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DEVELOPING A FUNCTIONAL DESCRIPTION OF A LOCAL ENERGY OPERATING SYSTEM

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ABSTRACT

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Energy communities using distributed renewable energy resources can play a significant role in combating the global environmental, social, and economic challenges brought about by the human induced climate change. This thesis focuses on microgrid energy communities specifically, due to their potential in providing rural communities self-sufficiency and resiliency in the face of environmental and economic disruptions.

Various obstacles for implementing microgrids are identified. The control and optimal management of the microgrid energy resources is deemed as critical for the operation of any microgrid system. This thesis examines a low carbon energy community project in South-Wales, the South Cornelly Local Energy Market, where a Belgian energy specialist company Challoch Energy is developing a Local Energy Operating System (LEOS). Under the guidance of Mike Parr of Challoch Energy, this thesis has built upon the Challoch Energy work and presents a functional description of the LEOS using the Smart Grid Architecture Model (SGAM) framework.

Multiple standards and frameworks for describing microgrids and microgrid control systems are discussed in the chapter 2, alongside exploring microgrid control strategies in the section 2.3. and discussing microgrid PV hosting capacity and Reverse Power Flow prevention in the section 2.4. Due to its fit for the European technical and regulation frameworks and the efficient structures it provides for system and functional level analysis, the SGAM framework is selected as the basis for the LEOS model. An implementation of the SGAM framework is available as an extension to the visual modelling and design software Enterprise Architect, which is used to produce the figures presented in this study. The SGAM Toolbox and the involved methodology is detailed in the chapter 3, together with the UML diagrams used to model the LEOS functionality.

The chapter 4 presents a case study scenario for the South Cornelly LEM and identifies the actors involved. A business case for the LEOS is established, with the corresponding high-level use case of utilising a LEOS. The high-level use case is then mapped into 18 primary use cases, which form the core of the LEOS functional description. For each primary use case, the actors involved and relations to other use cases are defined, after which UML activity and sequence diagrams are presented to detail the flow of actions and communication in each of the use cases.

The chapter 5 discusses the implications the LEOS model has for the South Cornelly LEM project and defines the limitations of the model. The presented model gives an overview on the systems required to operate the South Cornelly LEM and provides a basis for further expansion into the SGAM Communication, Information and Component layers. Possible future additions to the model or opportunities for further studies include using the SGAM framework to analyse and implement economic optimisation methodology, developing pricing and contractual frameworks, outlining cybersecurity measures, and expanding on reactive power control and better islanding capability.

Keywords: energy communities, renewable energy, energy management system, SGAM, Smart Grid Architecture Model, smart grids

TIIVISTELMÄ

Juha Köykkä: Developing a Functional Description of a Local Energy Operating System
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Hajautettuun uusiutuvaan energiantuotantoon perustuvat energiayhteisöt ovat merkittävässä roolissa ihmisen aiheuttaman ilmastonmuutoksen tuomien ekologisten, yhteiskunnallisten ja taloudellisten haasteiden torjunnassa. Tämä diplomityö keskittyy erityisesti mikroverkkopohjaisiin energiayhteisöihin, jotka parantavat maaseudun ja haja-asutusalueiden omavaraisuutta sekä resilienssiä ympäristön ja talouden muutoksille.

Mikroverkkojen käyttöönotossa ja ylläpidossa kriittistä on mikroverkon resurssien, kuten hajautetun energiantuotannon ja kysyntäjouston hallinta. Tämä diplomityö tarkastelee vähähiilistä South Cornelly Local Energy Market (LEM) -energiayhteisöhanketta Etelä-Walesissa, jonne belgialainen energia-alan konsulttiyhtiö Challoch Energy kehittää niinsanottua paikallista energiakäyttöjärjestelmää LEOS (Local Energy Operating System). Tämä työ pohjautuu Challoch Energyn tekemään pohjatyöhön ja Challoch Energyn puolesta työn toteuttamista on ohjannut Mike Parr. Työ esittelee Smart Grid Architecture Model (SGAM) -viitekehyksen mukaan rakennetun mallin LEOS:in toiminnallisuuksista.

Työssä käydään läpi eri standardeja ja malleja mikroverkkojen ja niiden hallintajärjestelmien kuvaamiseen, sekä tutustutaan mikroverkkojen ohjaushierarkiohin. Lisäksi työssä perehdytään mikroverkon jännitteen ja tehotasapainon hallintaan ja esitetään menetelmiä merkittävän aurinkoenergiatuotannon integroimiseksi matalajänniteverkkoon. Esitellyistä standardeista LEOS-mallin perustaksi valittiin SGAM-viitekehys, koska se soveltuu hyvin eurooplaiseen tekniseen ja lainsäädännölliseen toimintaympäristöön, sekä tarjoaa kattavasti rakenteita ja työkaluja mikroverkon hallintajärjestelmän toiminnallisuuksien kuvaamiseen. SGAM-viitekehyksen soveltamista mallinnukseen edesauttaa sen integraatio visuaalisen mallinnuksen ohjelmisto Enterprise Architectin kanssa. Tämän SGAM Toolbox -laajennuksen määrittelemä metodologia ja Unified Modeling Language (UML) -mallinnuskielen mukaiset kaaviot muodostavat pohjan työssä esitellylle LEOS-järjestelmän toiminnalliselle mallille.

Esitelty malli on suunniteltu tapaustutkimusskenaariolle, jonka rajoissa South Cornelly LEM -hankkeeseen liittyvät sidosryhmät ja toimijat on määritelty. Eri toimijoiden tavoitteiden pohjalta on johdettu liiketoiminllaiset tavoitteet, joita LEOS-järjestelmä toteuttaa. Näiden pohjalta on laadittu ylätason käyttötapaus LEOS-järjestelmälle. Tämä on jaoteltu 18:aan pääasialliseen käyttötapaukseen. Jokaiselle käyttötapaukselle on määritelty riippuvuussuhteet muihin käyttötapauksiin sekä eri toimijoihin. Tämän jälkeen käyttötapaukset on kuvattu yksityiskohtaisesti aktiviteetti- ja sekvenssikaavioiden avulla.

Lopuksi työssä käydään läpi suunnitellun LEOS-mallin merkitys South Cornelly LEM -hankkeen jatkolle sekä keskustellaan työn ja esitellyn mallin rajoitteista. LEOS-malli antaa yleiskuvan järjestelmistä ja toiminnallisuuksista joita South Cornellyn mikroverkon hallinta vaatii ja mahdollistaa mallin laajentamisen edelleen SGAM-viitekehyksen viestintä-, informaatio- ja komponenttitasoille. Mahdollisia tulevia kehitys- ja tutkimuskohteita ovat SGAM-viitekehyksen hyödyntäminen mikroverkon resurssien taloudellisessa optimoinnissa, tietoturvaominaisuuksien kartoittamisessa, sekä loistehon kompensoinnin että saarekekäytön kehittämisessä.

Avainsanat: energiayhteisöt, uusiutuva energia, energianhallintajärjestelmä, SGAM, älykkäät sähköverkot

PREFACE

When I moved from Tampere, Finland to Brussels, Belgium in mid-June 2021 to work on this thesis, I was full of excitement for finally realising my dream of living and working abroad. One and half years earlier, in February 2020, I had been as excited to fly to Beijing, China for exchange studies which I was hoping to eventually extend into a career abroad. I had spent a year learning Chinese, written my bachelor’s thesis on China, and even tried learning the cuisine. The February flight to Beijing never took off, however, as the COVID-19 pandemic swept over the world. Thankfully, the June 2021 flight to Brussels did. And now two years later, I am writing this from Paris, France. The dream of living abroad has come true, and this thesis has accompanied me through thick and thin.

In Brussels, I was very warmly welcomed by the Challoch Energy team and confident to finish this thesis around the end of 2021. After a great though rainy summer internship spent in Brussels, I moved to Paris for another internship at the IEA. By the spring of 2022 I had finished the initial LEOS modelling and started to write. At the IEA, I was moving to a part-time contract to allow me to finish the thesis. The summer flew past, and August arrived with an official contract in a new team at the IEA. I was struggling to find a new apartment. By the end of 2022, I had found a new place to live, but the thesis was on a standstill. So, 2023 has been a tough ride, managing between interesting but intense work, a record number of Finnish friends visiting Paris and an otherwise hermit-like lifestyle of writing and editing diagrams and writing and editing and… done, finally!

Time for thanks.

First, thanks to my parents, who have supported me since the day one (literally) and my amazing little sisters, who have supported me since their day ones. I hope I can support them in the same way. I want to thank the great Challoch Energy team, especially Mike who mentored me on this work and showed the best cycling routes in Belgium! Big thanks to my supervising professors Sami and Pertti, for your patience and support throughout.

I wouldn’t trade a day of my 10.5 years of studies. As the quote goes: “The University made me a MSc, but the Student Union made me a human.” Heartfelt thanks to TTYY, TREY and Tamy, especially TTYH17, and to KN16, Skilta, Spinni and TEA-club. Thanks to my first IEA manager Alejandro and my IEA mentor Jacques for support and flexibility with the part-time contract. Thanks to the core Paris crew Anders, Javier, Moaz and Jiyul, I’ve had the best time with you and there are great times ahead!

Paris, November 2023
Juha Köykkä

CONTENTS

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

API	Application programming interface
BES	Battery energy storage
CAES	Compressed-air energy storage
CEN	European Committee for Standardisation
CENELEC	European Committee for Electrotechnical Standardisation
COVID-19	Coronavirus disease 2019
DER	Distributed energy resource
DG	Distributed generation
DNO	Distribution network operator
DR	Demand response
DSM	Demand side management
DSO	Distribution system operator
EFTA	European Free Trade Association
EN	European Standard
ETSI	European Telecommunications Standards Institute
EU	European Union
EV	Electric Vehicle
GHG	greenhouse gas
GWAC	GridWise Architecture Council
HLUC	High-Level Use Case
HMI	Human Machine Interface
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
ISO	International Standardisation Organisation
LEM	Local Energy Market
LEOS	Local Energy Operating System
LNG	Liquefied natural gas
LV	Low voltage
MBSE	Model-Based Systems Engineering
MDE	Model-Driven Engineering
MV	Medium voltage
NIST	National Institute of Standards and Technology
OLTC	On-Load Tap Changer
PHES	Pumped hydroelectric energy storage
PPA	Power purchase agreement
RPF	Reverse power flow
SGAM	Smart Grid Architecture Model
SGIRM	Smart Grid Interoperability Reference Model
SME	Small and medium-size enterprise
Solar PV	Solar photovoltaic
STES	Seasonal thermal energy storage
SysML	Systems Modeling Language
TOU	Time-of-use
UML	Unified Modeling Language
UN	United Nations
UNDRR	United Nations Office for Disaster Risk Reduction
VPP	Virtual power plant
VRE	Variable renewable energy
WMO	World Meteorological Organization

1. INTRODUCTION

The World is in a state of rapid and irreversible change. The first years of the 2020s have already seen multiple era-defining events which will have lasting impacts for the decades to come. A global pandemic, the onset of new wars, and the subsequent economic and energy security crises have introduced novel challenges. Yet, even graver challenges loom ahead as the human induced climate change rapidly progresses and environmental degradation continues. Consequently, resolute action is required to cut greenhouse gas (GHG) emissions, to adapt to the changing climate, and to improve the resilience of communities vulnerable to economic and environmental changes.

To this end, this thesis argues for the implementation of distributed energy systems and energy communities. These not only provide low carbon energy sources for communities around the globe, but also improve their ability to withstand changes and provide the community members new social and economic opportunities. Especially microgrid energy communities utilising variable renewable energy (VRE) resources can help rural communities to achieve a high degree of self-sufficiency.

This thesis focuses on a low carbon energy community project in South-Wales, the South Cornelly Local Energy Market (LEM). A Belgian energy specialist company Challoch Energy has been developing a Local Energy Operating System (LEOS) concept for the control and optimal management of the South Cornelly LEM. This thesis began under the guidance of Mike Parr of Challoch Energy, with the goal of developing a functional description of the LEOS. Thus, the primary research question of this thesis is, how to present and define the functionality of a central LEOS, which interacts with household energy management systems (HEMS) and other microgrid assets, in a standardised manner? Another central objective for the LEOS is to use a modular and universal approach, inspired by similar design choices in computer operating systems. The goal is to create a flexible platform with standardised interfaces for different assets, possibly suitable for other energy community projects outside of the South Cornelly LEM project.

Next sections of this chapter explore the role of renewable energy and energy communities in responding to the global challenges of this era. After this literature background has been established, the premises of the South Cornelly LEM project and the LEOS concept are explained in detail. Lastly, a summary is given of the structure of this thesis and the contents of the following chapters.

1.1 A changing World faces new challenges

The onset of the global coronavirus disease 2019 (COVID-19) pandemic in 2019-2020 disrupted the World in a profound way, with serious impacts both on the society and economy. The long-term effects of the pandemic are still hard to quantify, but these will likely include a transition from highly globalised supply chains to more regional production of critical goods and materials [1]. The widespread adoption of teleworking and reduction in international travel might also have impacts on the transport industry, in combination with the emissions reduction goals on international aviation and shipping [2]. On 24.2.2022 Russia launched a war of aggression on Ukraine, the largest scale military conflict in Europe since the Second World War. This has had enormous geopolitical and economic repercussions for the Europe and the World. One of these is a major shift in energy politics, the accelerated disengagement of European Union (EU) countries from Russian energy products. The European commission has laid out the REPowerEU plan to achieve independency from Russian fossil fuels well before 2030 [3]. The United States (US) have also sanctioned the Russian energy industry; the White House has ordered an import ban on Russian oil, liquefied natural gas (LNG) and coal [4].

The environment is changing rapidly too. According to the World Meteorological Organization (WMO), the past seven years (2015-2021) have been the seven warmest years in recorded history [5]. The human-induced climate change has already caused the global average temperature to rise about 1.11 °C compared to pre-industrial (1850-1900) levels [5], [6]. The frequency of extreme weather events is increasing steeply; according to a 2020 United Nations Office for Disaster Risk Reduction (UNDRR) report, the period from 2000 to 2019 saw 7,348 major disaster events, compared to 4,212 disasters between 1980 and 1999. The amount of climate-related events has nearly doubled, from 3,656 to 6,681. [7] The Intergovernmental Panel on Climate Change (IPCC) recently released a new publication as a part of their upcoming Sixth Assessment Report, which forecasts that even with a low emission shared socioeconomic pathway, the global warming will temporarily exceed 1.5 °C. This has been a threshold set by the IPCC and the United Nations (UN) Paris Agreement as the targeted limit for global warming by 2050. Beyond 1.5 °C, drastic and dangerous changes in the environment and eco-systems are expected. [6], [8]

Stopping the human-induced climate crisis by sharply cutting greenhouse gas (GHG) emissions is one of the defining challenges of the 21st century. When combined with the economic turmoil caused by the pandemic and the drastic changes in the global geo- and energy politics brought about by Russia's war on Ukraine, the scene is set for a decade of changes not only in the energy sector, but in the global economy and society as a whole. The socio-economic implications of decarbonisation are immense, and for some sectors of the economy, such as agriculture, transportation and energy, the shift to carbon neutrality will bring about foundational changes. Around 2/3 of the world's current GHG emissions are estimated to come from the energy sector [9]. Therefore, the 2021 UN Theme Report on Energy Transition calls for a transformational effort, a thorough overhaul of the global energy system [10]. The World Energy Transitions Outlook 2022 by the International Renewable Energy Agency (IRENA) emphasizes that a massive transformation of how societies consume and produce energy is needed, and that to meet the 1.5°C Paris climate goal, the world needs to reach net-zero emissions by 2050 [11]. To reach the goal of net-zero emissions by 2050, the Net-Zero by 2050 roadmap by the Internal Energy Agency calls for immediate and massive deployment of all available clean and efficient energy technologies [9].

According to IRENA, reaching net-zero by 2050 would require three times more electricity generation than in 2020, with 90% of the total electricity supply provided by renewables. In this scenario, renewable energy would amount for 79% of the total final energy consumption in 2050, compared to 19% in 2019. The role of clean hydrogen as a form of long term energy storage is also highlighted, with a projected need of 614 Mt of clean hydrogen production in 2050, compared to the 0.8 Mt in 2020. [11] IEA assesses that the net-zero pathway would require quadrupling of the global annual capacity additions to solar photovoltaics (Solar PV) and wind power by 2030, to reach annual additions of 630 GW and 390 GW, respectively.

All three, IEA, IRENA and UNEP, call for a just and people centric transition, a concept that is also extensively studied by the academia [12]–[15]. UNEP voices a need for making the energy transition a participatory experience; with multi-sector collaboration empowering the citizens and local governments. [10] As the costs of VRE generation have fallen, new installations of onshore wind and solar PV now provide the cheapest levelized cost of electricity globally [16]. The affordability of VRE makes it accessible to individual consumers and local communities, enabling them to cover some or all of their energy consumption by their own local production. A 2022 review by López González & Rendon asserts that these distributed energy resources (DER) are important in fostering societal participation, bringing about significant potential for new VRE generation and flexibility. DER deployment promotes diversification of energy asset ownership, and contributes to decarbonisation, energy security and market efficiency. [17] Pagliaro & Meneguzzo discuss the topic from a systems viewpoint and call for integration of DER deployment into the local socioeconomic context instead of top-down energy policy approaches, taking into account that the energy ecosystems are heterogeneous [18].

1.2 Distributed renewable energy resources and energy communities in a sustainable energy system

DERs can be implemented for diverse needs, ranging from industrial users to urban commercial and household users to various rural communities. For industries, distributed generation (DG), along with power purchase agreements (PPA), provides a way of achieving tangible emissions reductions [19]. As industrial sites typically cover wide areas of land, the option to install PV or onsite wind turbines enables utilising the existing real estate for energy production. Especially rooftop PV allows for making effective use of otherwise mostly unused spaces. Rooftop PV is also advantageous for urban commercial and residential settings, where other forms of renewable generation are harder to accommodate due to lack of space. In rural areas, DG can reduce consumer electricity costs and GHG emissions, defer distribution grid investments, strengthen grid resilience and improve security of supply [20][21][22]. Extensive DG deployment in addition to energy storage and demand side management (DSM) can allow rural communities to approaching or reach energy independence [23], [24].

The deployment and operation of DERs can be facilitated in multiple ways. The infrastructure can be owned by energy companies, who install the generation capacity at the site hosts' premises and establish lease and power purchase agreements with the site hosts [25]. Individual DER units can be aggregated to form virtual power plants (VPP), which allow small producers or prosumers i.e., consumers who also produce electricity, to participate in the retail or balancing electricity markets. Due to minimum bid sizes in these markets, individual producers might not be able to participate on the markets without aggregation [26], [27]. VPPs can also allow for participation in production of various ancillary services and production can be coupled with demand response (DR) services [28]. While VPPs allow aggregating resources that are spread on a wide geographical area, energy communities provide an option for localised energy production where the energy assets are closely located and can be traded in a local energy market. Energy communities can be connected to the grid of a distribution system operator (DSO) or distribution network operator (DNO), the first expression being used in EU and the second in the United Kingdom (UK). However, an energy community can also manage an islanded microgrid, which is operating independently of the main power grid, either temporarily or perpetually [24]. A microgrid is, as defined by the IEEE 2030.7-2017 and IEC-TS 62898-1 standards, a group of interconnected loads and distributed energy resources, with defined electrical boundaries that acts as a single controllable entity and is able to operate in both grid-connected and islanded mode [29], [30] .

The 2019 EU directive on the common rules for the international electricity market describes two types of energy communities: citizen energy communities and renewable energy communities. Both are collectives of citizens, small and medium-size enterprises (SME) or local authorities. They provide affordable energy of a specific kind, such as renewable energy, for their members and stakeholders. Instead of profit making, the energy communities strive for mutual benefits through shared energy resources and services. [31] [32] The main differences of these are that the members of renewable energy communities need to be located near the energy resources and the resources need to be renewable, whereas in citizen energy communities there are no geographical limits to membership and no limits to the type of energy resources, although they are limited to the electricity sector [32]. In the 2014 Community Energy Strategy, the UK government defines energy communities as initiatives that focus on reducing energy consumption, improving energy management, generating energy, or purchasing energy. Focusing on shared benefits and social outcomes in addition to financial benefits is also emphasised. [33]

From a technical perspective, the energy communities foster the deployment of VRE and energy storage, energy efficiency, smart consumption patterns and demand response. From a social perspective, energy communities democratise the ownership of energy assets and increase citizen participation in the energy markets, alleviating energy poverty and bringing socioeconomic benefits to the local communities. [31], [34] There are positive system level impacts too, as energy communities operating microgrids have the potential to reduce congestion on the upstream networks and defer the need for new infrastructure investments. Consequently, self-sufficiency and proper management of power flows provides additional benefits for the energy community and the power system. [32] One additional system level benefit of energy communities and distributed generation is avoiding the high land use of utility scale renewable generation, commonly referred as energy sprawl. Distributed resources can be spread over rooftops and in rural communities, decreasing the need for large centralised wind and solar farms. [35]

According to the sixth European Commission Report on the State of the Energy Union, there are already over 7700 energy communities operating in the EU. The report estimates that 7% or 6.3 GW of the nationally installed renewable energy capacities are contributed by energy communities. [36] In the UK, 424 organisations working on community energy in 2020 were identified by a joint report of English, Welsh and Scottish community energy associations [37]. From 2019 to 2022, the UK government supported the formation of rural energy communities with a fund of £10 million. The EU too has multiple instruments that can provide funding for energy communities. Both the postcovid recovery package NextGenerationEU and the REPowerEU package implemented to cut the use of Russian fossil fuels heavily emphasise investments in distributed VRE capacity and housing energy efficiency [3], [38].

