)	10.45		

Table 10 shows the changes in the system LCOE and emissions intensity with the conceptual hybrid energy storage. While there is a large decrease in the environmental emissions for the selected end users, the overall cost does increase slightly, due to the capital cost of the energy storage systems. This means that an overall negative IRR will be observed if the economic assessment is conducted. The IRR does not take into account, however, other VPP services that could utilise the hybrid storage system for other revenue creating scenarios. The emissions intensity also assumed that all RES can be directed to the selected end users through a form of ‘proof of origin’ guarantee, as in the true system it is not possible to direct energy flow within the grid. The total capital cost of the hybrid storage system would be 383,660€.

Summary

The island of Gökçeada has a relatively high level of RES penetration but is variable due to the presence of two wind turbines. The sea cable has a large carbon impact compared with these renewable energy resources. By using the proposed hybrid energy storage system to minimise the impact of the sea cable on the selected end users, the concept design can significantly reduce carbon emissions. The overall energy cost is slightly higher as it is assumed the energy stored has to be bought as a standard market rate and cannot be bought at a less expensive value.

The pattern search optimisation procedure used with the devised multi-objective function was employed on the MATLAB/Simulink model to optimise the installed capacity of the proposed hybrid energy storage system. The results show the optimised system to consist of a 1,000kWh Lithium-Ion battery combined with a 10,000kWh hydrogen storage, which is charged using a 15kW electrolyser while electricity is regenerated by a 30kW fuel cell.

Expanding the system to cover other scenarios and reliability services may assist in boosting the profitability and therefore viability of the system. The next iterations of the concept should certainly consider these aspects moving forward. The use of the hybrid energy storage system in Gökçeada allows the selected loads to significantly reduce their carbon intensity due to a larger share of wind energy utilised by these loads. With this approach, the initial 348.6 gCO_2e/kWh is reduced to 100.9 gCO_2e/kWh, a reduction of 71.1%. The capital cost for the addition of the hybrid energy storage and the operational cost results in a LCOE of 10.68 €cent/kWh, however, further reduction in the LCOE can be expected when auxiliary services are offered to the DSO and/or TSO on the island of Gökçeada, as well as through a reduced number of outages. Therefore, the addition of a hybrid energy storage system can futureproof the energy grid of Gökçeada.

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6. CONCLUSION

The objective of the D2.4 Definition of Concepts deliverable is to identify and define the required conceptual components and systems that combine to create the novel VPP4ISLANDS architecture.

Firstly, a selection of state-of-the art VPPs are reviewed from literature, highlighting their defining structures, benefits, and challenges to implementation in their given environment. Particular emphasis on VPP concepts that have seen successful pilot studies and commercial roll out have been presented, such that the design and implementation decision could be considered when planning the VPP4ISLANDS conceptual definition.

The concept architecture relies on a high-level knowledge and understanding of the physical and virtual enablers, that are then combined to provide the services and scenarios for implementation in the lead islands. A review of physical enablers such as the RES, ESS, flexible and inflexible loads, and smart metering equipment that directly influence the design of the conceptual architecture. The VPP4ISLANDS system itself then contains the virtual enablers to facilitate the interaction, communication, control, and performance of the physical enablers described. The virtual enablers include advanced forecasting tools, DLT, DT, and P2P energy trading.

The established background understanding of VPP systems in combination with the required enablers then feeds directly into the high-level description of the VPP4ISLANDS concept – centred around the defined concept architecture. The design presents a three-level system of VPPIBox, VPPINode, and VPPIPlatform. The VPPIBoxes and VPPINode are the local systems to be installed on the field and perform local and regional scheduling, control and data management. The VPPIPlatform is the cloud-based service containing DT models and access to the shared KB for the entire VPP4ISLANDS concept.

The report then presents the first real world concept designs for the lead islands of Gökçeada and Formentera. The concept consists of an integrated hybrid fuel cell and battery system to serve the primary performance goals of improved energy costs and environmental emissions. The concepts employ real field data to perform advanced modelling and simulation of the optimised system design. For the Formentera system, the outcomes show that the concept is successfully able to reduce the costs and emissions intensity for the chosen building case study, with a decrease of 10.8% and 54.3%, respectively, with scope to improve performance further with optimisations and the addition of other buildings to create the envisioned energy communities concept.