It is noteworthy that energy communities also have a major global potential in contributing to the UN Sustainable Development goal 7, ensuring the access to affordable, reliable, sustainable and modern energy for all. The UN Agenda 2030 sets this goal to be achieved by 2030. Yet, current estimates indicate that many emerging economies are far from being on track to reach universal sustainable energy access by 2030, especially in Sub-Saharan Africa. [39], [40] Research has indicated clear benefits of utilising microgrids and community energy production in developing countries, enabling the electrification of household activities and local industry. [41], [42], [43]. Microgrids are also often economically more viable solution than expanding existing transmission grids, which speeds up the transition [44], [45].

As discussed earlier, the advancing climate change brings with it an increasing number of extreme weather events. These pose significant challenges for power grids both in developed and emerging economies. Droughts reduce available hydro power resources, prolonged heat-waves and cold spells strain the power grids, storms and floods cause damage to the grid infrastructure and raising sea levels threaten coastal energy resources [46], [47], [48]. Protecting transmission lines from these threats is expensive; available measures include managing the vegetation around the lines, active monitoring of the network and undergrounding the lines. Building back-up capacity to compensate for potential disconnection or disablement of utility scale power plants is expensive too. [48] Therefore, deploying microgrids and DG can become a cost-effective way of increasing overall security of supply and grid resilience. Islanding capable microgrids can secure power for rural communities during outages and deployment of DG spreads the generation resources over a wider geographical region, decreasing the risk of all units being affected at the same time. [23], [48], [49] DERs can also be used to improve system level resilience, by coordinating participating DERs for black start capability services. This is studied in the UK in a National Grid ESO, SP Energy Networks and TNEI partnership project Distributed ReStart [50].

Deploying microgrid energy communities which operate VRE resources has many benefits; they foster VRE adoption and decarbonisation, bring economic and social benefits to the communities involved, have potential to defer grid investments and improve grid resiliency. However, planning and implementing these microgrid communities comes with its own challenges. When a community relies heavily on locally produced VRE, the inherent intermittency of VRE makes it challenging to balance the local production and demand. Combining multiple different resources, such as wind power and solar PV, can mitigate these issues to an extent, as their temporal distribution is different both in the short- and the long-term. Solar PV is more easily forecastable, as the day-night cycle and yearly fluctuations in solar irradiation are very consistent. Wind on the other hand is also available during the less sunny winter months, and depending on the local geographical characteristics, it can be prominent in the night time too [51]. However, there will always be days when clouds limit solar irradiation, and the wind speeds are low. Also, even if the average power output throughout a day is sufficient, the intraday variations can cause major power fluctuations in the microgrid. Therefore, flexibility resources need to be added to the local power system. In the demand side, this can include controlling different household appliances, smart charging of electric vehicles (EV) and influencing residential behaviour patterns [52]. If the community includes commercial or industrial actors, those may also be able to participate in DR. If the community is connected to the wider distribution grid, they may act as an aggregator of community DR and participate in the DR markets for economic benefits.

Another way for increasing the flexibility of a microgrid power system is the addition of energy storage resources. Depending on the size of the energy community, these can range from utility scale pumped hydroelectric energy storage (PHES) systems at a capacity around 5MW to sub 1MW systems like micro compressed air energy storage (CAES). Other typical solutions are battery energy storage (BES), seasonal thermal energy storage (STES), and green hydrogen production via electrolysis. [53] So called hybrid storage systems can combine slower response storage systems with fast response systems, such as supercapacitors and flywheel storage, to achieve more desirable response characteristics. However, these systems are also more complex to operate. [54] In order to keep the energy community projects economically viable, the storage solutions need to be cost effective and simple to operate and maintain.

In addition to covering for periods of low VRE production, energy storage systems are also crucial when the VRE output into the microgrid exceeds demand. According to a 2019 report by the Lawrence Berkeley National Laboratory, the median capacity of residential PV systems has reached 6.4 kW in the US [55]. This is far more than a typical noon residential peak load in the summer, with estimations ranging from to 0.39 kW in the UK to 0.5 kW in the Philippines [56], [57]. Although higher deployment of air conditioning systems may increase this demand, it is evident that in a community with high penetration of rooftop PV, the combined peak output of the PV systems can easily surpass the community wide demand. In a low voltage network, this surplus causes a reverse power flow, with a risk of over-voltages, over-loading of conductors and transformers and harmonic distortions. The different methods for increasing the solar PV hosting capacity i.e., the grid capacity of accommodating varying solar PV generation, are discussed more in detail in the section 2.4. The viability of different solutions depends on the practical features of the microgrid and the operation model of the energy community in question. Also, the local DNO/DSO rules set requirements for reverse power flow management.

In addition to solving the aforementioned technical challenges, operating a microgrid energy community also requires economic optimisation of the available resources and accounting of the individual members’ contributions and consumption. To enable a community to transition from individual consumers and producers to a community with a functioning local energy market, some form of mutual resource management is needed. The management tasks can be handled by one or multiple systems. The system or systems would need to manage both the real-time physical security of supply and the medium- to long-term forecasting and optimisation of the system assets.

1.3 An operating system for local energy communities

Standard definitions for a microgrid control system include: A system operating and controlling energy resources and loads of the microgrid (IEC-TS 62898-1:2017) [30], or: a system that includes the control functions that define the microgrid as a system that can manage itself, operate autonomously, and connect to and disconnect from the main distribution grid for the exchange of power and the supply of ancillary services (IEEE Std 2030.7-2017) [29]. The IEEE standard continues to define some of the basic functions of a microgrid control system: The control system needs to be able to operate both in grid-connected and islanded modes. It needs to be able to automatically transition from grid-connected to islanded mode and to resynchronize and reconnect from islanded mode back to grid-connected mode. The microgrid control system needs to perform energy management to optimise both real and reactive power generation and consumption. It also needs to implement ancilla services that support the grid and enable participation in the energy market and utility system operation as applicable. [29] A microgrid control system can also perform both monitoring and data acquisition and utilise meteorological data in load and generation forecasting. In addition, the control system can provide Human Machine Interfaces (HMI) for the grid operators, producers and consumers. [58] Some sources use the term energy management system in place of microgrid control system. [58]–[60] Some others define energy management system as a subsystem or sub-functionality of a microgrid management system. [61] Commonly the microgrid control system is depicted as a system of systems, which has sub-systems implementing the different functionalities of the system on different levels of control and different time and stakeholder domains. [62], [63] These interact with each other and with other grid assets such as load, generation, monitoring and security equipment and external assets such as the DNO distribution grid, data providers and the electricity markets.

The literature discussing real-time control and protection strategies in microgrids is quite abundant [24], [61], [64], [65], as is literature discussing the economic optimisation algorithms for different energy assets in microgrids [42], [60], [66]–[68]. There are also multiple studies on the architectures of microgrids and microgrid control systems [69]–[72]. The literature indeed covers many of the high-level concepts of microgrid control and provides detailed deep dives into individual functions and subsystems of a microgrid control system. However, only a few studies provide the structural and functional descriptions bridging the gap between the high-level concepts and detailed individual functions. [61], [73], [74] For a practical implementation of a microgrid, a framework is needed to detail the responsibilities, control hierarchies, communication pathways and functional processes between the various assets that form the microgrid. This thesis aims to fill this gap by presenting a functional description of a Local Energy Operating System.

The LEOS design was developed for, and in collaboration with, a Belgian company Challoch Energy BV. The design work was supervised by Mr. Mike Parr and Dr Simon Minett. Key features of the proposed LEOS include a modular approach and developing standardised interfaces for different assets, to flexibly accommodate various compositions of microgrid components. This approach is inspired by computer operating systems, hence the name energy operating system instead of an energy management system.

The LEOS is a part of Challoch Energy’s work on a LEM project in Bridgend County Borough, South Wales, UK [75]. This South Cornelly Local Energy Market project, which contributes to the Bridgend County Borough Council’s Low Carbon Communities initiative, aims to create a renewable energy community in a 220 household rural village [76]. The goal of the LEM project is to cut emissions and provide reliable and renewable energy for the community. In addition to the local community and authorities, other important stakeholders in the project include the local DNO National Grid and the local gas utility Wales & West Utilities. Also the licensed suppliers, the electricity retailers in the UK, can be counted as stakeholders [77]. However, no individual licensed suppliers are named, as different households might still have different suppliers even while participating in the LEM. The village is fed from one substation, which is positioned in a central location. This and the compact size of the village, along with the fact that many houses in the village can be fitted with rooftop solar PV, has made the village an optimal choice for a LEM pilot. Although the village is connected to the MV network operated by National Grid, the aim is for the community to be as energy independent as possible and only import power through the substation when VRE and stored energy resources cannot cover the demand.

The plan is to deploy rooftop solar PV around the village and supplement the solar PV with electricity sourced from a nearby wind farm through a private wire connection. To balance the short-term fluctuations of VRE resources, batteries will be installed both to the household premises and to a central location, referred to as the Energy Centre. For long-term storage, electrolysers are planned for turning excess solar PV and wind power output into hydrogen. The hydrogen could be used either to fuel local farming and earth moving machinery, or fed to the natural gas grid, starting with a blend of 20% and in time growing towards 100% [75]. An important technical constraint for the LEM project is that there can be no backfeed into the National Grid medium voltage (MV) network through the substation. This is a safety constraint from the National Grid side and on the other hand the goal of the LEM project is to maximise the local consumption of the energy produced. This limits the participation to the wider electricity market. The LEM could still provide DR services, but this is not a major goal in the project, as the focus is on reserving available DR capacities for local balancing needs. Due to the requirement of backfeed prevention, voltage regulation and especially overvoltage protection in the low voltage (LV) grid is crucial for the network power quality and security of supply. One solution is the curtailment of the rooftop PV production, but this would result in losing significant amounts of the available generation, especially in the summertime. Therefore, the electrolysers play an important role in both the overvoltage protection and improving the economic viability of the LEM project. The technical constraints of the network and the voltage regulation are examined in detail in the section 2.4.

During the writing process of this study, the legislative landscape for energy communities has been evolving in the UK. This thesis is based on the assumption that the South Cornelly LEM community would be able to sell the energy produced with community owned resources back to the community members at preferential rates. However, this is not possible within the current legal framework in the UK. Currently individual households have to purchase electricity from the licensed supplier. Likewise, the distributed generation can only be sold to the licensed supplier. Consequently, extensive community energy schemes as detailed in this thesis cannot yet reach their full potential. At the time of writing this, a new bill labelled the Energy Bill is in the final stages of entering into law in the UK. During the process, the bill was first amended with a clause “Community and

Smaller-scale Electricity Supplier Services Scheme" which would have required the licensed suppliers to offer energy communities a service agreement which would allow them to sell electricity local customers. However, the government opposed this amendment, and it was removed from the bill on September 5th, 2023. [78] This development leaves the South Cornelly LEM project, and other similar community energy projects, in an uncertain state. The ability for the community to co-own the energy produced by the community energy resources and to share the energy produced by resources located at the premises of individual households is a key goal of the South Cornelly LEM project. Without the ability of a community to establish a LEM, there would also be little need for a system like the LEOS. As the goal of this thesis is to establish a functional description for the LEOS, this thesis is considering a scenario where the required legislation is in place, even though it is unlikely to be passed in the near future. An important factor in this consideration is that, unlike in the UK, the EU legislation already allows local energy communities to provide affordable energy to the community members and to share energy, as discussed in the previous section 0 [31], [79]. Thus, developing the LEOS concept can already be useful in the EU framework, even if the South Cornelly LEM project would be limited by legislation.

As shown in Figure 1, the assets of the community are divided into centralised assets and household assets. The centralised assets would be located at the energy centre, which is connected to the substation feeding the local low voltage network. As mentioned earlier, this substation is the only link between the medium voltage network operated by National Grid and the low voltage network. The assets located in the energy centre are controlled by the energy centre inverter, which in turn receives instructions from the LEOS. However, the LEOS does not directly control every detail of the energy use in the village. The optimisation of energy use in individual households is left for a HEMS.

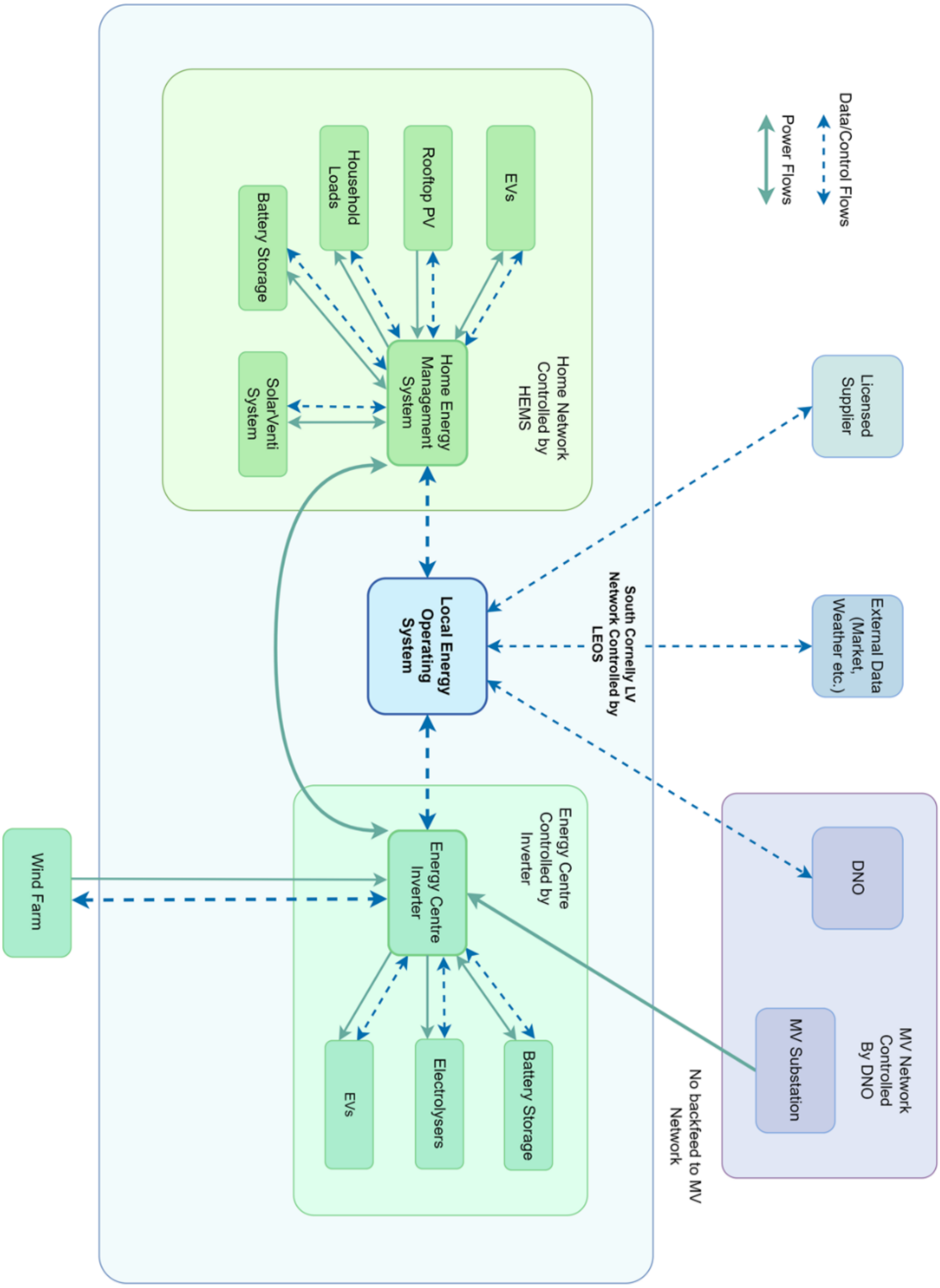

***Figure 1** An overview on the power and data flows between different subsystems of the South Cornelly LEM and between systems operated by external stakeholders.*

To structure the LEOS functionality and the interactions between various LEM assets, a formal approach to modelling is needed. Using universal standards helps a diverse array of stakeholders to interpret the models. Multiple modelling conventions are identified and compared in the chapter 2, and the Smart Grid Architecture Model framework is found out to be the most suitable modelling framework for the LEOS. The modelling is done in Enterprise Architect and a detailed explanation of the design is presented in the chapter 4. Additional model diagrams can be found in the Appendix A. The economic optimisation of energy flows and storage in the LEM would warrant for a separate study and it is not covered in detail in this thesis. The detailed physical implementation of the LEOS and LEM hardware and the related communications technologies are also out of the scope of this thesis, but an overview on the microgrid control strategies is given in the section 2.3. In addition, the section 2.4 discusses microgrid frequency control and solar PV hosting capacity. As this thesis does not cover component level designs or the selection of communication protocols, the cybersecurity aspects of the microgrid are not discussed in this study. The chapter 3 details the SGAM methodology, alongside the relevant Unified Modelling Language concepts utilised. The chapter 5 summarises the major observations made during the design process and discusses additional improvements to the LEOS design and to the South Cornelly LEM project. The last chapter, chapter 6, concludes the thesis with an overlook on the study and reflects on the research questions posed in this section. Lastly, suggestions are given for subsequent research on the topic and for the next steps in possible LEOS implementation.

2. REVIEW ON THEORETICAL CONCEPTS AND EXISTING STUDIES

The previous section identified multiple key functionalities needed in a LEOS, in addition to challenges faced in the operation of a PV based microgrid system. This section details how these challenges and features are addressed in the existing literature. Major standards and concepts are explored and the found solutions form a basis for the methodology used in mapping and defining the functionality of the LEOS in chapter 4.

Since the early 2000s, it has been evident that the power grids need to adapt and accommodate to an ever-increasing amount of DER generation and VRE resources. More variable generation and more generators in different parts of the network have made especially the operation of distribution grids a more complex task. New equipment and assets are connected to the grid, with a need for reliable, low-latency communications links between these assets in order to coordinate real-time responses to changes in generation and consumption. This need is amplified by the decreasing share of synchronous generators with large rotating masses in the generation mix, which weakens the inertial response of the grid. To mend the lack of grid inertia, fast, automated frequency control resources are needed. Maintaining the grid frequency and voltages are not the only drivers pushing for more communication between grid assets, however. With more and more consumers acquiring Solar PV systems, the line between consumers and producers is becoming blurry. VRE and energy storage resources are no longer concentrated in one place but scattered in different parts of the network. When the production exceeds demand in a network branch, some branches of the network may experience reverse power flows. The scattering of generation resources also significantly complicates detecting and spotting faults, as the fault currents may be fed by multiple generators. Therefore, managing a network with a high penetration of VRE resources requires extensive monitoring and intelligent, automated control equipment. Data collection is also essential from an accounting perspective. Smart meters enable the correct billing of consumers with their own generation capacity, and they allow the incentivisation of load-shifting through pricing mechanisms based on grid congestion and time-of-use (TOU). In principle, a grid which meets the above-described qualifications, constitutes a Smart Grid. Indeed, quoting a definition by the European Commission, Smart Grids are upgraded electricity networks, to which two-way digital communication between supplier and consumer, intelligent metering and monitoring systems have been added [80]. As microgrids are a subtype of smart grids, the general concept of a smart grid is explored first, to establish a framework for analysing smart grids and specifically microgrids.

2.1 Smart Grids and standardisation

Smart grids require a high degree of coordination and interconnection between various systems, stakeholders, and pieces of equipment. To achieve this, a number of standards are needed to set the roles of different entities and ensure combability and reliable communications between them. [30], [63], [81]–[85].

As expressed by the European Parliament, standards define technical and quality specifications for products, production processes and services. They boost the competitiveness of businesses by facilitating free movement of goods and services, network interoperability, means of communication, technological development, and innovation. [86] European Standards (EN, Europäische Norm) are developed by the three European Standardisation Organisations: The European Committee for Standardisation CEN, the European Committee for Electrotechnical Standardisation CENELEC and the European Telecommunications Standards Institute ETSI. These organisations are officially recognised as the European standards bodies by the European Union, the European Free Trade Association (EFTA) and the United Kingdom. [87] As the standardisation needs are often global, international coordination reduces duplication of work and speeds up standard preparation processes. Therefore, the European Standardisation Organisations collaborate with international standardisation bodies, such as the International Organisation for Standardisation (ISO) and the International Electrotechnical Commission (IEC).

In the field of Smart Grids or electrical engineering in general, a majority of the globally used standards are issued either by the IEC or the American National Standards Institute (ANSI). The ANSI coordinates the development of standards among multiple different organisations, out of which the Institute of Electrical and Electronics Engineers (IEEE) is largely responsible for the standards that affect Smart Grids. The IEEE has a more North American focus, while the IEC has an international approach, albeit being centred in Europe [88]. The European CENELEC has collaborated extensively with IEC since the 1996 Dresden Agreement, which enforced common planning of new work and parallel voting. The co-operation has continued through the years, which has led to a significant level of technical alignment between IEC and CENELEC standards. Today, nearly 80% of CENELEC standards are either identical to IEC standards or based on IEC publications [89], [90]. This thesis focuses on Europe and specifically the UK, hence the IEC standards form the basic framework of this study. However, the IEEE standards cover many of the same aspects as the IEC standards, so it is beneficial to compare multiple approaches before committing to one.

In 2009, The European Commission set up a Smart Grids Task Force to advice the commission on policy and regulatory frameworks and in co-ordinating the implementation of Smart Grids [91]. The Task Force set out to define six high level services and functionalities for European Smart Grids: integrating users to the network, enhancing efficiency of day-to-day grid operation, network security of supply and system control, improving network investment planning, enhancing market functions and customer service and promoting consumer involvement in their energy use and management [81]. In March 2011, the European Commission mandated the European Standardisation Organisations to develop standards that enable the implementation of the aforementioned high-level functionalities within the common European Framework. The M/490 EN Standardisation Mandate to support European Smart Grid deployment also emphasised ensuring the interoperability of different computing and communications technologies, electrical architectures and relevant processes and services. Three main deliverables were specified in the M/490 mandate [92]:

- A technical reference architecture to represent the functional information data flows between Smart Grid domains, integrating various systems and subsystem architectures.
- A set of consistent standards, such as communication protocols and data models, to support in information exchange and the integration of all users into the operation of the electric system.
- Sustainable standardisation processes and collaborative tools to enable stakeholder interactions and to enable continuing adaptation and improvement of the standards. Adhering to higher level system constraints such as interoperability, security, privacy, and harmonisation of use cases.

The Coordination Group for the mandate was formed by CEN, CENELEC and ETSI. The group set out to produce guidelines on how to efficiently manage the complex issues in Smart Grid standardisation. The principal idea adopted was that the Smart Grid should be treated as a system of systems, and as such, would require an approach specifically tailored for complex systems, namely, systems engineering.

2.2 Smart Grid Architecture

To work on complex systems, simplified representations i.e., models are needed. These models describe the major parts of a system and show how those parts are structured and interacting with each other. The models also provide understanding on which stakeholders are interacting with the system and who or what is performing or using the system functions [92]. Working groups were set out to map pre-existing standards and frameworks and to develop models and concepts as building blocks for Smart Grids analysis. Initially, a Reference Architecture was established. It was designed to align with the existing Smart Grid Conceptual Model by the National Institute of Standards and Technology (NIST) and the eight-layer Interoperability Context-Setting Framework by the GridWise Architecture Council (GWAC). Due to the Reference Architecture drawing heavily from these previous designs, it is in order to present them here first, to provide background and comparison between these approaches. [92]

2.2.1 The GWAC Interoperability Context-Setting Framework

The GWAC was formed by the US Department of Energy in 2004 to further interoperability among entities that interact with the electric power system [93]. As defined by GWAC, interoperability stands for the ability of two or more networks, systems, devices, components, or applications to exchange information and to use that information. In order to identify and address issues hampering interoperability, GWAC proposed a context-setting framework, to organize concepts and terminology in a universally understandable way. This was based on a general Interoperability Framework developed by the Australian National E-Health Transition Authority [94], and it identified four different levels: On the highest level is a *framework*, setting the broad concepts and context. Next, they identify *models* or *architectures*, which provide a technology independent analysis of a specific problem space and its requirements. Below models, *designs* map the model requirements into a family of solutions based on standards and technical approaches. Lastly, on the lowest level, *solutions* transfer designs into practical applications and makes sure the applications comply with the specified frameworks, models, and designs. [93]

The GWAC identified key issue areas for interoperability and placed them on an Interoperability Context-Setting Framework, depicted in the Figure 2. The framework is split into three layers: The *Organisational layer* covers the pragmatic business aspects of interoperation in electricity management. The *Technical layer* deals with syntactic issues of interoperation in communications networking and information technology. Lastly, the *Informational* layer in the middle deals with semantic aspects of interoperation, converting information into understanding and knowledge to support the electricity business. [82], [93]

Figure 2 *GWAC Interoperability Context-Setting Framework Categories* [93].

2.2.2 The NIST Smart Grid Conceptual Model

In 2007, the US Energy Independence and Security Act appointed the NIST as the primary coordinator for developing a Framework and Roadmap for Smart Grid Interoperability Standards. Using the work by GWAC as a starting point, The NIST produced their first release of a Smart Grid Conceptual Model in 2010. It was designed to support in the planning and organization of the diverse interconnected networks that form Smart Grids. The first release of the Conceptual Model from describes seven Smart Grid *domains*, each of which include different Smart Grid *actors* and *applications*. These domains are described in the Table 1. The actors consist of devices and systems which make decisions and exchange information needed in performing actions. Examples of devices and systems include smart meters, VRE resources, and control systems. Applications are functionalities executed by one or more actors in a domain, such as home automation or energy generation and storage. The Smart Grid operations consist of these actors interacting with other actors across different domains. Although actors within the same domain typically have similar goals, there can be differences in communications requirements, or the actors may overlap between domains. For example, a DSO would mainly reside in the Distribution domain, but also have a distribution management system in the Operations domain and meters in the Customers domain.

***Table 1** Domains and Actors in the NIST Smart Grid Conceptual Model (1.0)* [82].

Domain	Actors
Customers	The end users of electricity. May generate, store, and manage the use of energy. Traditionally, three customer types are discussed, each with its own domain: residential, commercial, and industrial.
Markets	The operators and participants in electricity markets.
Service Providers	The organizations providing services to electrical customers and utilities.
Operations	The managers of the movement of electricity.
Bulk Generation	The generators of electricity in bulk quantities. May also store energy for later distribution.
Transmission	The carriers of bulk electricity over long distances. May also store and generate electricity.
Distribution	The distributors of electricity to and from customers. May also store and generate electricity.

The NIST Smart Grid Conceptual Model presents a high-level overview of actors in a Smart Grid and the possible communications path between them. It also helps in identifying interactions within and between domains and provides understanding on the applications and capabilities enabled by these interactions. Using the four levels of framework concepts referred by GWAC, the Conceptual Model covers the levels of frameworks and models. However, it does not provide designs or practical solutions implementing those solutions. Therefore, the NIST point out that the Conceptual Model is a tool intended to aid in analysis, but it is not intended as a prescriptive design for implementation.

The NIST Framework also introduces the concept of use cases: they describe the interactions between users and systems and the functional requirements to achieve the objectives of these interactions. NIST divides these use cases into two varieties: “black box” use cases, which leave the inner details of a systems open and “white box” use cases, which describe both the inner details and the interactions and requirements associated with the system. As the NIST Interoperability Framework takes a descriptive approach rather than a prescriptive one, they prefer the black box use case which leave the design and solution level implementations of the use case open for the implementer. [82]

Although the first release of the NIST Smart Grid Conceptual Model provided a solid groundwork for describing Smart Grids, it lacked some features that are critical for the development and analysis of modern Smart Grids. Further models have been developed by other organisations, extending the GWAC and NIST work and providing tools for bridging the Smart Grid analysis from the framework and architecture levels all the way down to the implementation of practical solutions.

2.2.3 The IEEE Smart Grid Interoperability Reference Model

In the US, the IEEE had been supporting NIST and set out to produce new Smart Grid Standardisation in the form of the IEEE Standard 2030-2011: IEEE Guide for Smart Grid Interoperability of Energy Technology and Information Technology Operation with the Electric Power System (EPS), End-Use Applications, and Loads. It expands on the concepts mapped by NIST, placing emphasis on defining interfaces between entities within a smart grid architecture. The guide introduces the Smart Grid Interoperability Reference Model (SGIRM), which splits smart grid architecture into three Interoperability Architectural Perspectives (IAP): power systems, communications technology, and information technology. Each of the three IAPs is in turn divided into the seven domains introduced by NIST (Table 1). The SGIRM populates each domain with entities, such as devices, communications systems, and software. These entities are connected to each other through interfaces. The interfaces are defined as logical connections between entities, which support one ore multiple data flows. In the SGIRM, data flows are defined as application-level communications from entities which provide data to entities which consume data.

For each of these IAPs, the SGIRM establishes detailed design tables which list all identified entities and the interfaces each entity has between other entities. These interfaces are then defined in their own respective design tables. In addition, reference tables are provided for the classification of data flow characteristics and constraints. The SGIRM also provides tier classes and a hierarchy table for smart grid communications. The tier classes asses both the criticality and latency requirements of the communications in question. Three tier classes are established:

Tier class 1: Critical. Communications dealing with control and safety. Malfunctions have a risk of causing personal injuries or damage to assets. Very low to low latencies required for communications relating to safety equipment, such as relays. Medium to high latencies tolerated for distribution control.

Tier class 2: Important. Communications dealing with control. Malfunctions pose potential damage to assets. Medium to high latencies tolerated.

Tier class 3: Informative. Malfunctions pose no potential damage to assets. High or very high latencies tolerated.

After the publication of the original IEEE 2030-2011 standard, IEEE has extended it with complementary standards that focus on how smart grids interact with different assets such as energy storage systems [95], [96]. Later complementary standards have also stepped from the architecture level down to physical designs and solutions, such as the IEEE 2030.9.-2019 IEEE Recommended Practice for the Planning and Design of the Microgrid [84]. This standard establishes a control hierarchy for microgrid control systems, which will be discussed in the section 2.3.

2.2.4 The European M/490 Standardisation Mandate

In Europe, the Smart Grid Coordination Group formed by CEN, CENELEC and ETSI used the NIST Smart Grid Conceptual Model as a reference in the M/490 standardisation mandate. The Conceptual Model formed a basis for the M/490 European Reference Model, but significant additions were made to the NIST Model in order to account for the key European objectives of DER and flexibility deployment. The European Reference Model introduced a new DER domain and a new flexibility concept which groups consumption, production, and storage together in a flexibility entity. These ideas were further developed in the next phase of the M/490 mandate. Among other deliverables, three concepts and models of specific relevance for the scope of this thesis were delivered [97]:

- A market roles and actors model, which ensures that the methodology is able to support the evolution of market structures in Europe
- A Smart Grid Use Case Model to support the definition and design phases of standard developments.
- The Smart Grid Architecture Model (SGAM), a technology neutral reference model for analysing and visualising different smart grid use cases.

The market roles and actors model aims to define actors and market roles in terms of responsibilities that are independent from specific market structures, allowing for the development of standards that are agnostic to market structures [97]. The model has four categories of elements:

- **Party:** Legal entities, either natural persons or organisations as judicial persons. Can have multiple roles.
- **Responsibility:** specify external behaviour to be performed by parties.

- **Role:** Represents the responsibility of a party. The roles cannot be shared. Although one party can have multiple roles, multiple parties cannot have the same role.
- **Actor:** represents a party that participates in a transaction. Within the transaction, actor performs tasks in a specific role or roles. To differentiate business context from technological discussions, terms business actor and system actor can be used.

2.2.5 The Smart Grid Use Case Model

The Smart Grid Use Case Model utilises use cases, a construct developed for software engineering projects and applied to systems engineering. The utilisation of constructs like these in modelling and describing systems or software is central in Model-Driven Engineering (MDE) and Model-Based Systems Engineering (MBSE). As explained by Zečević et al., these represent a methodological approach to software development and systems engineering, where formal definitions of solutions are represented by models that can be transformed into executable specifications for a given target platform [98].

When used in the context of formal modelling, the concept of a use case is defined by the Unified Modeling Language (UML) and its derivative Systems Modeling Language SysML. UML and SysML are general purpose and object-oriented modelling languages, which, according to Zečević et al., enable direct and formal expression of concepts related to a given domain through the use of base modelling constructs [98]. These modelling languages and application of a model-based approach as a methodology for describing and designing smart grids is further discussed in the chapter 3.

Use cases are defined in the UML version 2.5.1 as specifications of behaviour that are used as a means to capture the requirements of systems. Every use case has a subject, which is the system the use case applies to. Users and other systems interacting with the subject system are described as actors. [99] In other words, a UML use case represents a scenario where a request or interaction by an actor triggers a system functionality. The SysML version 1.6 defines use cases similarly, as use of a subject system by its actors to achieve a goal. SysML further describes use cases as functionalities or capabilities accomplished through the interaction between the subject and its actors. In SysML 1.6, the actors represent classes of user types or external systems. [100] This is compatible with the definition given above in the market roles and actors model, where actors are defined as parties participating in transactions.

In the smart grid use case model, a template derived from the IEC standard 62559-2 “Use case methodology – Part 2: Definition of the templates for use cases, actor list and requirements list” is applied. It helps in describing, comparing and administering use cases [97], [101]. The template includes:

- Administrative information, such as version control
- Descriptions of functions, comprising of general narrative descriptions and detailed descriptions with figures
- The subject system of the use cases and its design scope
- A list of actors associated with the functions and activities
- Information for classification and giving context to the use cases, such as linking them to the wider picture of standards, regulation and the model architecture

As use cases can be utilised to describe a broad range of interactions and functions, it is necessary to find ways for grouping and classifying them. These can include a split into use cases by subsystems and domains, distinctions between the high level and primary use cases and differentiation between use cases of different nature, such as business use cases, system use cases and test use cases. The classification of use cases and construction of use case diagrams by linking actors and use cases within a system’s boundaries are discussed more in detail in the section 3.1.

2.2.6 The Smart Grid Architecture Model

The Smart Grid Architecture Model (SGAM) is a technology neutral reference model for analysing and visualising smart grid use cases and comparing diverse approaches to Smart Grid solutions. It is a three-dimensional architectural framework that allows the modelling of interactions and exchange of information between different actors in the Smart Grid system. Among various standards and frameworks that the SGAM builds on are the GWAC Interoperability Context-Setting Framework Categories and the NIST Conceptual Model [82], [93], [97].

The three dimensions represented in the SGAM are Interoperability Layers, Domains, and Zones. There are five interoperability layers specified: Business Layer, Function Layer, Information Layer, Communication Layer and Component Layer. As shown in the Figure 3, these can be derived from the eight GWAC Interoperability Categories by grouping them into more general concepts. Definitions of each of the SGAM Interoperability Layers are listed in the Table 2.

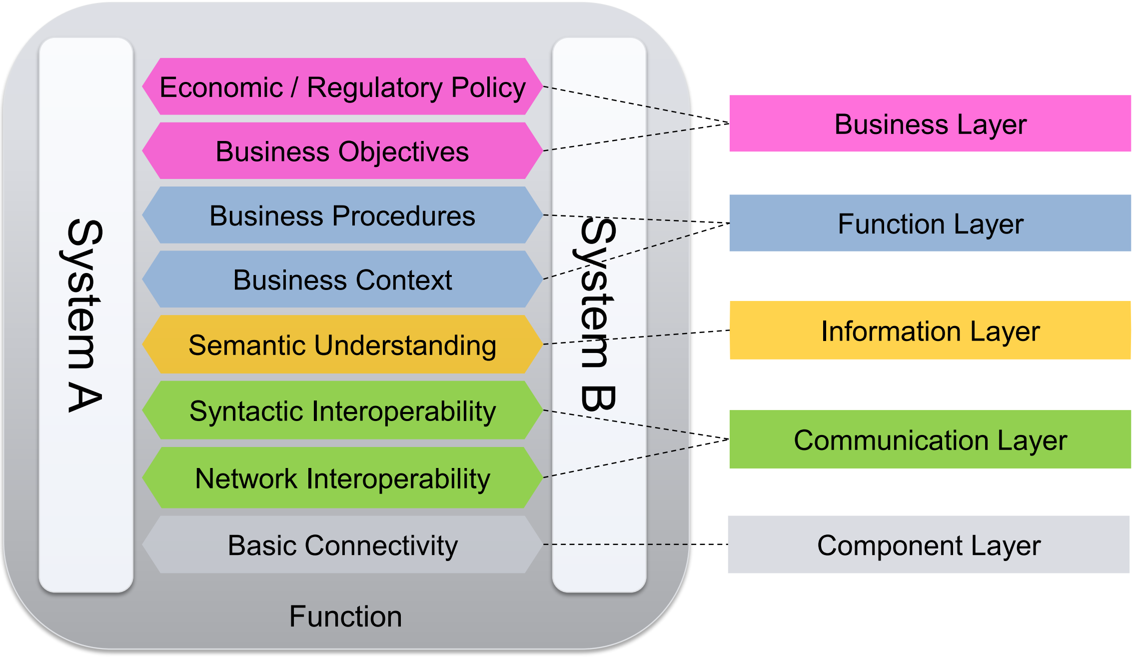

Figure 3 *Grouping GWAC Interoperability Categories into SGAM Interoperability Layers* [102].

Table 2 *SGAM Interoperability Layers* [62].

Business Layer	Represents business view on the smart grid information exchange. Supports both business and regulatory decision making. Can map regulatory and economic structures and policies, market parties, business models, business processes and business capabilities.
Function Layer	Describes functions, services, and their relationships from an architectural perspective. Functions are derived by extracting use case functionality. They are represented independent from actors and physical implementations.
Information Layer	Describes information that used and exchanged between functions, services, and components. Represents the common semantics of functions and services in unified data models and information objects.
Communication Layer	Describes the protocols and mechanisms by which the information exchange is carried out between the system components.
Component Layer	The component layer describes the physical hardware representation of different smart grid components such as system actors, applications, power system control and protection equipment and communications network infrastructure.

The operation of a power system can be split into managing the physical electrical energy conversion chain and into information management. In the SGAM, the electrical process from generation to consumption is represented in five physical domains: Generation, Transmission, Distribution, DER and Customer Premises. [103] These are specified in the Table 3 below.

***Table 3** SGAM Domains* [62].

Domain	Description
Generation (Bulk)	Large-scale electricity generation, such as fossil, nuclear and hydro power plants and large-scale PV plants and wind farms. Generally feeding the transmission system.
Transmission	Infrastructure for long distance electricity transportation.
Distribution	Infrastructure for distributing the electricity to customers.
DER	DERs that are directly connected to a public distribution grid, and which have the primary business goal of providing generation, storage, or ancillary services to the grid. Small to utility-scale power generation and consumption, which can also be directly operated by the DSO/DNO.
Customer Premises	Encompasses both the consumption and production of electricity when it happens on customer premises and is primarily contributing to the customer's needs, such as home, building or industry energy management. Includes all customer types, whether industrial, commercial, or residential.

On the information management side, the SGAM splits the power system into five hierarchical zones: Process, Field, Station, Operation, Enterprise, and Market. These zones form a hierarchical model for power system management, which emphasises data aggregation and functional separation. As the quantities of data collected in the process and field levels add up with each step of the hierarchy, aggregation is needed to reduce the amount of data communicated and processed on the higher zones. Data is also aggregated spatially from distinct locations to wider areas, to keep it relevant for each level of power system management. The different zones host different functions, with specific goals, requirements, and user philosophies. Functional separation stems from the different nature and different positioning of the functions. Many real-time functions such as automation and protection are located on the field and station zones, whereas long-term optimisation and trading are located on the enterprise and market zones. [103] The definitions of each zone are specified in the Table 4.

***Table 4** SGAM Zones* [62].

Zone	Description
Process	The physical, chemical, and spatial transformation of energy, including the equipment directly involved. Encompasses for example DER generation, transformers, circuit breakers, power lines and cables, and electrical loads.
Field	The equipment to protect, control and monitor the power system processes, such as protection relays and intelligent electronic devices which collect metering data

Station	The areal aggregation of the field level, concentrating data and aggregating functions. Includes for example substation automation, local SCADA systems and plant supervision.
Operation	The power system operations of the respective domain, such as microgrid control systems, distribution management systems, EV fleet charging management and transmission system management.
Enterprise	Commercial and organisational processes, services, and infrastructure for enterprises. These can range from billing, procurement and logistics to asset and staff management and customer relations management.
Market	Contains the market operations across the whole energy conversion chain, such as energy trading, DR markets and retail markets.

Together the domains and hierarchical zones form a two-dimensional Smart Grid plane, which maps the different levels of interactions occurring between entities on different domains. The Smart Grid plane is visualised in the Figure 4.