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Overall, this report presents the VPP4ISLANDS concept definition, with design decisions informed by an in-depth review of the state-of-the-art systems and enablers. The proposed architecture will be used by later tasks and deliverables and provide a foundation for system integration and management of services and scenarios.

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APPENDIX A: DATA COLLECTION

To define a suitable VPP4ISLANDS concept, it is important to first analyse the lead island requirements and services to guide the strategic formulation of potential services and scenarios. In this section, the data collected from the lead island of Gökçeada, Turkey, and Formentera, Spain, are presented. First is a short summary of the current island energy system and the planned implementation of the VPP4ISLANDS concept. The static and dynamic data are then presented and analysed, further establishing the required concept components that will be discussed in depth in the following section.

Static data describes the system information that is not time or domain variable, such as rated power of a generator, or material properties of transmission lines. Dynamic data by contrast describes the time variable machine data that can be collected from the system. The static and dynamic data will be expanded as the project continues, but the current information can form the foundation level of understanding to carry forward to the concept definition.

7.1. GÖKÇEADA

Island Summary

Gökçeada is a small island off the west coast of Turkey in the Aegean Sea in the province of Canakkale. The island has a population of 8,769 (2017) and an area of 282.7km^2 [83]. The island energy system consists of two wind turbines and a PV solar installation, equating to approximately 2MW of total installed capacity. The island also has a peak demand of ~6MW during peak season (June to August) due to the increase in tourist visits. As part of the VPP4ISLANDS project, the local DSO UEDAS are considering the installation of an energy storage system to improve grid stability and monitoring. The island is connected to mainland Turkey through a sea cable interconnector.

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Static Data

Table 11: Preliminary Gökçeada energy system static data

Data Name	Value
Wind turbine rated power	2x900 kW
PV Solar rated power	210 kW
Diesel generator rated power	770 kVA
Diesel generator power factor	0.8
Sea cable interconnector voltage	36kV
System frequency	50Hz AC
Island distribution voltage	15kV
Generator and transformer locations	NA
Number of MV transformers	186