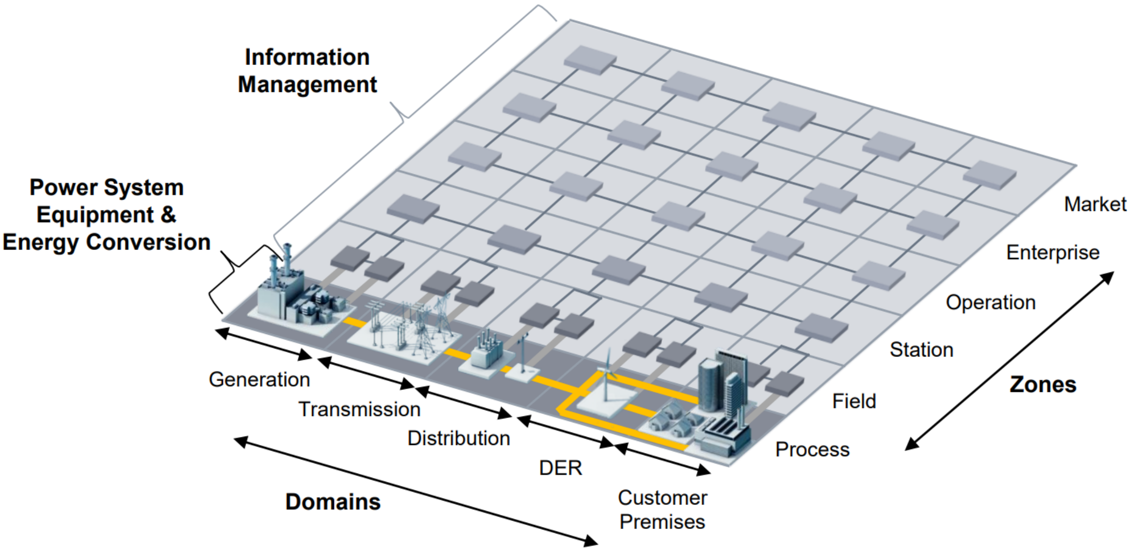

Figure 4 *Smart Grid plane - domains and hierarchical zones* [62].

The full SGAM framework takes the Interoperability Layers and combines them with the domains and hierarchical zones. The result is a three-dimensional framework depicted in the Figure 5, which covers the whole power system and allows for creating complete models of smart grid systems. It can be used to map both high-level concepts like business objectives and regulations and implementation level details such as physical communications hardware and used data models and protocols. The versatility of the SGAM framework stems of its ability to include everything from power system level goals to practical local designs and solutions in the same model and map the relationships and interactions between these elements on the dimensions of interoperability, information management and electrical processes. [62]

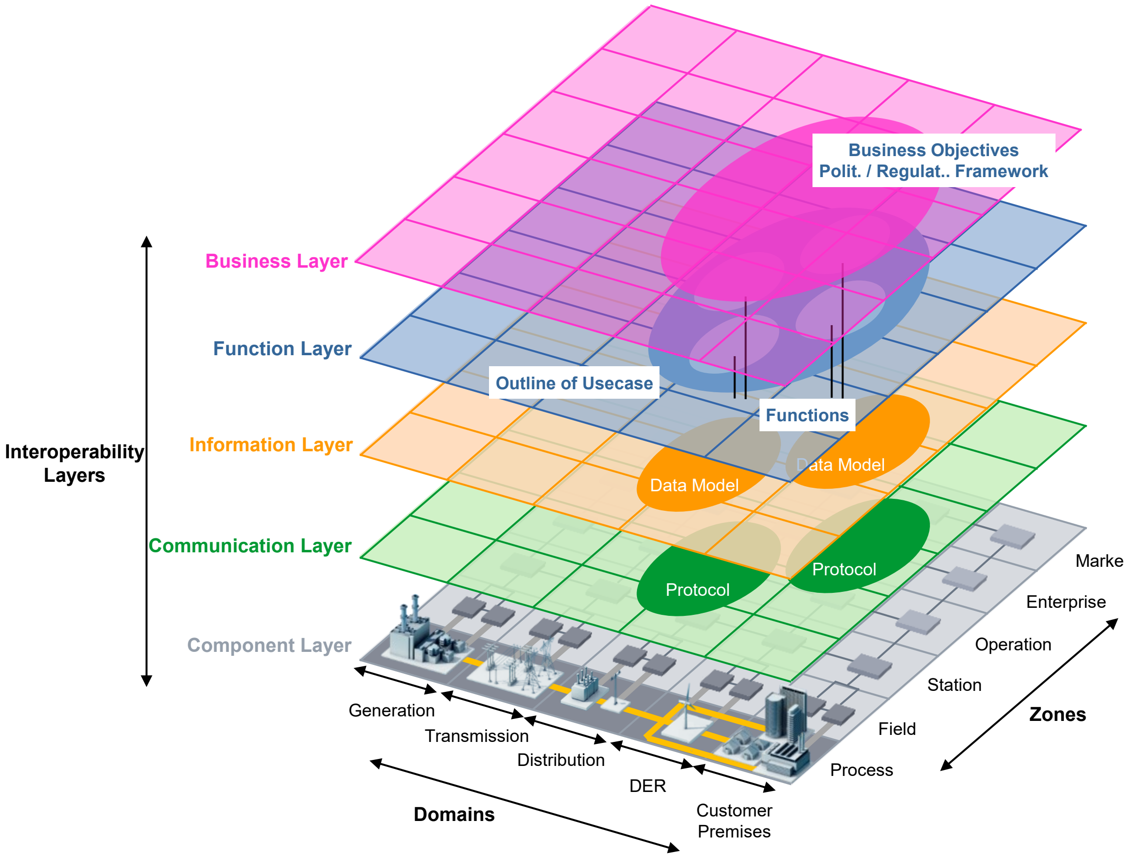

***Figure 5** SGAM Framework* [62].

The SGAM framework also includes a description of a formalised methodology for utilising the framework in smart grid analysis and modelling. It starts with analysing and describing the use cases existing in the smart grid system, utilising the UML use case concepts and use case diagrams. The methodology then proceeds with mapping the entities and relations on all the interoperability layers, starting with the Component Layer and Business Layer, and proceeding through the Function, Information and Communication Layers. This methodology and the UML concepts and diagrams used will be discussed more in detail in the chapter 3.

2.2.7 Basing the LEOS on the SGAM framework

As discussed in the section 2.1, the European Standardisation Organisations work in close collaboration with international standardisation organisations. After the Smart Grid co-ordination group formed by CEN, CENELEC and ETSI, formalised the SGAM framework as part of the European standardisation mandate M/490, it was also adopted by the IEC as the IEC Systems Reference Deliverable 63200:2021. The IEC document provides an official definition for the SGAM framework, links it with other IEC smart grid standards and prepares the framework for potential extensions into gas and heating systems. [85]

The SGAM framework and the IEEE SGIRM both extend the scope of the original NIST Smart Grid Conceptual Model. The first NIST Conceptual Model lacked in the implementation of DERs and in describing interfaces between entities. However, since its first release in 2010 [82], the NIST Smart Grid Framework has been extended too. Firstly, the newest Release 4.0 upgrades the Conceptual Model domains to include DER in the Generation domain, diversifies the actors and roles in the Customer domain to account for generation and storage on customer premises and expands on the role of the Distribution domain. Secondly, the Release 4.0 includes multiple communications pathways scenarios, covering High-DER grids, Hybrid grids with centralised and distributed functionality, and Microgrids. These scenarios describe the communications pathways and interfaces between different actors and domains, including the communications networks used. [104]

The SGAM, the IEEE SGIRM and The NIST Smart Grid Conceptual Model can all be effectively utilised in analysing smart grid systems and they have many similarities, being based on the GWAC Interoperability Categories. However, for this thesis, the approach of SGAM is chosen. While the NIST Conceptual Model Release 4.0 provides a dedicated communications pathways scenario for microgrids and tools for mapping interactions through logical interface reference models and interoperability profiles [104], the SGAM is better equipped for identifying functionalities and actors. Similarly, the SGIRM focuses more on interoperability between predefined actors and entities, rather than mapping and describing functionalities. The extensive design tables of entities and interfaces provided by the SGIRM are very useful for smart grid analysis, and the interoperability architectural perspectives visualise these in a detailed way, but as the SGIRM is copyrighted to the IEEE and not publicly available, their utilisation in this thesis will be limited.

In addition to the above-mentioned differences in approaches between the frameworks, the SGAM, although an international standard, is developed to fit into the European technological and regulatory ecosystems. It has seen use in multiple studies on European smart grid and microgrid projects and is well established as a framework for analysis in Europe [61], [73], [105], [74]. This makes it a good fit for the South Cornelly LEM project and easy for various stakeholders to find information about.

Lastly, the ease of practical implementation and drafting model diagrams favours the SGAM. There are numerous methodological guides available on the implementation of SGAM and it has also been integrated into professional visual modelling and design software [62], [103], [106]. In particular, the SGAM Toolbox developed by Christian Neureiter at the Salzburg University of Applied Sciences, integrates the SGAM as an extension to the software suite Enterprise Architect by Sparx Systems [107], [108], [109]. Although the Enterprise Architect is a proprietary software, a free trial version is available. The SGAM Toolbox module itself is available free of charge, accompanied with guides on use of the toolbox features, UML concepts and the SGAM methodology [109].

2.3 Microgrid Control Strategies

Microgrids differ vastly in structure, stakeholders, and mode of operations. Some microgrids only consist of assets concentrated on a limited geographical area, with all of the assets close to each other. An industrial facility or a village-sized energy community would fit into this category. Other microgrids can have assets spread in multiple centres, such as in a rural farming community with multiple farms connected on the same network. Some microgrids primarily operate in grid-connected mode, whereas some operate fully or mostly in islanded mode. Some microgrids might only contain generation and load assets, while other microgrids might contain energy storage systems. There are also differences in how the assets are distributed within the microgrid. A system with one large wind farm and a centralised battery storage system is operated in a different manner than a system with numerous rooftop solar PV systems around the microgrid. There are also differences in how the grid assets are owned and manged. In an industrial facility, the assets are utilised in a centralised manner to achieve a common objective. In a suburban energy community between households, where each of the households owns their own PV systems, the assets might participate in energy sharing and aggregation or sell the produced energy individually to the markets.

2.3.1 Hierarchical Levels of Control

The examples above highlight the diversity of environments and scenarios where microgrid systems exist. All of these examples point out to properties which require different approaches to microgrid control. Common ways to categorise these microgrid control strategies include dividing by hierarchical control levels, by communication modes, and by operating modes [44], [61], [110]. Typically microgrid control can be split into four hierarchical control levels: primary, secondary and tertiary control, and a zero or inner loop control level [61], [69], [72], as shown in the Figure 6 below.

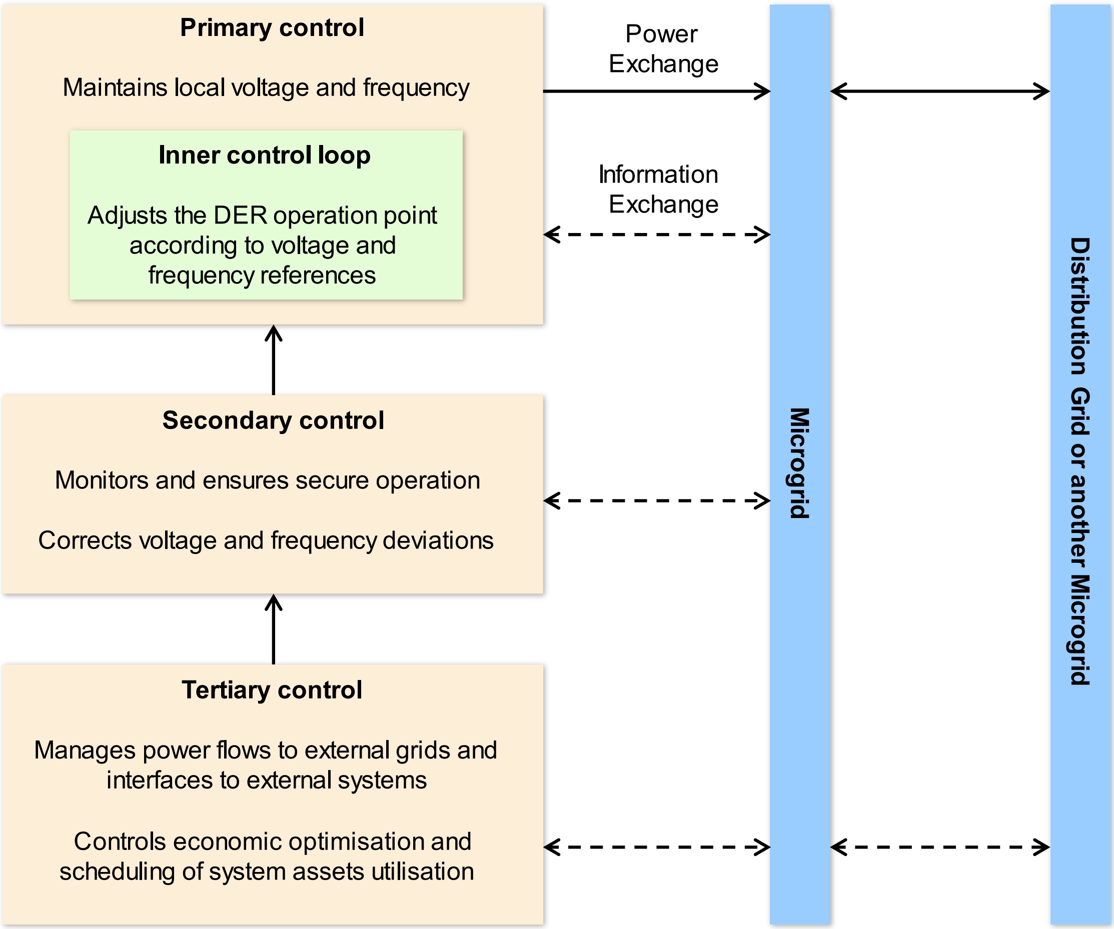

***Figure 6** Microgrid Hierarchical control structure. Adapted from* [72], [111].

The control level zero contains the inner current and voltage control loops of DERs, such as maximum power point tracking in PV systems. These control loops optimise generation from the source by adjusting the operation point while adhering to the voltage references provided by the primary control level [72].

At the lowest microgrid control level, the primary control is responsible for maintaining the voltage and frequency stability of the system. In conventional grids, the grid inertia from rotating masses fulfils this role. In microgrids where the grid inertia is typically lower, the primary controllers restore the balance between generation and load after disturbances [24], [71], [72]. Due to the primary control level operating in the milliseconds range, it is often implemented using methods that do not involve communication with other assets. These approaches include droop-based control and virtual synchronous generators, out of which the virtual synchronous generators are generally viewed to be better at providing inertia and frequency damping to the grid [112]. However, if a high speed communication network is available, a centralised master-slave control method can be utilised too [72], [113].

The secondary control level monitors the system and maintains secure and reliable operations both in grid-connected and islanded modes. The secondary control level is also responsible for correcting voltage and frequency deviations produced by the primary control actions. In addition, the secondary control determines the optimal dispatch of DERs and energy storage units. [24], [69], [72] Due to the nature of the secondary control level as the supervisory level of a microgrid, the secondary control is commonly implemented as a centralised system [72]. As the secondary control functions in the sub-second range, high bandwidths and low latencies are required in centralised systems where the central controller transmits reference voltages and frequencies for all primary controllers and collects monitoring data simultaneously [71]. Due to the high communications requirements in larger systems and the risks involved if the centralised system were to fail, alternative distributed and decentralised approaches have been researched [65], [71], [72], [114]. Although progress is being made in error proofing, the distributed methods still face challenges due communication delays and clock drift which is inherent to the digital processors used to implement the local control of inverters [65], [114].

The tertiary level is the highest control level in a microgrid system. It operates in the seconds and minutes range and manages functions that are not time-critical, such as managing the power flow between the microgrid and the distribution grid. The tertiary control is also responsible for long-term optimisation of the microgrid operations. It is in control of the economic optimisation and scheduling of system assets and demand response management. [24], [71], [72] To support the economic optimisation functions, the tertiary control level collects both internal load and generation data, and external data such as market prices and weather data. These data are used in mid- and long-term forecasting and feed into the system economic decision-making processes. Tertiary level is also the control level implementing participation in energy markets and it is responsible for financial transactions and accounting. From the point of view of a microgrid operator or participant, the tertiary control is the level which provides human machine interfaces with the system, such as diagnostics tools or access to customer data [61]. Lastly, in multi-microgrid systems, the tertiary control exchanges information with other microgrids. In some studies, the tertiary control level is only active when the microgrid is connected to a distribution grid [72] or the tertiary control is even placed outside of the microgrid system, to control the operation of multiple microgrids [69].

2.3.2 Islanded and Grid-Connected Operating Modes

Microgrids can operate in two typical operating modes: islanded or grid-forming mode and grid-connected or grid following mode. These operating modes affect the dispatch and scheduling decisions on secondary and tertiary control levels too, but the main differences between these operating modes are found on the primary control level. When the microgrid is operating in islanded mode, at least one of the power converters in the grid needs to operate in grid-forming mode, setting the voltage and frequency references for the other power converters to follow [72]. Often the power converter of the DER with the highest output will have this role. In a master-slave mode, it is also possible to dynamically change the grid-forming converter when the outputs of the DERs change [115]. When the microgrid is operating in grid-connected mode, the power converters are operating in grid-following mode and their control is based on current control. The reference values are derived from the active and reactive power values in the distribution grid [72].

2.3.3 Centralised and Decentralised Approaches to Control

The hierarchical control layers can be implemented either with a centralised or decentralised approach. Depending on the layer, these communication modes can affect the physical location, number and roles of the controllers, or affect the management strategy of system assets [110]. As discussed above, some control layers are more suited for centralised control, some for decentralised control. For example, it is possible to implement fully centralised control of the primary level, but due to the need for very low latency and high bandwidth communications networks, this approach is suited only for limited implementations [115]. On the other hand, for the secondary control level, the centralised approaches are currently more common, as discussed earlier. Therefore, a practical implementation of a microgrid control system is likely to combine both centralised and decentralised communication modes. On the tertiary control level, the question between centralised and decentralised strategies depends on the size of the system, the ownership of system assets and on the objectives set for the system. In a centralised approach the system assets are utilised to achieve a common goal. A central controller calculates an optimal operating scenario, matching the demand with the available resources in the most economical way. It decides how much power, if any, is imported from the distribution grid and sends the local generators and controllable loads control signals to realise the operating scenario [110]. However, if the microgrid system covers a large number of nodes, such as DERs or households, a centralised approach becomes heavy in terms of optimisation and the volume of information exchanged. Likewise, if the DERs are owned by different entities with different goals and if the households are participating in the electricity markets as individuals, it becomes challenging to find a common operation scenario which would satisfy all the objectives set by different actors. There may also be limitations on what extent the actors are willing to relinquish control over the management of their loads or the output of their DERs. Therefore, in a system consisting of actors with different objectives or a high number of actors and assets, a decentralised approach to tertiary control may be more practical. The system can be divided either into smaller microgrids or aggregations, or each actor can have a dedicated controller for their assets. These separate microgrids or decentralised controllers will then seek to optimise their production and consumption by competing or collaborating with the other controllers and grids, with the electricity market prices as a common control signal. [110]

2.3.4 Selecting a Control Strategy for the LEOS

The LEOS and the planned South Cornelly LEM microgrid described in this study operate both in grid-connected and islanded mode, with an emphasis on minimising the power imported from the distribution grid in the grid-connected mode. Hierarchy wise, the LEOS and its submodules operate on the tertiary level of control. On both of these levels, centralised control is exercised, although some functionality is delegated to sub-modules and systems. The primary control level is taken care of by the power converters of each DER and the management systems of each energy storage resource. A special case is formed by the HEMSs, which are external to the LEOS, but receive secondary and tertiary level control signals from the LEOS. The HEMSs can be viewed as self-contained systems, which implement features from the secondary and tertiary levels of control in managing the household energy assets. The households which have a rooftop solar PV system installed, also house a solar PV inverter, which performs the primary control functions. The HEMSs have autonomy on normal operations, making decisions based on the control signals received from the LEOS and the settings specified by the users. However, emergency control signals from the LEOS, such as commands to curtail solar PV output to the grid override the HEMS’s own dispatch decisions. The management strategy implemented in the LEOS and the included control functionality are discussed in detail in the section 4.5.

2.4 Reverse Power Flows and PV Hosting Capacity in a VRE Based Microgrid

With the deployment of more and more intermittent solar PV systems in low voltage distribution networks, technical challenges have started to arise [116]. These include violations of voltage limits, thermal overloading, and voltage fluctuations and unbalances [117]. One of the main mechanisms behind these issues is reverse power flow, wherein the power in a feeder flows in the opposite direction to normal. According to Holguin et al., two primary causes for RPF can be identified [118]: firstly, RPF can occur when the output of one or multiple solar PV systems on a local feeder exceeds the demand by loads on the feeder, either due to increased output from the PV systems or due to reductions in the local demand. This overgeneration in the feeder causes a change of direction in the power flow, in addition to voltage peaks. Another cause for RPF can be a fault current, which is flowing in the opposite direction than the normal current. These kinds of fault currents may result from solar PV systems injecting power to the network in a fault situation, which causes irregularities in the protection system. Although solar PV is discussed here, similar challenges can appear if high numbers of other DERs, such as microturbines, are integrated into low voltage distribution networks.

These issues have showcased that there is a limit to the amount of solar PV generation capacity that may be integrated into a given system, without hampering the normal system operations and power quality. This concept, called hosting capacity is not straightforward to define as it depends on a plethora of factors that differ from grid to grid. These factors include network loading, the characteristics of network feeders, the locations and capacities of individual solar PV systems on the network, and the possible load shifting procedures in place in the system [116]. Common approaches to estimating the PV hosting capacity in a system include stochastic methods, which commonly use probabilities for overvoltage as an indicator for hosting capacity [119], [120] and deterministic methods, which derive an estimate for the hosting capacity from the properties of the network and the feeder [121]. Another, simplistic approach for rough estimates of hosting capacity is presented in the IEEE standard 1547.2-2008 [83]. It states that a distribution network can host DERs up to the point when the aggregated generation capacity in the network reaches 15% of the feeders' annual peak load. Or alternatively, up to the point when the capacity of DERs installed reaches 50% of the value of the feeders' annual minimum load. However, Chathurangi et al. point out limitations in these approaches [116]. Both the stochastic and deterministic approaches are tailored for specific case studies, giving out hosting capacity values which are not applicable to other networks or analysis. The IEEE approach in turn lacks the ability to account for the impact of the PV system locations on the hosting capacities of individual feeders. Therefore, Chathurangi et al. propose a more generalised approach to assessing hosting capacities, in the form of nomogram diagrams and generalised solar PV approval criteria based on the nomograms.

In addition to providing a tool for assessing the PV hosting capacity of a solar PV system, they also list ways of increasing the hosting capacity. These include utilising smart PV inverters, installing voltage regulation equipment such as on-load tap-changer (OLTC) transformers and capacitor banks, reinforcing the network, and integrating BES systems [116]. Another effective solution for preventing RPF would be the limiting of the active power output of the solar PV systems i.e., curtailment. However, curtailment is not economically optimal for the owners of the solar PV systems, and it is counterproductive for emissions reductions targets. Therefore, instead of active power control, Almeida et al. explore four different reactive control techniques aimed at reducing the risk of RPF [117]. These include fixed power factor control, scheduled power factor control, power factor control as a function of injected active power, and voltage-dependent reactive power control. All of these techniques are based on injecting reactive power into the grid to increase the voltage when the voltage drops below the lower limit, and absorbing reactive power to decrease the grid voltage when the voltage exceeds the upper limit. This reactive power injection and absorption can be performed by the solar PV inverters, when their full capacity is not used for active power injection. According to Almeida et al., solar PV inverters work below their rated capacities 95% of the time, which frees capacity for reactive power control. This capacity could be further increased by installing oversized inverters that have more capacity than the maximum output of the solar panels. This would allow for reactive power compensation even during periods of peak solar irradiance. Out of the reactive power control techniques assessed in the study, the voltage-dependent reactive power control, or volt-var control was found the most effective. However, Almeida et al. also warn of overcompensation, which can cause significant network losses. They also point out, that in some networks the interaction guidelines may pose too stringent power factor limits for reactive power control to be viable. Instead, BES systems are proposed for more constrained networks. [117]

In a 2020 study, Sousa et al. assess the active and reactive power control techniques in combination with BES systems, with the objective of increasing the network hosting capacity for solar PV [122]. They found a mixture of active and reactive power control in the form of Volt-Var + Volt-Watt control to be the most cost-effective solution, with the highest increase in hosting capacity (250%). When implemented separately, the study found active power limiting to result in higher increase in hosting capacity (56.25%) than reactive power control (37.5%). However, the active power control comes with the cost of lost production. The effects combining a BES system with the other control techniques were found out to be positive, with a 212.5% increase in hosting capacity achieved when combined with active power control and a 118.75% increase achieved when combined with reactive power control. Yet the investment costs of BES systems are pointed as a barrier for adoption. [122]

Expanding the hosting capacity of a low voltage network using electrical energy storage was also studied by Hashemi & Østergaard in 2016 [123]. They present a novel control method for electrical energy storage management, which adjusts the set points of the electrical energy storage units based on forecasts and estimates. Estimates for active power generation and demand are formed based on internal and external factors, such as weather forecasts and network characteristics. After the reactive power absorbed by each solar PV inverter is estimated, using two droop control methods: power factor as a function of injected active power and reactive power as a function of voltage (volt-var). Hashemi & Østergaard found this dynamic set point method for electrical energy storage management allowed a maximum PV penetration of 75% in the grid, compared to a 50% penetration achieved with a static set point method. In addition, they noted that in the grid analysed, a droop control method with power factor as a function of injected active power was more efficient in lower levels of PV penetration, whereas the volt-var droop control was more efficient at higher PV penetration levels. [123]

In addition to increasing the hosting capacity and of solar PV in a low voltage network and reducing the risk for RPF, BES systems can also be used for peak shaving in networks with high penetration of PV, as shown by Pimm et al. in their 2018 study. The study assessed the impact of household BES on typical low voltage networks in the UK, estimating a potential for 50% reduction in substation peak loads if all households had a 2 kWh of BES installed. Pimm et al. also explored the synergy between heat pumps and BES. They estimate that for households with fully heat pump powered space and water heating systems, 3 kWh of BES per household would be sufficient for keeping the demand at current levels. Thus, they conclude that BES systems are effective at supporting both heat pump and solar PV deployment and reducing the peak power flows in low voltage networks. As a challenge they see how to encourage the consumers to adopt and appropriately operate BES systems. [56]

2.4.1 Utilising BES and Electrolysers to Prevent Reverse Power Flows in the South Cornelly LEM

Overcoming the operational barriers mentioned in [56] is a good example of how a microgrid control system, or indeed the LEOS proposed in this study, could lower the threshold for households to adopt new energy resources such as solar PV and BES. The literature shows that energy storage systems and DERs have considerable potential for reducing the grid burden inflicted by high penetration of renewables, when properly managed. The following sections of this study explore how this management could be arranged in the case of the South Cornelly LEM, describing the functionalities the LEOS and its subsystems should implement in order to provide a platform which is easy for the households to join.

One of the guiding principles behind the South Cornelly LEM is to maximise the share of self-produced renewable energy in the energy consumption of the community. Therefore, it is crucial to ensure the output from the rooftop solar PV systems installed in the village is used in an efficient way. Additionally, the main constraint of the project is preventing any backfeed from occurring through the substation onto the medium voltage side, operated by the DNO National Grid. To keep any backfeed or voltage limit violations from occurring at the point of common coupling or in the low voltage network, the scenario discussed in this thesis utilises BES and electrolysers to absorb excess active power during high solar PV output and low demand. Additionally, active power injection limiting of the solar PV systems is used as an emergency measure. Lastly, as pointed out in [117], [122] and [123], reactive power control using the volt-var method shows great potential for increasing the solar PV hosting capacity of a low voltage network, while also reducing the risk of RPFs. If the LEM participants of South Cornelly are willing to invest in sufficient solar PV inverter capacity, reactive power control may become a viable option for improving security of supply and power quality and reducing possible solar PV curtailment. However, an analysis on the possible grid losses incurred in the particular network should be performed before committing to this method.

3. THE SGAM METHODOLOGY

This chapter presents the SGAM methodology and the related UML concepts used for describing the LEOS in the chapter 4. The reasoning behind selecting the SGAM architecture for the basis for mapping the LEOS functionality was explained in the section 2.2.7. In addition, section 3.1 of this chapter introduces the SGAM Toolbox extension for the software Enterprise Architect, which was used in creating the model diagrams of the LEOS and its subsystems presented in the chapter 4.

This thesis uses the SGAM methodology defined in the SGAM User Manual [103], applied to the context of the SGAM Toolbox following the Introduction to the SGAM Toolbox guidelines [109]. As established in the section 2.2, Smart Grid can be seen as a system of systems. Therefore, it is practical to use model-based systems engineering (MBSE) practices, and the Model Driven Architecture paradigm when describing the functionalities of the LEOS [73], [124]. The Model Driven Architecture can be used to separate functional and technological aspects of a system [73]. Two model concepts introduced in the Model Driven Architecture are especially useful: the Computation Independent Model (CIM) and the Platform Independent Model (PIM). The CIM describes a system from an outside perspective, looking at the whole system level. Its focus is on the delivered functionality, not on the technologies used in implementing the functionality [73], [109], [124]. In the SGAM this corresponds to the Business and Function layers of interoperability [109]. The PIM focuses on the system architecture, decomposing the system into the main functional blocks, but without specifying the technical aspects of individua components [73], [109], [124]. In the SGAM, the CIM corresponds to the Information, Communication and Component Layers. The CIM and PIM are similar models in terms of keeping the descriptions on a functional level, but they inspect the system at a different level of granularity. While the CIM considers the functionality of the complete system, the PIM considers each function separately and breaks them into sub-elements.

3.1 System Analysis Phase

The SGAM methodology can be broken into phases, which implement the concepts of CIM and PIM. As defined in the Introduction to the SGAM Toolbox document, these phases are [109]:

- **System Analysis Phase**
    - Use Case analysis

  - Developing Business Case Model (Business Layer)
  - Developing Use Case Models (Function Layer)
- **System Architecture Phase**
  - Developing Component Layer
  - Developing Information Layer
  - Developing Communications Layer

The System Analysis Phase starts with defining the system specifications, mapping the actors involved and describing their relations. First, all the entities in the system and the external stakeholders interacting with the system are identified. These are the actors in the model, described in an actor list [62]. After the system actors have been identified and defined, the interactions between actors and the system or sub-systems are described using use cases. In this Use Case analysis sub-phase, use cases are identified, and the actors and use cases are split into categories, based on which interoperability layers they are located. The use case categories used in this study include Business Use Cases, High-Level Use Cases (HLUC) and Primary Use Cases (PUC). More use case types are defined in [103], such as Test Use Cases, which can be utilised in building models for test scenarios and systems [61]. To describe the use cases, the templates defined by the IEC 62559-2:2015 standard use case methodology are applied [103], [125]. The standard introduces three templates: short, general, and detailed. The short template documents use case concepts. It accompanies use case narrative and diagrams, which provide most of the information. The general template makes a distinction between business and system use cases, which is described in the nature of the use case. In business use cases, the actors are treated as roles, whereas in system use cases the actors are treated as systems and devices. Details on the objective and scope of the use case is added to clarify system boundaries and to provide references for defining supporting interfaces and standards. Lastly, the detailed use case template implements a step-by-step analysis to define the environment the use case exists in. For business use cases, business processes related to the use case are defined. For system use cases, the information exchanged is analysed and requirements for the communications layer are defined alongside with non-functional requirements. To structure the use case analysis, a Use case checklist is provided in the SGAM User Manual [103].

In the SGAM Toolbox methodology [109], the Use Case Analysis sub-phase is followed by building the Business Case Model. A Business Case Diagram is created, utilising an adapted version of the UML Use Case Diagram format. The Business Actors are mapped on the diagram and Business Goals are assigned to each of them. Next, the actors are assigned Business Cases, which aim at achieving the Business Goals. Lastly, the Business Cases are connected to the respective HLUCs, that implement different aspects of the Business Cases. Formally, the Business Case Model is represented in a Business Case diagram utilising UML concepts and relations. An example diagram provided in the SGAM Toolbox presented in the Figure 7. The model consists of Business Actors, which are connected to one or more Business Goals with a *“dependency”* relation. The Business Actors are connected to the Business Cases with a *“use”* relation and each Business Case is in turn implementing a Business Goal with the *“realise”* relation. The Business Cases can also have dependencies between each other. Lastly, the Business Cases *“invoke”* HLUCs.

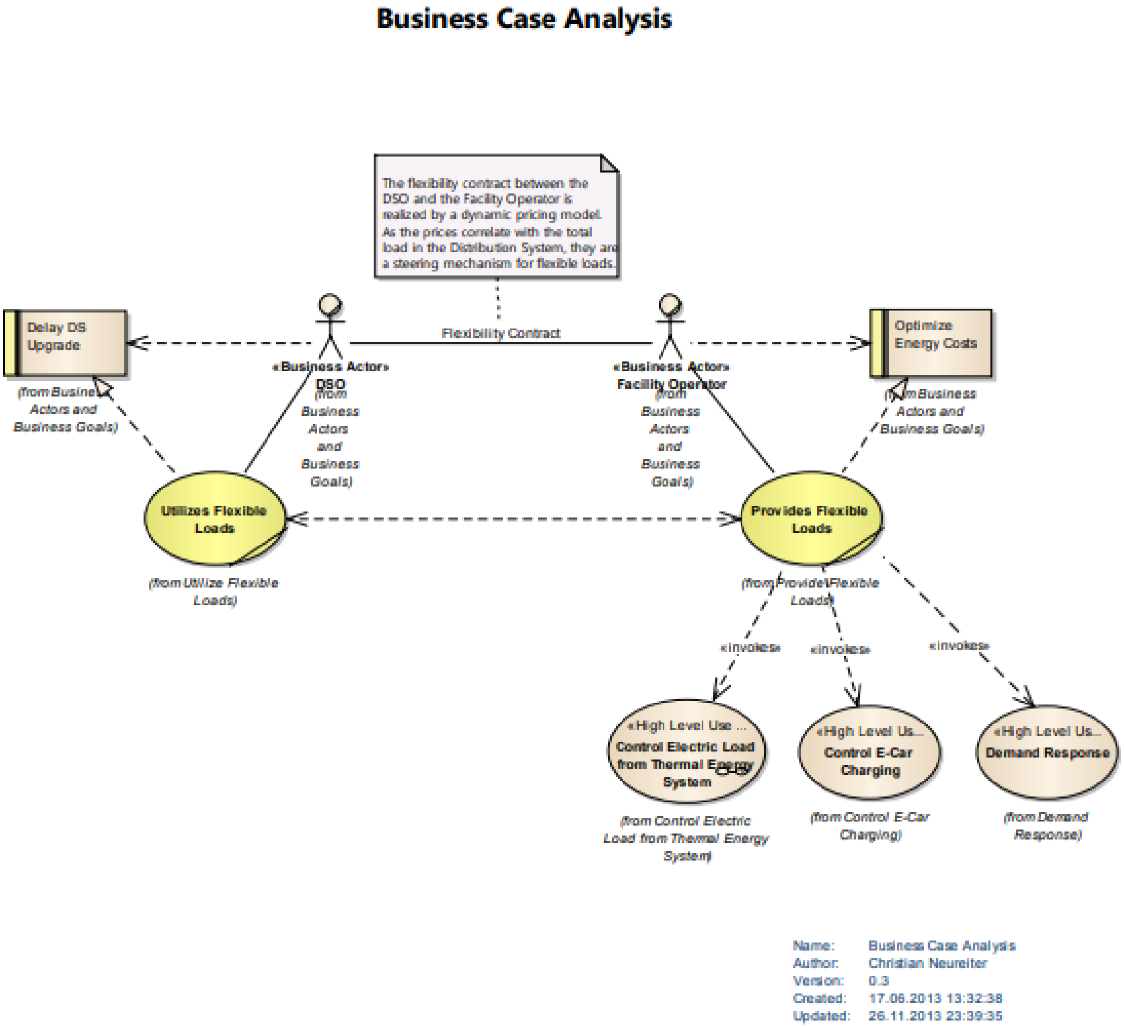

***Figure 7** SGAM Toolbox Example Business Case Model* [109].

Next step in the System Analysis Phase is building Use Case Models for the HLUCs identified in the Business Case Model and decomposing the HLUCs into constituent PUCs [109]. For each HLUC, a HLUC Model is developed. In the model, system and external actors are identified and a dependency connection is made between each PUC that the actor uses or interacts with. Some actors may belong to a more general category of actors. For example, DER inverters could include both solar PV inverters and BES system inverters. To model relations like this and to make the model simpler, the actors can be assigned to inherent the features of a general actor with a generalisation relation. In addition to actors, the PUCs too can be related to each other. When the execution of a PUC requires the execution of another use case, the supplementary use case is connected to the PUC with an *"include"* relation. It is also possible, that a supplementary use case extends the behaviour of the main PUC but is not always executed. These optional use cases are connected to the PUC with an *"extend"* relation. As the PUCs may have relations to many other use cases, one use case can act both as a primary use case and be included to or extend other use cases. [99] An example of a HLUC Diagram is presented in the Figure 8. In order to map the step-by-step execution of different interlinked use cases, they can also be mapped on Activity Diagrams. The Activity Diagram models the flow from one activity to another activity, through actions, decisions, and control flows.

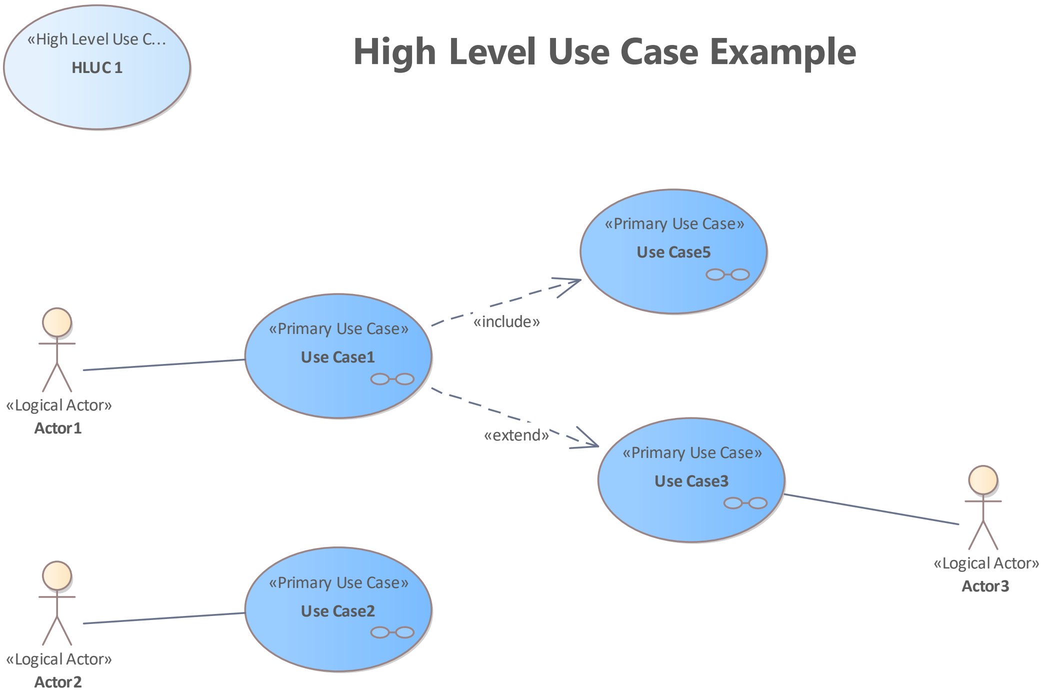

Figure 8 *Example of a High Level Use Case Diagram.*

When all the PUCs and the related actors have been placed on the HLUC Model, the next step in the SGAM Toolbox Analysis Phase is preparing the descriptions of each individual PUC [109]. For these purposes, Activity and Sequence Diagrams are used. When defining the internal steps of a PUC, in addition to mapping the actions and decisions involved, also the exchange of information needs to be modelled. This is done using information objects. At the Function Layer level, the contents of these information objects are not separately modelled, but their purpose can be explained in text. For each activity that creates, passes, or receives an information object, a *"dependency"* relation is drawn to connect the activity with the corresponding information object. While Activity Diagrams show the flow of activities, the Sequence Diagrams describe the interactions between actors. The sequence diagrams are organised so that the time dimension flows top-down, and the actors are represented horizontally on the top row, with each having their own vertical column, called a lifeline. Messages are passed from actor to actor, from lifeline to lifeline and new messages are added on the rows below the preceding messages. When a message transmits an information object, it is signified by an "Information Flow." Examples of Activity and Sequence Diagrams are depicted in the Figure 9 and Figure 10 respectively.

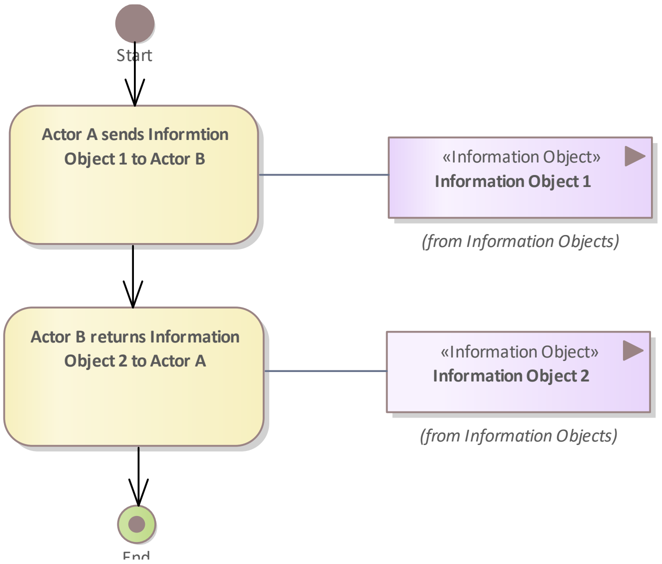

Figure 9 *Example of an Activity Diagram.*

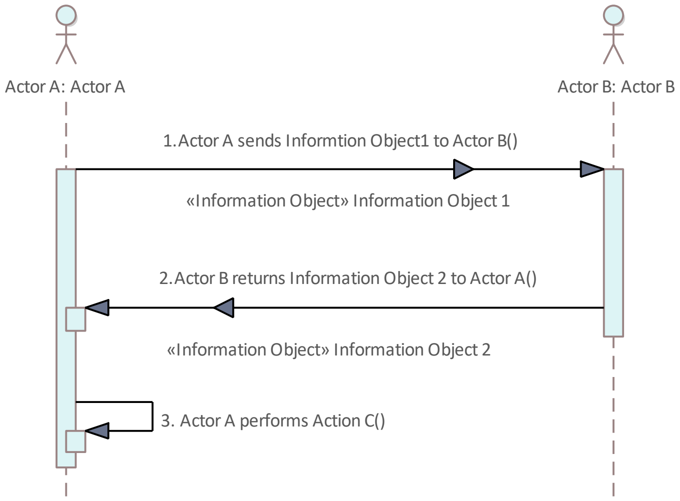

Figure 10 *Example of a Sequence Diagram.*

In addition to formalising the Business Case and Use Case Models with the related supporting diagrams, the SGAM Toolbox System Analysis Phase includes mapping the Business Cases and Use Cases onto the Business Layer and Function Layer, respectively. This is done by assigning each actor and Business/Use Case on the correct SGAM Domain and Zone. Especially the Business Cases commonly cover multiple Domains and Zones. [109] In the LEOS model, these definitions are not included in the use case descriptions, as the system covers a limited number of Domains and Zones.