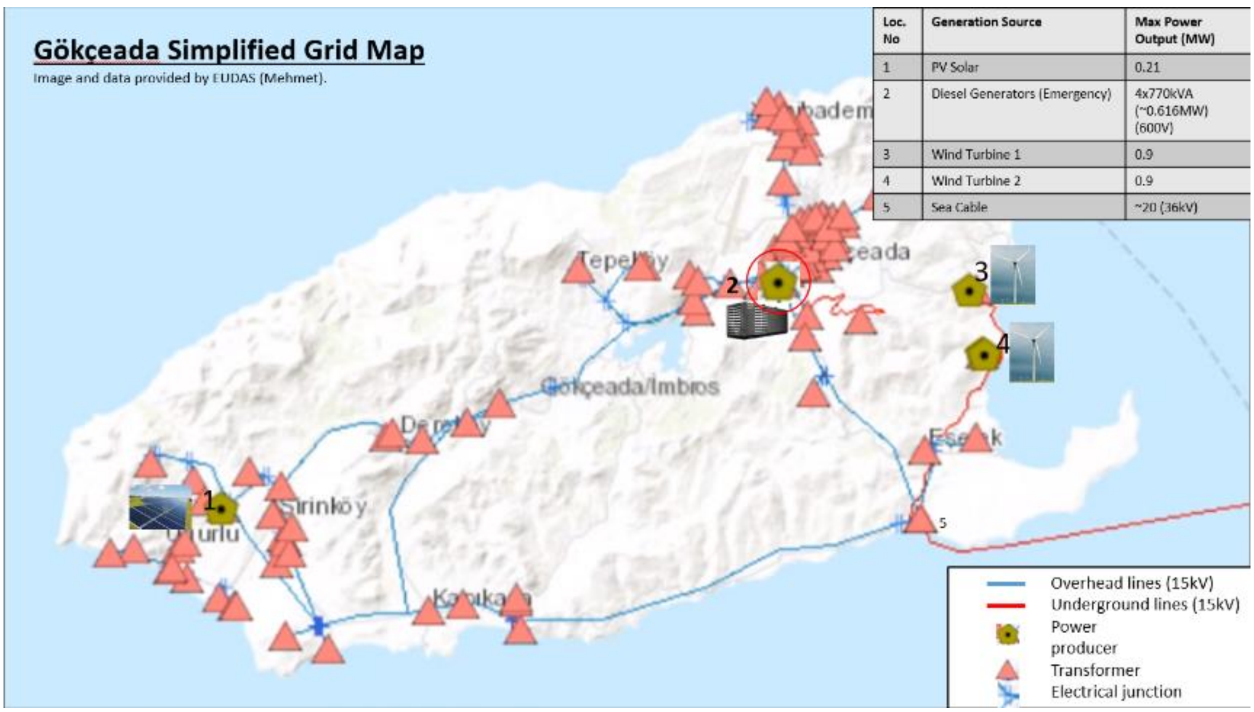

Figure 42: Gökçeada energy system map with locations of generators

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Dynamic Data

Table 12: Gökçeada energy system dynamic data summary

Data Name	*Timescale and Unit*
Renewable energy generation	2017-2020 (10-minute steps) kW
Sea cable import active power	2017-2020 (10-minute steps) kW
Sea cable import reactive power	2017-2020 (10-minute steps) kVA
Island carbon impact (approx.)	2017-2020 (10-minute steps) gCO2e/kWh
End users demand (sample of 94 users)	2017-2020 (10-minute steps) kW (kVA)
Wind Speed (10m)	2017-2020 (10-minute steps) m/s
Wind direction	2017-2020 (10-minute steps) degrees
Irradiance (global horizontal)	2017-2020 (10-minute steps) W/m^2
Air temperature	2017-2020 (10-minute steps) °C
Pressure	2017-2020 (10-minute steps) mBar