3.2 System Architecture Phase

After the Use Cases have been described, the SGAM methodology continues with developing the Communication, Information and Component Layers [103]. In the SGAM Toolbox this phase is named as the System Architecture Phase [109].

The different layers can be defined in differing orders. The SGAM Toolbox starts with mapping the logical actors into physical components, in order to transition from a CIM to a PIM. This transition maps the functional description of a system to a general architectural solution [109]. The SGAM Manual methodology begins with defining the information and communication flows on their respective layers. To implement these flows, the required information objects and communications services are defined. Next, the used protocols and data models are defined [103]. The SGAM Toolbox describes the Information Layer first, identifying and defining the needed data model standards. After this, the Communication Layer is described and the technologies and protocols used to communicate between individual components are defined [109]. At this stage, the two methods converge. The single components are designed so that they support the communications protocols and data models required. Finally, a realisation of relationships is completed. Each Business process is realised by physical elements defined on the component layer [103], [109]. In the SGAM Toolbox this is represented by Component Responsibility Models, which are created for each component [109].

3.3 State Machine Diagrams

In addition to the diagrams presented in the SGAM Manual and the SGAM Toolbox, one more diagram is required to represent the functionality of the LEOS. In order to describe the control logic of the LEOS Real Time Control Module, a State Machine Diagram is used to represent the different system states and transitions between them. State Machine Diagrams depict the states that an object can go through during its lifetime [99]. It encapsulates the sequence of events affecting the object and the responses the object has to these events. The object can have a different reaction to an event, depending on which state the object is on when the event occurs. The State Machine Diagrams start at the initial state of the object. If the diagram reaches the final state, the object terminates at that state. However, so called closed loop State Machine Diagrams may not have any “final state. The objects represented by these diagrams exist as long as the system they belong to exists. Different states are connected to each other with transitions. The causes of the transitions are defined as *“triggers”* and the conditions that need to be met for a trigger to activate are named *“guards.”* A transition can also have an *“effect”* which is invoked on the object when the transition occurs. The states can have substates, which have their own initial and final states. The states can also include internal effects that occur when the state is entered or left. In the LEOS model, values for variables are included in the states. These set the target active power injection or absorption values for different system assets for each system state. [126] An example of a State Machine Diagram is presented in the Figure 11.

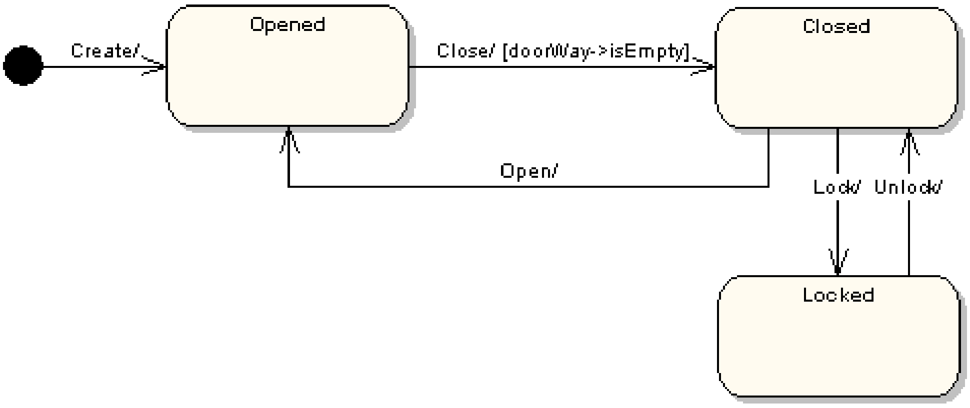

Figure 11 *State Machine Diagram Example* [126].

The focus of this study is on the functional description of the LEOS, which corresponds to the SGAM Toolbox System Analysis Phase. Before presenting the model diagrams developed, an overall introduction on the South Cornelly LEM is given. The studied LEM scenario is explained, alongside describing the prior work on the project by Challoch Energy. This thesis considers the physical designs of the South Cornelly microgrid and the LEOS only to a limited extend and therefore no analysis on the SGAM Communication, Information and Component level implementations is performed in this study.

4. A FUNCTIONAL DESCRIPTION OF THE LEOS

This chapter starts by establishing one possible scenario for the implementation of the South Cornelly LEM, based on the project plans at the time of writing and on the prior work done by Challoch Energy. This scenario is used as the basis for a functional description of the LEOS, which is presented by utilising the SGAM methodology and models introduced in the SGAM Toolbox. All of the UML diagrams presented in this study have been created in the visual modelling and design software Enterprise Architect [108], utilising the SGAM Toolbox extension [107]. Other figures presented this chapter have been designed using the Draw.io web platform [127] and Microsoft Power Point [128].

4.1 Establishing the studied South Cornelly LEM scenario

As discussed in the section 1.3 and presented in the Figure 1, the South Cornelly LEM consists of households with a HEMS installed, some of which also have rooftop Solar PV installed, and households who participate in the LEM, but only have a smart meter installed. Not all households in South Cornelly are expected to participate in the LEM. In the scenario studied in this thesis, a majority of 70% of the 220 households in South Cornelly village are assumed to participate in the LEM. However, the real participation rate of an energy community like this would likely vary over time and during the first years of operation the participation rate could also be below 50% of the households. All LEM participants are assumed to have a HEMS installed. The HEMS manages the possible energy resources at the household premises, such as rooftop PV and BES systems. The HEMS also schedules household loads, such as appliances or EV charging, according to user preferences and control signals from the LEOS. The households are assumed to utilise SolarVenti solar air collection systems [129], which combine a solar thermal collector for heating air and PV powered fans which circulate the warm air into the building. These systems are likewise controlled by the HEMS. As discussed in the section 1.3, this thesis is based on a scenario where the UK legislation would allow for the community to share the produced energy between members, bypassing the licensed supplier.

In addition to the energy assets at household premises, the studied scenario for the South Cornelly LEM assumes the community to possess a number of centralised energy assets. These include a BES system, hydrogen producing electrolysers, and a central EV charging station. These centralised energy assets are utilised for the benefit of the community, supporting the operations of the microgrid. The location of these assets is called the Energy Centre, and it is connected to the South Cornelly LV network via the Energy Centre Inverter. This system is responsible for managing the energy resources of the Energy Centre, according to LEOS control signals. The Energy Centre is also connected to the DNO operated substation and the medium voltage network. Furthermore, a nearby wind farm is connected to the Energy Centre via a private wire connection. The Energy Centre acts as a nexus for the power flows in the South Cornelly microgrid. This study describes the functionality of the Energy Centre as if the Energy Centre is one entity. The Energy Centre Inverter is a term used to encapsulate all functionalities of the Energy Centre control system. The practical implementation of the components that provide this functionality is left undefined. The Energy Centre is treated as a “black box” which could consist of multiple components in different configurations, making various hardware implementations possible. These are left to be decided in possible later stages of the project, by entities with sufficient understanding of the relevant financial constraints and local preferences. A practical location for the Energy Centre would be in the vicinity of the MV substation, which is the point of common coupling between the South Cornelly village LV network and the DNO MV network. As discussed in the section 1.3, in the current UK legal framework the DNO owns the distribution networks and operates them. In the studied scenario, it is assumed that an agreement with the DNO has been made to give the South Cornelly LEM community a degree of responsibility over the active network management in the South Cornelly LV network.

While the Energy Centre is considered the nexus for power flows in the South Cornelly LV network, the LEOS with its subsystems, is the administrator of information flows in the South Cornelly microgrid and LEM. It is also the principal decision-making entity in the system. Most of the system energy resources are not directly controlled by the LEOS, instead they are either controlled by the HEMS or the Energy Centre Inverter. However, the LEOS issues priority control signals for these intermediary controllers, which are then distributed to all components of the system. In terms of the hierarchical levels of control introduced in the section 2.3.1, the LEOS primarily operates on the tertiary level and the Energy Centre and the HEMSs on the secondary levels of control. Additionally, from the perspective of the energy resources of a household, the HEMS operates also on the tertiary level of control, making decisions on the optimisation of power flows in the household premises.

Prior to this study, Challoch Energy had already established the basic concepts of a LEOS. This work had mainly been undertaken by Mike Parr, who also acted as the supervisor of this thesis from the Challoch Energy side. The initial Challoch concept for the

LEOS utilised a framework derived from the Open Systems Interconnection model standard, which splits the data flows in communications systems to seven abstraction layers. These include the Application, Presentation, Session, Transport, Network, Data link and Physical layers [130]. In the initial LEOS concepts, four layers had been identified: Enterprise Layer, Transaction Layer, Data Layer and Physical Layer. The Enterprise Layer covered the whole South Cornelly LEM, whereas the Transaction Layer corresponded to an Accounting System and the Data Layer to an Energy Management System. The gas and electrical networks were placed on the Physical Layer and the customers i.e., the LEM members were situated between the Data and Physical Layers.

This concept was developed further, inspired by the computer operating systems and the Global System for Mobile Communications (GSM) [131] standard. These systems provide extensively defined general functions for different types of components and equally robust interfaces allowing these components to communicate with each other. This makes for platforms which are easy to expand and has allowed numerous manufacturers to utilise these systems, leading into diverse new hardware and functionality. Drawing from these ideas, Challoch Energy decided to define the energy management system for the South Cornelly LEM as a Local Energy Operating System. The concept of the LEOS is not intended as a one-off solution just for South Cornelly. Instead, the governing idea behind its design is to provide an open platform with transparent and well-defined functionality, in addition to interfaces for expanding the system with various energy resources and assets.

In addition to the LEOS design principles, Challoch Energy had established a logic for power flow management in the South Cornelly LEM network. Different system states had been identified, matching with the solar PV and wind power generation conditions in the network. As discussed in the section 2.4.1, the main objective of the system is to maximise the use of locally produced solar PV, while preventing any backfeed to the MV network side. Therefore, the initial power flow logic prioritised solar PV consumption, with surplus energy stored in the BES. In case of the BES being full, the logic shifted surplus power to electrolysers. If solar PV could not cover the entire demand, wind power would be imported from a local wind farm through a private wire connection. Details of the power purchase contract between the South Cornelly LEM and the local wind farm operator are out of the scope of this thesis. In this thesis, it is assumed that the LEM has a prioritisation for the wind farm output and that the surplus is sold to the market. In reality, this kind of preferential contract is not necessarily likely, and the possible further developments of the LEOS model should take into account different contractual scenarios with varying availability of wind power. If the demand were higher than the combined output of wind power and solar PV, the BES would be discharged. If necessary, power would also be imported from the MV network. This initial power flow logic has been used as the basis for the LEOS control logic introduced in the section 4.5.7. It has been expanded to account for system states with multiple or all DERs in simultaneous use, and special states such as system initialisation and curtailment of solar PV. Although this thesis does not deal with the specific implementations of these functionalities, solar PV and wind power production are to be forecasted based on weather forecasts. These then feed into the economic optimisation of the load and consumption in the South Cornelly LEM. The premise of the discussed scenario is that no solar PV production is sold to the external power market and that power is imported from the distribution grid only when other available energy resources are insufficient to cover the LEM demand. Therefore, interaction with the day-ahead power markets is not detailed in this thesis. However, from an economic point of view, it is entirely possible that for many hours of the day the prices in the day-ahead market are lower than the costs of producing energy locally due to Distribution use of System Charges incurred by the DNO. Including the day-ahead markets in a possible future economic optimisation module is one of the options of for further developing the LEOS concept.

The scope of this thesis is limited to the Business and Functional Layers of the SGAM. As discussed in the section 1.3, this thesis does not cover the communications protocols, data models or automation infrastructure and hardware needed to realise the general system functional description proposed. Therefore, this thesis does not conduct the System Architecture phase detailed in the section 3.2 and thus does not build the Communication, Information or Component Layers of the SGAM. Nevertheless, the partitioning of the LEOS functionalities into modules does represent the assets described in the South Cornelly LEM scenario, such as grouping communal DERs under the Energy Centre and including a HEMS module for households.

The choice of communications hardware affects properties such as data losses, bandwidth, and frequency. These in turn have implications for which communications protocol should be selected. A connectionless protocol has less overhead but is susceptible to data losses. Connection oriented protocols on the other hand require establishing a communication channel before any data payloads can be transferred but have more robust error proofing to prevent data losses. Many functions of the LEOS could be realised using different approaches to communications. For example, a communication link can be based on robust transactions with large packets of data transmitted, or on a connectionless link where small data packets are transmitted at a high frequency, ensuring some of them get to the receiver in near real time. The LEOS could also use a combination of approaches, as different functionalities have different needs for timeliness and the type of data transmitted. This thesis does not explore these factors further and therefore these are excluded from the sequence diagrams featured in the sections 4.5.1 to 4.5.14. In other words, the sequence diagrams do not explicitly state whether a confirmation is exchanged between the sender and receiver after each communication and do not detail whether some of the messages would be sent multiple times or even be continuously transmitted at certain intervals. For further exploration of the communications infrastructure in microgrids, existing standards such as IEC 61850 and IEEE 2030.7-2017 provide a robust framework [132], [133].

4.2 Describing the LEOS in general functional blocks

The Challoch Energy groundwork on the LEOS and the South Cornelly LEM project is well suited for the SGAM methodology. The initial concept of the LEOS has already been split into four conceptual layers, which mostly align with the SGAM interoperability layers. In addition, the open and expandable design philosophy behind the LEOS fits into the platform independent approach adopted in the System Analysis Phase of SGAM Toolbox methodology.

The SGAM User Manual lists function groups and flow charts as ways for detailing the use cases and the inner behaviour of functions [103]. In this study, these methods are utilised before defining the use cases, to begin structuring the LEOS into different subsystems and to identify the various actors involved. In the beginning of the project, a Functional Block Diagram was established with Challoch Energy, to map metering and control flows between system entities and functional blocks or groups. This diagram is presented in the Figure 12. The Functional Block Diagram can be seen as a detailed and expanded version of the power and data flows diagram shown in the Figure 1.

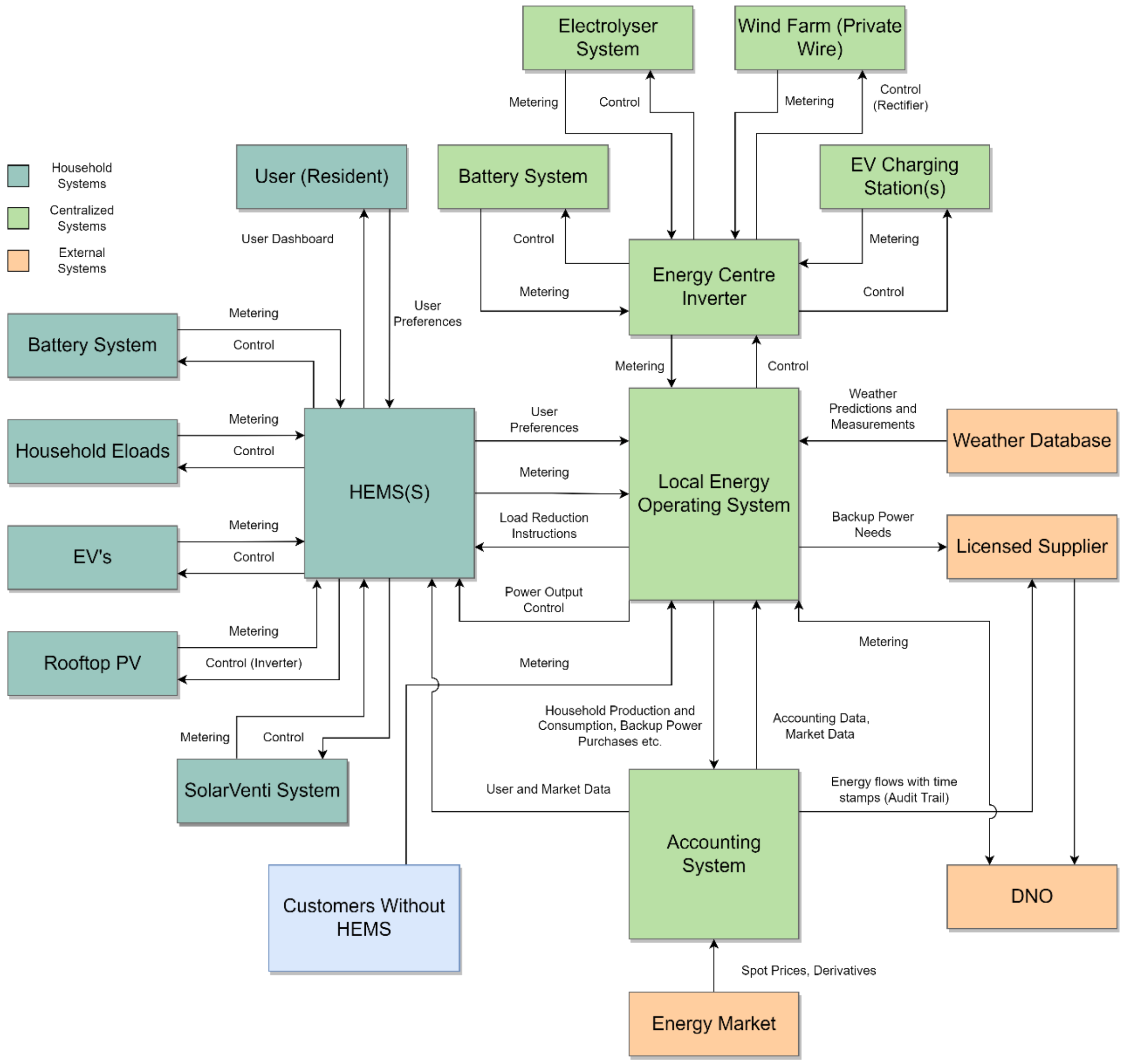

***Figure 12** LEOS Functional Block Diagram.*

The Functional Block Diagram introduces three different systems, which together are responsible for the management of the South Cornelly LEM. In the centre is the LEOS, which acts as the primal controller of the system. It is the decision-making authority in the system, and the hub for relaying information between different components and stakeholders. The second system in the LEM is the Accounting System, which was defined by Challoch Energy as the system in charge of the Transaction Layer in the initial four-layer architecture. In the SGAM framework, the Accounting System operates mainly on the Business Layer, collecting financial and accounting information from all SGAM zones from the Process zone to the Market zone. The third system identified in the Functional Block Diagram is the Energy Centre Inverter, which acts as a secondary level controller for the energy resources located in the Energy Centre. This allows the LEOS to send aggregated control signals to the Energy Centre Inverter, which then adjusts them for each energy resource utilised. In SGAM framework terms, the LEOS operates on the

Station and Field Zones, whereas the Energy Centre Inverter and the HEMS operate on the Process and Field Zones.

4.3 Identifying actors relevant to the South Cornelly LEM

As discussed in the section 3.1, the first step in the SGAM methodology is to identify both the system actors and business actors relevant to the smart grid. The Functional Block Diagram provides a starting point for this, but a more granular split of actors is needed. To structure the actor analysis, the actors are grouped similarly to the functional blocks identified in the Functional Block Diagram. However, the Household grouping is updated to LEM actors, which includes all LEM components and participants which are not part of the LEOS, Accounting System, or the Energy Centre inverter. The LEM actors are described in the Table 5. We continue by identifying actors external to the South Cornelly LEM in the Table 6. Finally, we identify the system actors which form the LEOS, the Accounting System, and the Energy Centre Inverter. These are described in the Table 7.