Generation

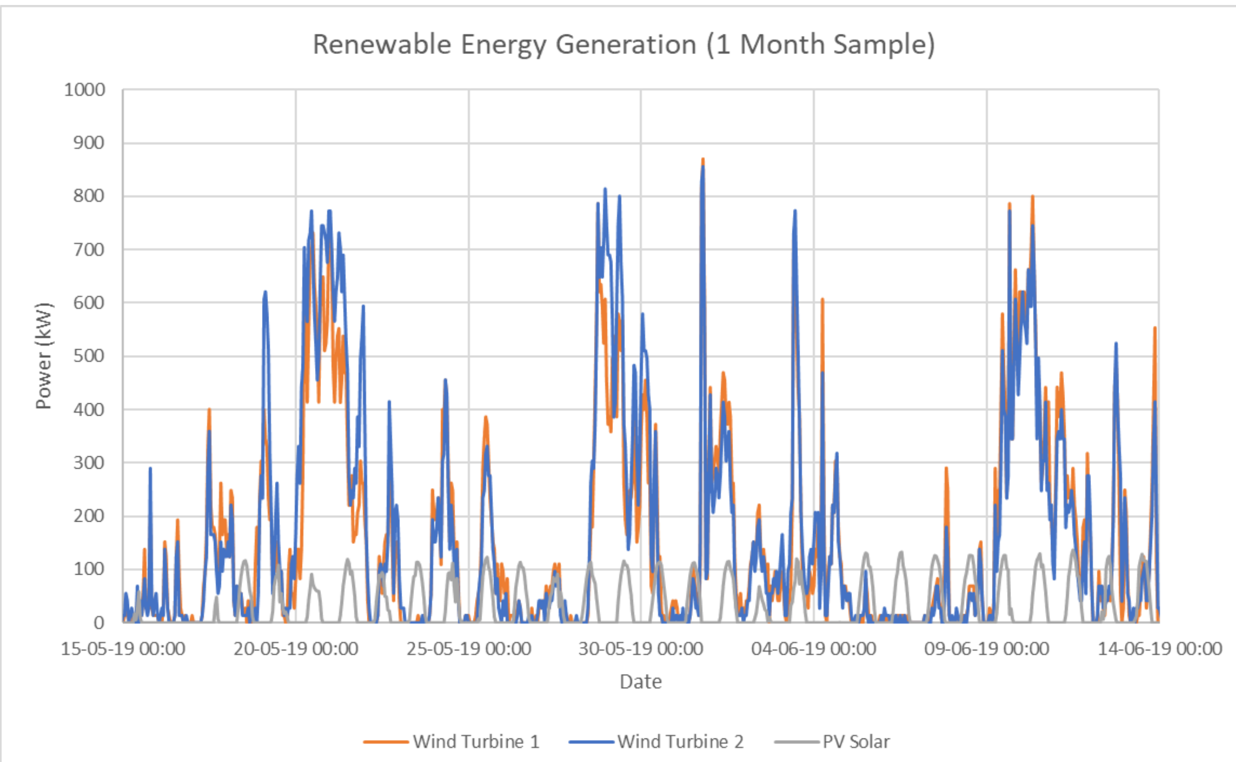

Figure 43: Sample of the energy generation in Gökçeada from RES resources

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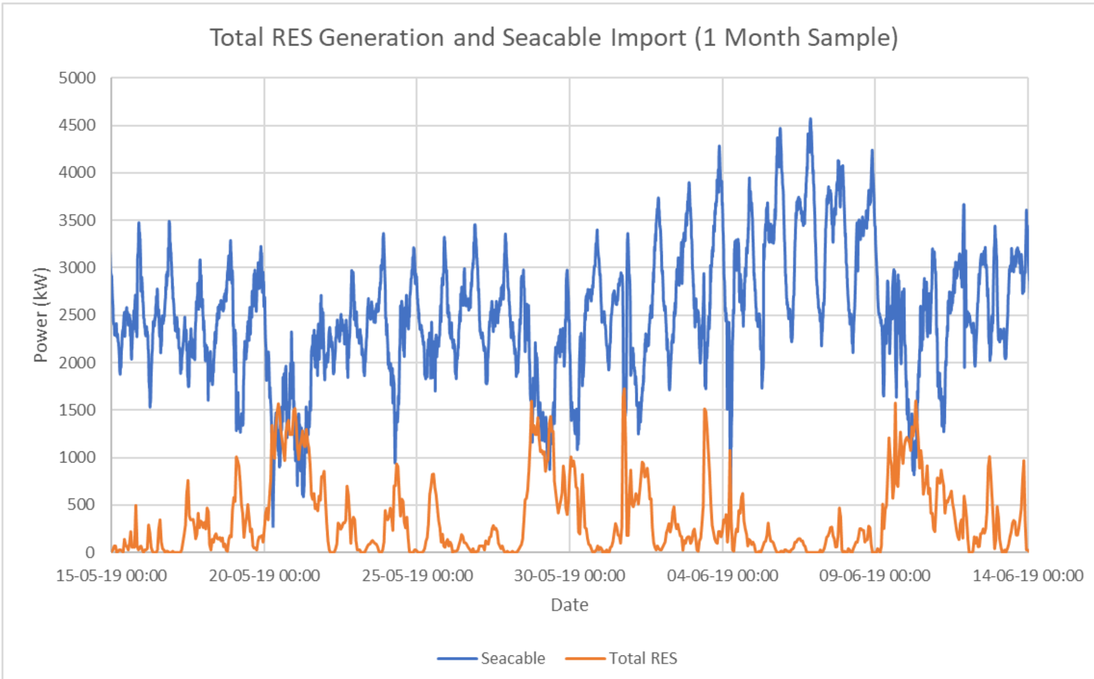

Figure 44: Sample of the total RES generation and sea cable import power

Carbon Impact

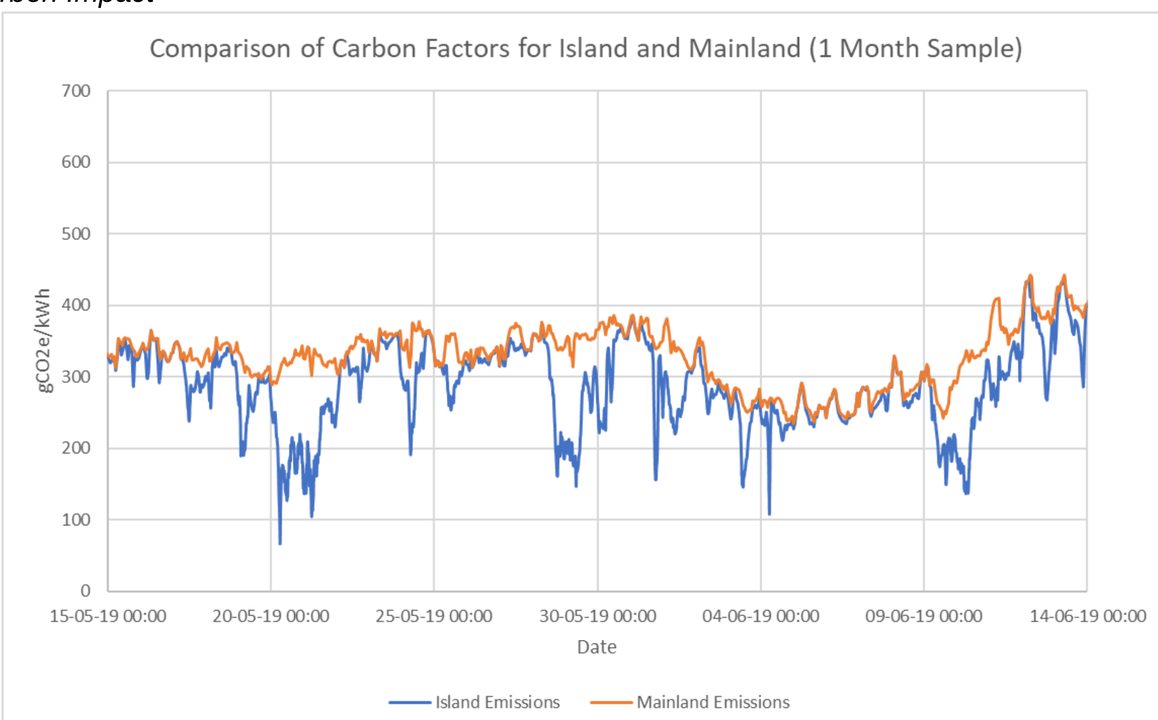

Figure 45: Carbon impact factor comparison for the island with RES and mainland Turkey

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7.2. FORMENTERA

Island Summary

Formentera is a small island south of Ibiza, one of the Balearic Islands off the coast of Spain in the Mediterranean Sea. The island has population of approximately 12,000 but like Gökçeada can increase considerably in the summer months [84]. The local island energy system consists of a 2MW PV solar farm, six diesel generators and a backup gasoline turbine. The focus for this project, however, is on the building of energy communities on the island. Therefore, several potential buildings have already been identified, with the view of expanding the community further in the project. Consul de Formentera have seven community installed PV solar arrays on the island, which as formed the foundation analysis of the initial island concept.

Static Data

The VPP4ISLANDS concept for the island of Formentera is based on the seven community PV installations – the key data is given in the Table 13 below.

Table 13: Summary of community PV installations on the island of Formentera

Location	*General Location*	*Number of panels*	*Rated power (W)*	*Installer*	*Manufacturer and model*	*Voltage at rated power (V)*	*Current at rated power (A)*
Ed. Centre Social Es Molí	**San Francesc**	15	4800	TFV Instalaciones Frigoríficas SL	Trunsun Solar TSP-72	38.19	8.38
Antic Ed. Cultura, Educació i Patrimoni	**San Francesc**	60	15600	Insafor SL	Futura Sun SRL FU270P	31.22	8.65
Ed. Escorxador	**San Francesc**	24	6240	Insafor SL	Futura Sun SRL	Unknown	Unknown
Col·legi de La Mola	**San Francesc**	8	2080	Enervega SLU	QANTUM Q.PLUS G4.3 280Wp	31.67	8.84

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Col·legi Mestre Lluís Andreu (dalt)	**San Francesc**	56	14560	Enervega SLU	Canadian Solar CS6K-275P	25	9.45
Col·legi Mestre Lluís Andreu (baix)	**San Francesc**	36	9360	Enervega SLU	Canadian Solar CS6K-275P	40.5	8.45
Camp de Futbol		58	28900	Enervega SLU	Unknown	Unknown	Unknown

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