Table 5 *LEM Actors.*

Actor:	**Description**
HEMS	HEMS manages the energy resources of a household. These can include solar PV, BES system, solar air collection systems, EV charging and controllable household loads such as heating and appliances. Although these sub-systems have been mapped as separate functions, from the point of view of the LEOS the HEMS will be treated as one block which contains and manages all these functionalities. The HEMS acts as a secondary controller, while each of the energy resources contain a primary controller, such as solar PV inverter or a Battery Management System. The HEMS schedules the energy resources independently according to the data provided by the LEOS and the preferences set by the user. The real-time control signals sent by the LEOS take priority over the HEMS scheduling in case of solar PV curtailment for overvoltage protection. The HEMS provides the user an interface to view their accounting data and to monitor and understand the energy flows and costs in the LEM.
Household in LEM, but without HEMS	Some South Cornelly households may want to participate in the LEM but are not able to install a HEMS system. For accounting and system monitoring purposes these customers are still required to have a smart meter installed. The smart meter sends real-time data to the LEOS.
Household not participating in the LEM	These households are connected to the South Cornelly LV network, but they do not participate in the LEM. These households purchase their electricity from a Licensed Supplier. Contractually they are external actors to the LEM, but from the perspective of the LEOS they are included in LEM actors, as it is necessarily to take their consumption into account when estimating the total network demand. The consumption is estimated by deducting the metered LEM demand from the power flows observed at the substation transformer. In islanded mode the whole demand is covered by generation from the LEM energy resources, so the consumption by non-participants can be estimated by

	deducting the metered total consumption of LEM participants from the metered total generation.
EV Charging Customer	EV Charging Customers are actors who use the public EV charging station at the Energy Centre. By default, these customers are billed on the spot. However, it is possible to include certain amount of free of charge charging for the LEM customers. In addition, offering Time-of-Use pricing schemes can encourage users to charge outside of the peak hours. Smart charging and vehicle-to-grid can also be considered, depending on the capabilities of the charging equipment.
Feeder Protection Relay	In this study, the Feeder Protection Relay is used to group together three distinct functionalities: sensing faults and disturbances in a network feeder, metering feeder voltage, frequency, current and power factor, and separating faulted feeders. In practice, the protection relay and the switch performing the separation would be separate devices. However, from the perspective of the LEOS, the Feeder Protection Relay controls the switch and is therefore considered to include this functionality.
Point of Common Coupling Protection Relay	The Point of Common Coupling Protection Relay senses faults and disturbances on the MV network side. It controls a switch which is used to separate the South Cornelly LV grid from the MV network at the point of common coupling if there is a fault or an uncontained disturbance on the MV network side. The separation is also performed if a disturbance on the LV network side is uncontainable by separating the LV network feeders. In this event, the LV network Feeder Protection Relays would still separate the feeders first. The LEOS views the separation as a function performed by the protection relay, although in practice the switch would be a separate device controlled by the protection relay.
LEOS Administrator	The LEOS Administrator is the overseer of the LEOS system. This can be a human actor tasked to monitoring and initialising the system, a software entity, or a combination of both. The LEOS Administrator initialises the startup of the system and gets alerted in fault situations. The LEOS Administrator communicates with the DNO in fault situations. If the LV network is operating in an islanded operating mode due to a fault on the MV network side, the DNO sends the LEOS Administrator a confirmation when it is possible to re-synchronise with the MV network.
Local Community Council	The Local Community Council is the decision-making body of the South Cornelly village. It defines the outline for the South Cornelly LEM and decides on investments, such as acquiring energy resources or control systems. The Local Community Council sets the long-term objectives of South Cornelly development and drives the decarbonisation efforts.

Table 6 *External Actors.*

Actor:	**Description**
Wind Farm Power Converter	In the studied scenario, it is assumed that a private wire connection links the Wind Farm to the South Cornelly LV network and a Power Converter is used to synchronise the output with the LV network. Although the Wind Farm is external to the LEM, the Wind Farm Power Converter is placed under the LEM actors as it receives secondary control from the Energy Centre inverter. The power converter acts as the primary control for the wind farm.

Substation Transformer	The Substation Transformer connects the South Cornelly LV network to the MV network operated by the DNO. The Substation Transformer also acts as a data provider that relays monitoring data on the power flows, frequency, and voltage between the South Cornelly LV network and the MV network.
DNO	The DNO manages the MV network which the South Cornelly LV network is connected to. From a regulative standpoint, the DNO is responsible of the South Cornelly LV network too and is entitled to Distribution Use of System Charges from the use of the network. These charges have to be taken into account when calculating the optimum economic dispatch of system resources.
Weather Database	The Weather Database provides the LEOS with current weather measurements, alongside with short- and mid-term forecasts. One weather dataset is used by all system actors which need it. The dataset it includes for example wind speed forecasts, temperature forecasts, rainfall forecasts and solar radiation forecasts.
Licensed Supplier	Licensed Suppliers are the electricity retailers for both LEM participants and the non-participating households. The Accounting System provides the Licensed Suppliers data on the electricity consumption of the LEM participants. The non-participating households interact with the Licensed Suppliers independently and have regular electricity contracts.
Market Data Provider	Market Data Provider is an entity providing data on the intraday, day-ahead and futures markets for various energy commodities. The Economic Optimisation Module of the LEOS utilises these data in deriving optimised economic dispatch plans for the LEM.
Payment Service Provider	Facilitates the payments between the South Cornelly community and the EV Charging Customers.
EV Charging Customer (not LEM participant)	EV Charging Customers are actors who use the public EV charging station at the Energy Centre. The customers who are not part of the LEM, are not able to benefit from possible preferential pricing schemes or free charging offered to the EV Charging Customers who are LEM participants. Generally, these external customers are billed on the spot. Time of Time-of-Use, smart charging and vehicle-to-grid schemes could in theory be offered to external customers too, but it might be harder to implement these for customers who are not part of the general LEM pricing and accounting system and the related incentives.

Table 7 *System Actors.*

System Actor:	**Description**
LEOS	LEOS is the primal decision maker and coordinator of the South Cornelly LEM system. It facilitates communication between different system elements and collects both system and external data.
LEOS System Timer	The System Timer is a LEOS sub-process, which initiates various actions at specified time intervals.
LEOS Real-Time Control Module	The Real-Time Control Module is as sub-system of the LEOS, which is responsible for the management of real-time power flows in the South Cornelly LV network. The Real-Time Control Module sends control signals to the Energy Centre Inverter and the HEMSs, acting as a tertiary controller in the system. In emergency situations with a risk of overvoltage or RPF for example, the Real-Time Control Module acts as a secondary controller, sending control signals that override the HEMS and Energy Centre Inverter existing control plans. The Real-Time Control Module has a control logic which is based on system states. The control logic ensures power balance and security of supply in the network.

	The Real-Time Control Module constantly compares this base logic with the Optimum Economic Dispatch Plan provided by the Economic Optimisation Module. When possible, the Real-Time Control Module follows the dispatch plan, however the base control logic takes priority when necessary to maintain the network power quality.
LEOS Economic Optimisation Module	The Economic Optimisation Module is a sub-system of the LEOS, which optimises of the dispatch of system energy resources and provides scheduling for controllable loads. The module takes market prices data, demand estimates, LV network monitoring data and weather forecasts as inputs and outputs Optimum Economic Dispatch Plans. These dispatch plans are updated cyclically when the system Load Predictions are updated, either prompted by the System Timer or when a household sends new user preferences. The Economic Optimisation Module operates on the tertiary level of hierarchical control. As discussed in the section 2.3.1, the frequency of updates should fall in the seconds and minutes range. As a non-time-critical system, the module mainly operates based on the System Timer. Updates to user preferences are expected to occur infrequently compared to the timer cycle. As calculating Load Predictions and updating the Economic Dispatch Plans may be resource intensive operations, the less frequent cycle of updates reduces computation resources required. The optimisation algorithms used by the Economic Optimisation Module are not detailed in this thesis.
Accounting System	The Accounting System stores all financial and accounting information collected during the system operation. These data include the production and consumption by each LEM participant and the power flows to and from the communal energy resources. In addition, the Accounting System collects and stores electricity market data and provides data to external stakeholders, such as the Licensed Supplier.
Energy Centre Inverter	The Energy Centre Inverter acts as a secondary controller for the energy resources located at the Energy Centre. It receives control signals from the LEOS and adjusts these for each of the energy resources.
Battery Management System	The Battery Management System acts as the primary controller for the communal BES located at the Energy Centre. It receives secondary control from the Energy Centre Inverter.
Electrolyser System	The Electrolyser System acts as the primary controller of the communal electrolysers located at the Energy Centre. It receives secondary control from the Energy Centre Inverter.
EV Charging Station	The EV Charging Station provides communal access to EV charging at the Energy Centre. It facilitates payments from the EV Charging Customer to a Payment Service Provider. The EV Charging Station collects transaction data and consumption data, sending these to LEOS, which relays them to the Accounting System.

When examining the identified actors, it is evident that some of the actors could be categorised under a more general high-level actor group. These generalisations can be used to improve the expandability of the model, standardising the interactions with a category of actors. Therefore, three generalisations are introduced. The actors which are requesting data from the LEOS or Accounting System, such as the Licensed Supplier, are categorised under the generalisation “External System.” The second general actor introduced is “Metering Data Sender” which covers all actors that send metering data to the LEOS. The third generalisation applied is “LEM Participant” which encompasses all households who participate in the LEM, whether they have a HEMS or not. Using these actor generalisations allows for specifying use cases that standardise the data requesting and sending processes independently of the actors involved. This makes it possible to extend the model with new actors, without having to specify these functions again for each new actor.

4.4 Defining South Cornelly LEM Business Cases

Following the SGAM Toolbox methodology, the functional analysis of a Smart Grid system begins by identifying and defining the Business Cases involved. As detailed in the Business Case Model presented in the Figure 13, the identified Business Actors can have mutual Business Goals. The Local Community Council seeks the decarbonisation of the South Cornelly energy system. The Council aims to improve the security of electricity supply and to benefit from local energy production. These two goals are shared by the LEM participants, who are in addition seeking to reduce energy costs. Improving the security of supply is also a goal of the DNO. For the DNO, another important goal is avoiding investments to network infrastructure, which are needed when the share of VRE resources in the network grows. These Business Goals are realised by implementing a local energy market. This thesis does not go into detail on the different possible internal mechanics of the local energy market, as this would depend on the economic and ownership structure on which the community is established. It is assumed that the produced energy is shared between community members based on a community wide optimisation scheme, but the monetary transactions involved are not defined in this study. Similarly, it is not defined whether the utilisation of energy resources at the premises of household’s is compensated in an aggregated manner or using a household-to-household trading scheme. Nevertheless, the term local energy market is used here to distinguish the energy community operations from the external energy market.

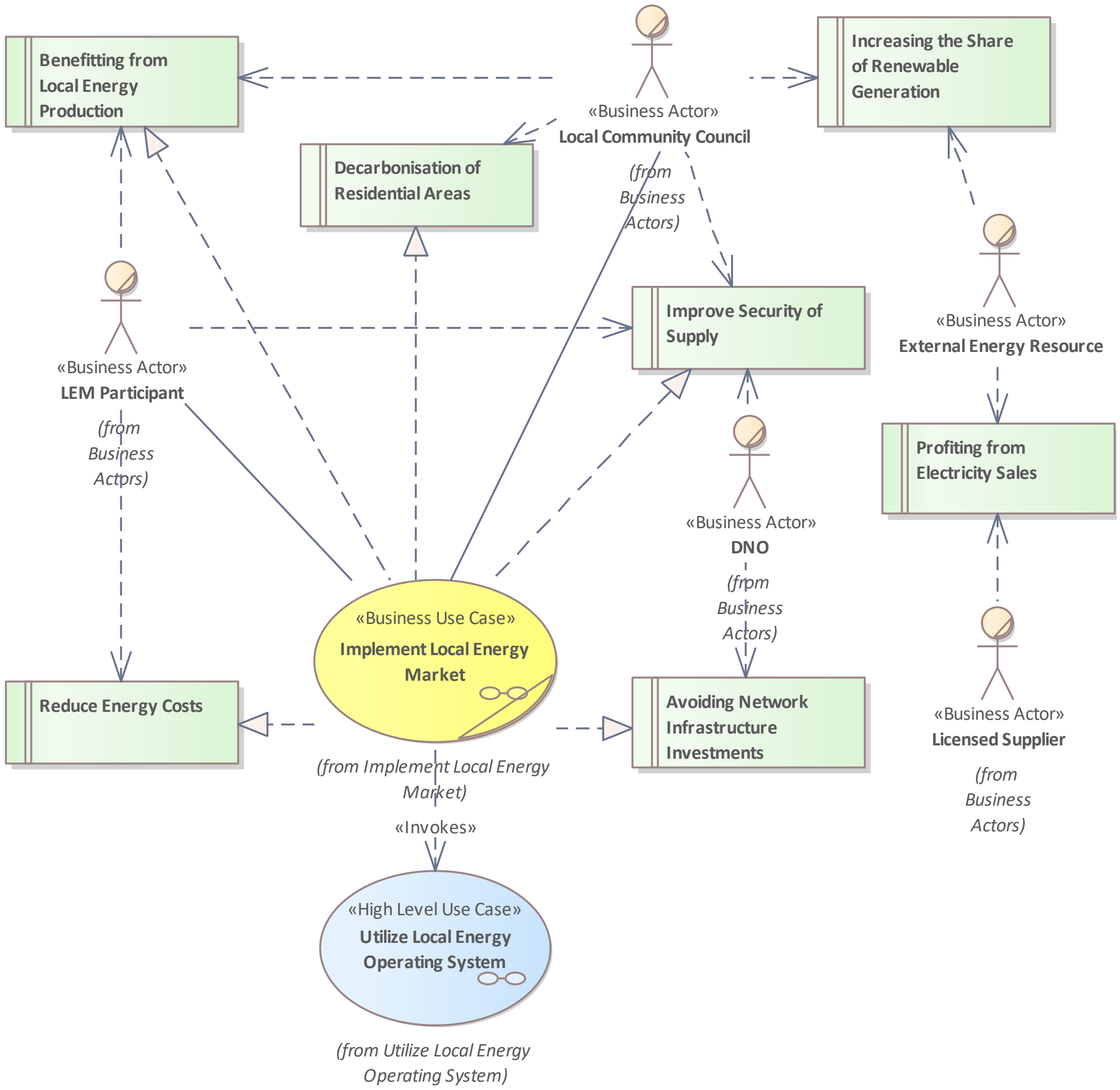

***Figure 13** South Cornelly LEM Business Case Model.*

The Business Actors are important stakeholders in the LEM project. Although not directly involved in the Local Energy Market, External Energy Resources such as the nearby wind farm in the case of South Cornelly, can help the community in sourcing affordable electricity and increasing the share of renewables use. Even though a stakeholder might not share the same goals as the others, there can be synergies. The Licensed Suppliers aim to profit from electricity sales, which can be considered somewhat contradictory with the goals of the LEM Participants and the Local Community Council, as local production of electricity reduces the sales of the Licensed Suppliers. A Licensed Supplier and the Local Community Council could however, work together to establish a more accurate model on the LEM consumption. The synergy here would be enabling more accurate predictions for demand, which would help the planning of the Licensed Supplier and could let the LEM Participants optimise their consumption to coincide with the cheapest hourly electricity prices. Although the Licensed Suppliers are not considered core stakeholders in this project, they are still included as important reserve electricity providers for times when the energy resources of the LEM cannot cover the entire demand.

After the Business Case has been defined, the next step is to implement it in HLUCs. In this thesis, the focus will be on the HLUC Utilise Local Energy Operating System, which is invoked by the Business case Implement Local Energy Markets.

4.5 Developing a Use Case Model for the HLUC Utilise Local Energy Operating System

After constructing a Business Case Model of the studied Smart Grid system, the SGAM Toolbox System Analysis Phase continues with the describing the HLUCs identified. A Use Case Model is created, which defines each PUC contained in the HLUC and the relations of these PUCs to each other and to actors identified. Each PUC is in turn described using an Activity Diagram and a Sequence Diagram, which identify the information objects passed between actors. The Use Case Model for the HLUC Utilise Local Energy Operating System is shown in two parts in the Figure 14 and Figure 15. The full use case diagram can be found in the Appendix, in the Figure 72.

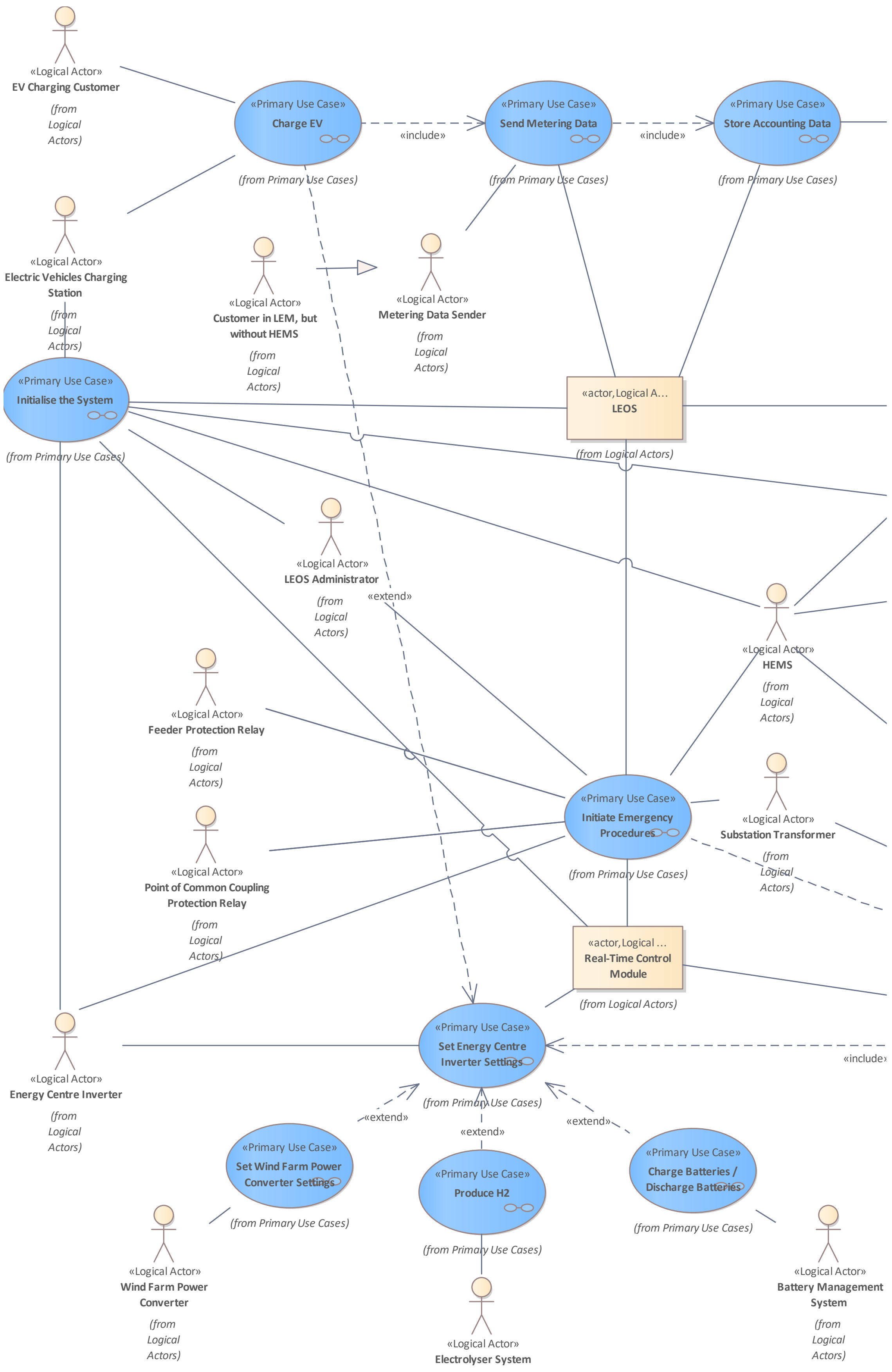

***Figure 14** HLUC Model - Utilise Local Energy Operating System (part 1/2).*

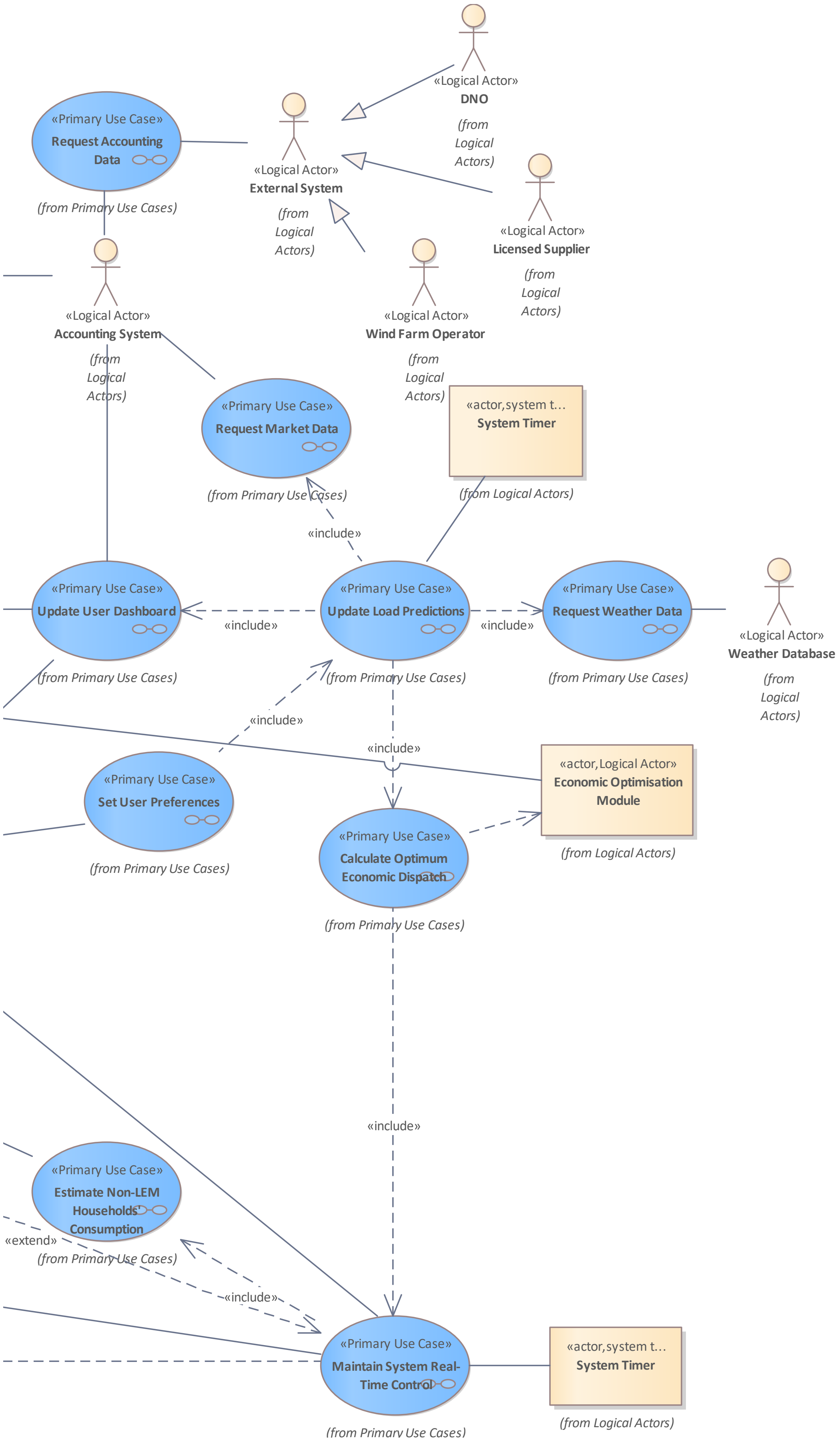

Figure 15 *HLUC Model - Utilise Local Energy Operating System (part 2/2).*

4.5.1 PUC – Initialise the System

To start up the LEOS system, an initialisation procedure has been developed. This Initialise the System use case involves all of the system actors identified in the Table 7, excluding the Accounting System. In addition, communications are also sent to the HEMSs. The actors involved in the use case are depicted in the Figure 16. It is assumed that the system initialisation process begins in a state where the system is turned off. the initialisation starts with bootstrapping processes that bring LEOS hardware online, and the first messages sent by the LEOS to other modules and systems are initialisation parameters, which are followed by status report request. Essentially, these steps are taken to start up needed hardware and to initialise and test communications connections between different system elements. This process is described in a general manner in the Figure 17 below. However, the specifics of what initialisation and status reports entail for each module or system are not in the scope of this thesis, as this would depend on the choice of system hardware, communications equipment, and communication protocols. For example, different protocols utilise different levels of error checking from robust to none at all and can operate in a connectionless mode or require establishing and maintaining a communication session.

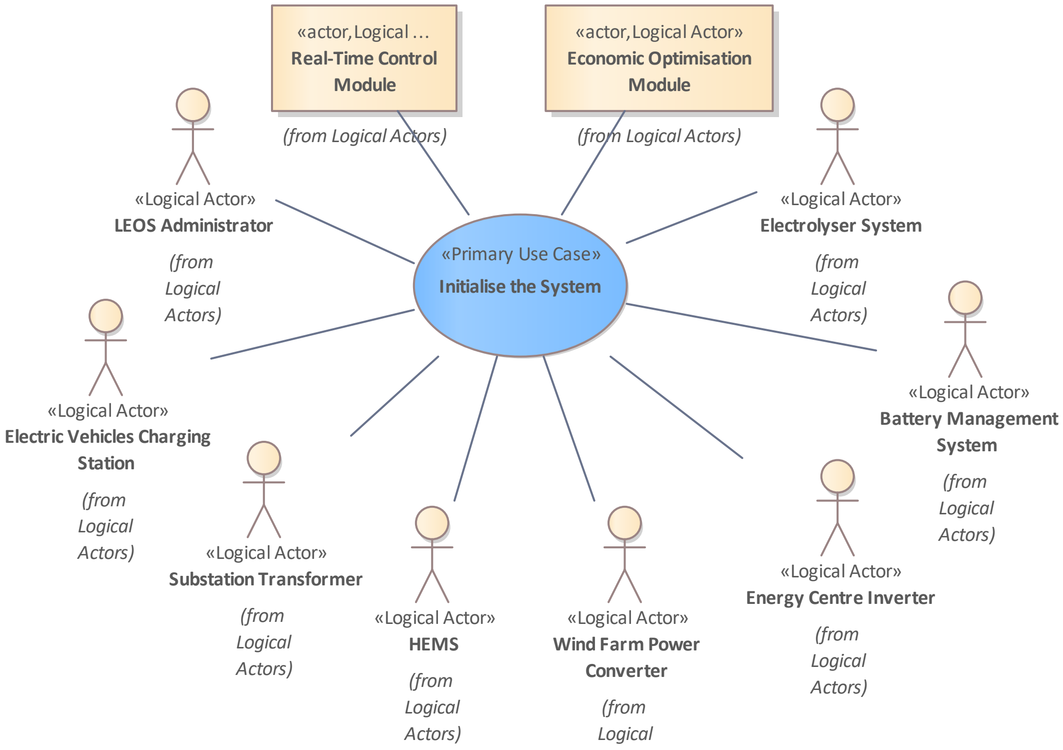

Figure 16 *PUC - Initialise the System.*

The activity diagrams for this use case have been split in four parts. The sequence diagram is split into two parts and can be found in the Appendix in Figure 73 and Figure 74Figure 73. As seen in the first two parts of the activity diagram in Figure 17 and Figure

18, the system initialisation is commenced by the LEOS Administrator. The LEOS Administrator sends a System Initialisation Message to the LEOS. This starts the LEOS bootstrapping process, which brings the LEOS hardware online. Next, the LEOS initialises the Real-Time Control Module, a sub-system responsible for the real time control of the network power flows. The Real-Time Control Module follows a control logic based on system states, which is detailed in the section 4.5.7. The control logic starts in an Initial State, where the South Cornelly LV network is exporting all power through the Substation Transformer and is under the management of the DNO. The Real-Time Control Module transmits settings corresponding to this Initial State to the Energy Centre Inverter, which in turn transmits them to all energy resources connected to it. These initial settings are represented by the information object Initial Parameters. The Real-Time Control Module also sends these Initial Parameters to the HEMSs, prompting them to fully curtail PV production. After the initialisation, the LEOS connects with the Substation Transformer and requests a Status Report information object. Similar requests are made to the HEMS and the Energy Centre Inverter. The contents of the information object Status Report should be adjusted based on the components selected for the system, it is not fully detailed in this study. In principle, it should at least include power flow measurements and assessment of available capacity for the DERs. Each HEMS reports on the status of energy resources on the household premises, including solar PV, BES systems and possibly also connected EVs, if smart charging or vehicle-to-grid are utilised. The Energy Centre in turn reports on the status of energy resources it manages.

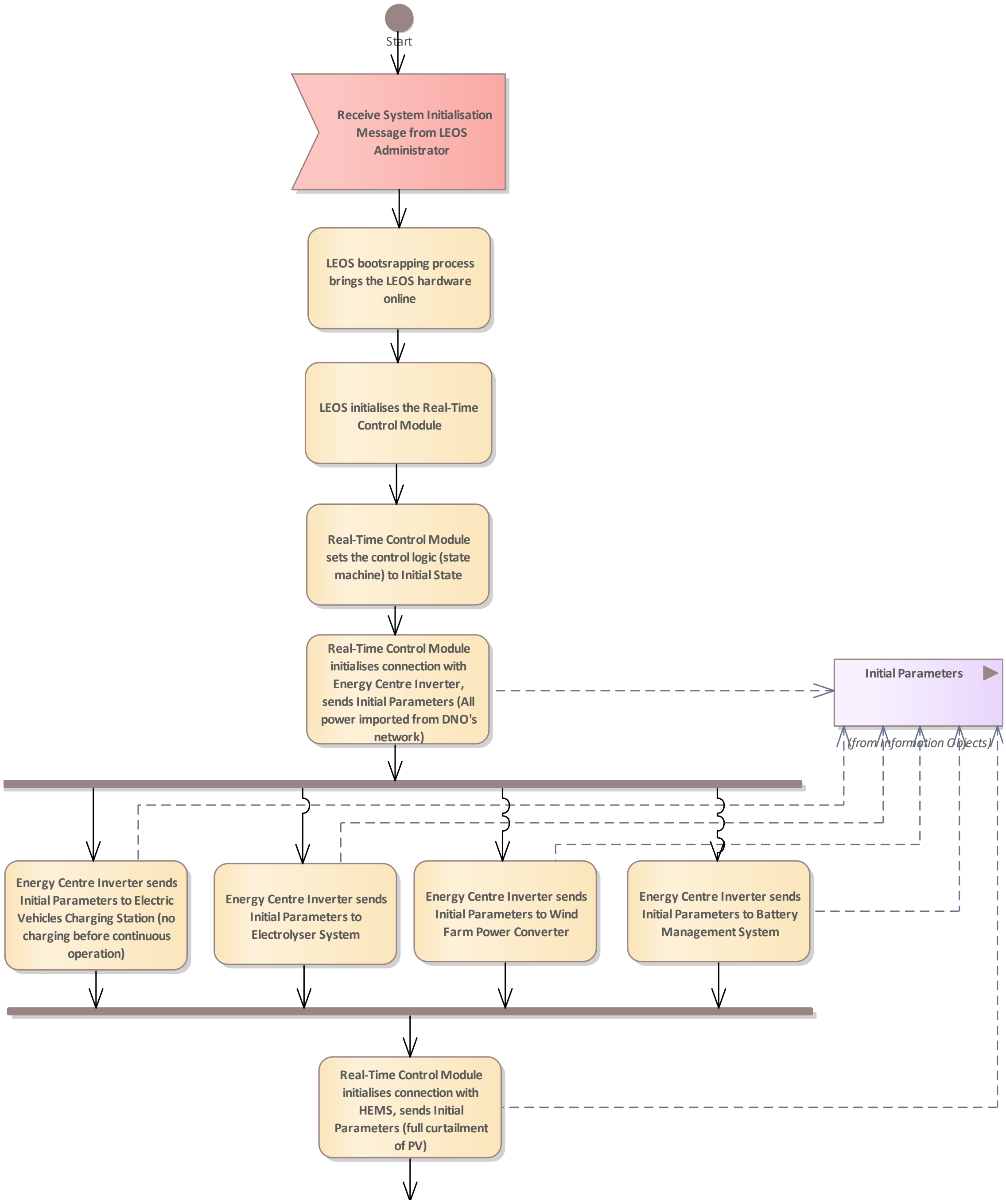

Figure 17 *Activity Diagram - Initialise the System (part 1/4).*

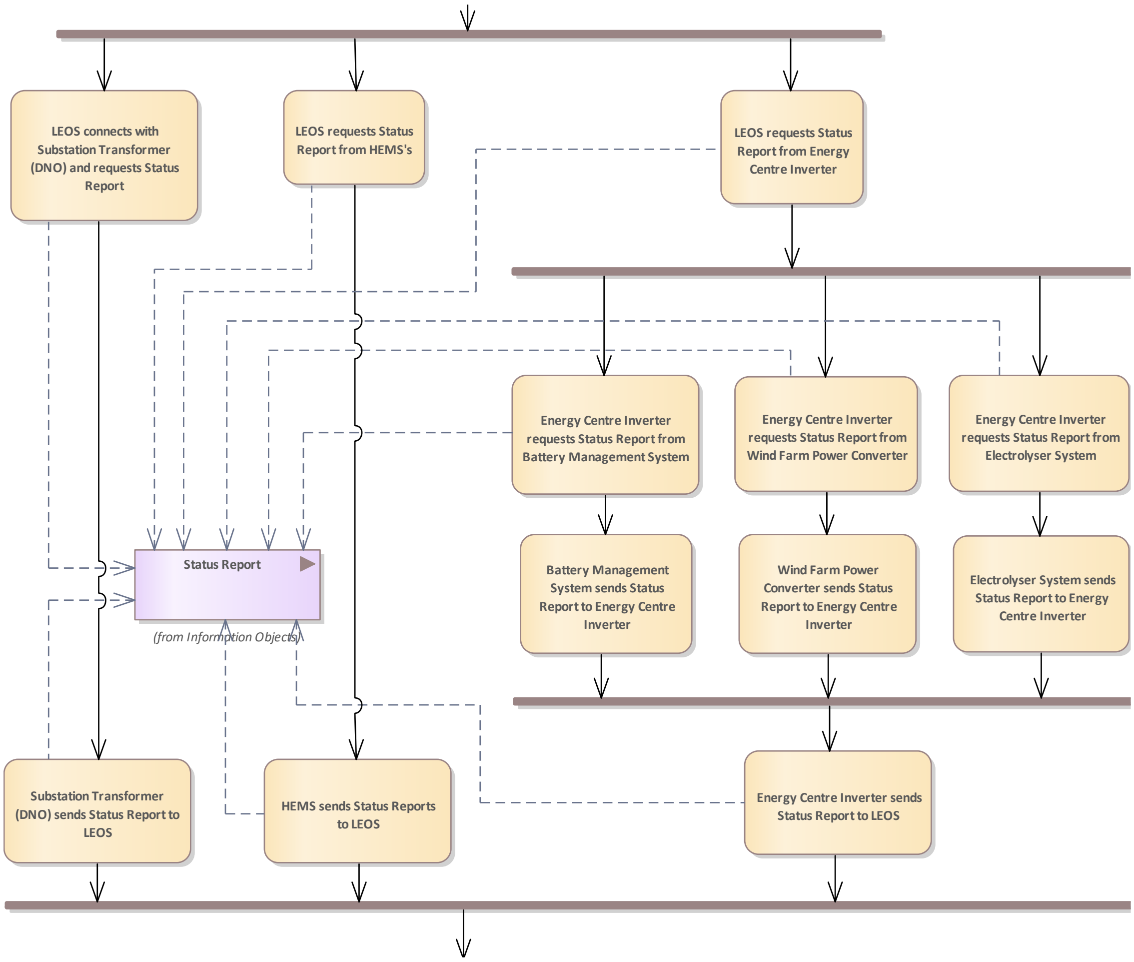

Figure 18 *Activity Diagram - Initialise the System (part 2/4).*

Continuing in the Figure 19 and Figure 20, we see that upon receiving the Status Reports, the LEOS calculates System Status. This represents the frequency, generation, demand, and available reserve generation and storage capacity in the system. The System Status can also contain measurements of the voltages, currents and power factors measured in different feeders in the network. The System State is used by the Real-Time Control Module to position the control logic at the correct System State. The Real-Time Control Module then sends State Change Instructions to the Energy Centre Inverter, which instructs connected energy resources to adjust generation or storage accordingly. The Real-Time Control Module also sends general Load and Generation Management Instructions to the HEMSs. The LEOS then queries the HEMSs for the User Preferences set by the households and instructs the Economic Optimisation Module to calculate an Optimum Economic Dispatch Plan, which takes into account the updated HEMS User Preferences. The use case Calculate Optimum Economic Dispatch is presented in detail in the section 4.5.6. After the Optimum Economic Dispatch Plan has been calculated, the Real-Time Control Module compares it to the current control logic System State and sends updated instructions to the HEMSs and the Energy Centre Inverter. At this point all processes needed for the normal operation of the South Cornelly LEM system are in place and running.

The LEOS initialisation can be considered to consist of three phases. The first phase includes the start-up of hardware, establishing connections between sub-systems, sending Initial Parameters to all sub-systems to reset each to default start-up settings, and acquiring Status Reports. The section 4.5.7 details the use case Maintain System Real Time Control and the state machine which contains the system control logic. The Initial Parameters sent to all sub-systems follow this control logic. Thus, the system initialisation always starts with all energy resources being disconnected, with the consumption fully covered by power imported from the DNO MV network. The second phase starts, when the Real-Time Control Module has received the System Status from LEOS and begins sending State Change Instructions to other sub-systems according to where the System Status places the system in the control logic. This is the phase when system energy resources start to be connected to the LV network. The third phase starts, when the Economic Optimisation Module has completed calculating the Optimum Economic Dispatch plan. This can be considered as the normal operating mode of the system, where the System State is updated continuously and compared to the Optimum Economic Dispatch plan to find the most optimal dispatch of resources within the limits of the System State. This process is repeated continuously during the normal operation of the system and is detailed in the sections 4.5.7 and 4.5.6. If something goes wrong in during the system initialisation process, the system does not move to the next phase of operation before the problem has been solved. If a problem emerges in the first phase, the system will continue importing all power from the DNO network. If a problem emerges in the second phase, the system will continue operations according to the control logic but is unable to perform economic optimisation.

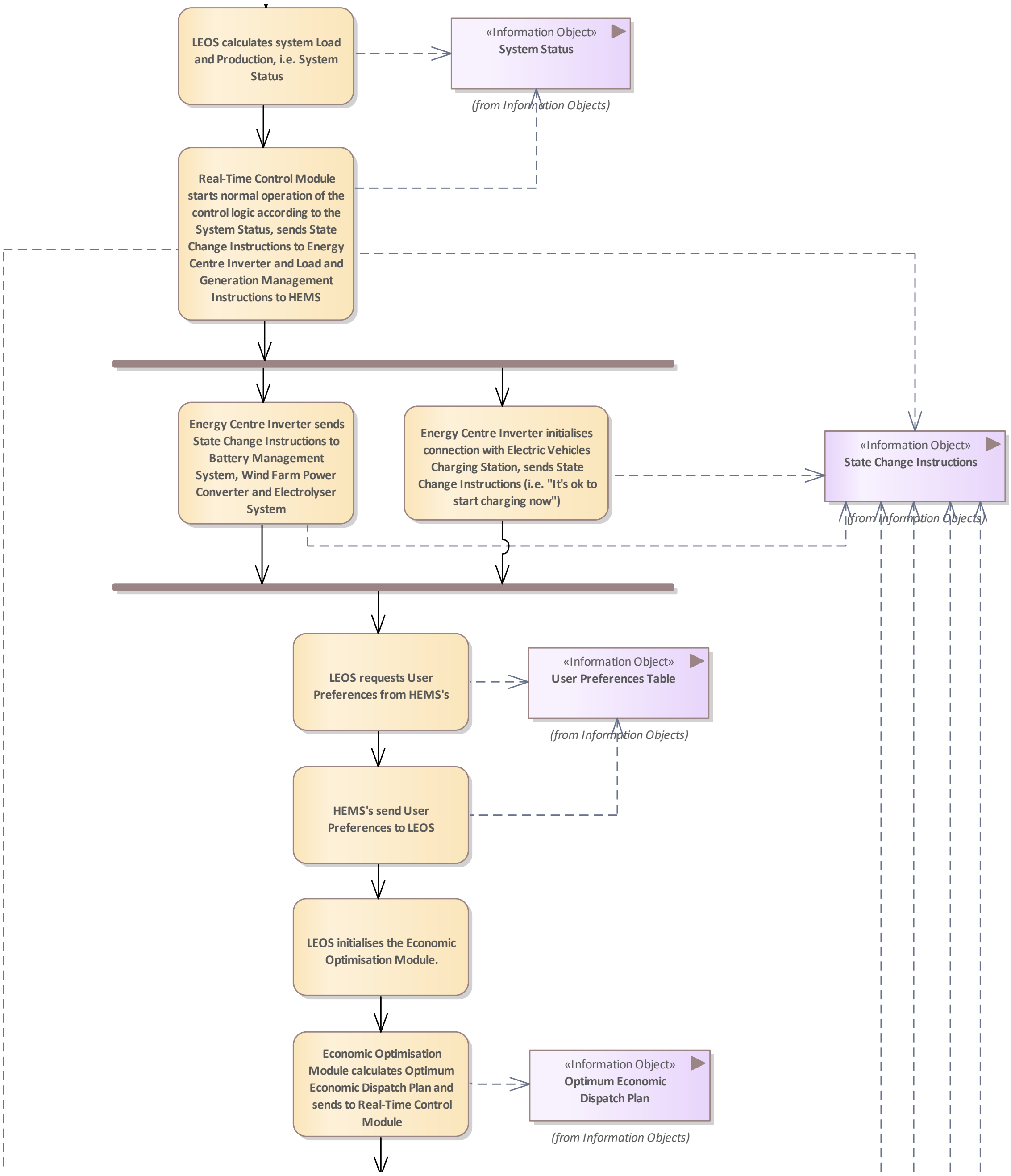

Figure 19 *Activity Diagram - Initialise the System (part 3/4).*

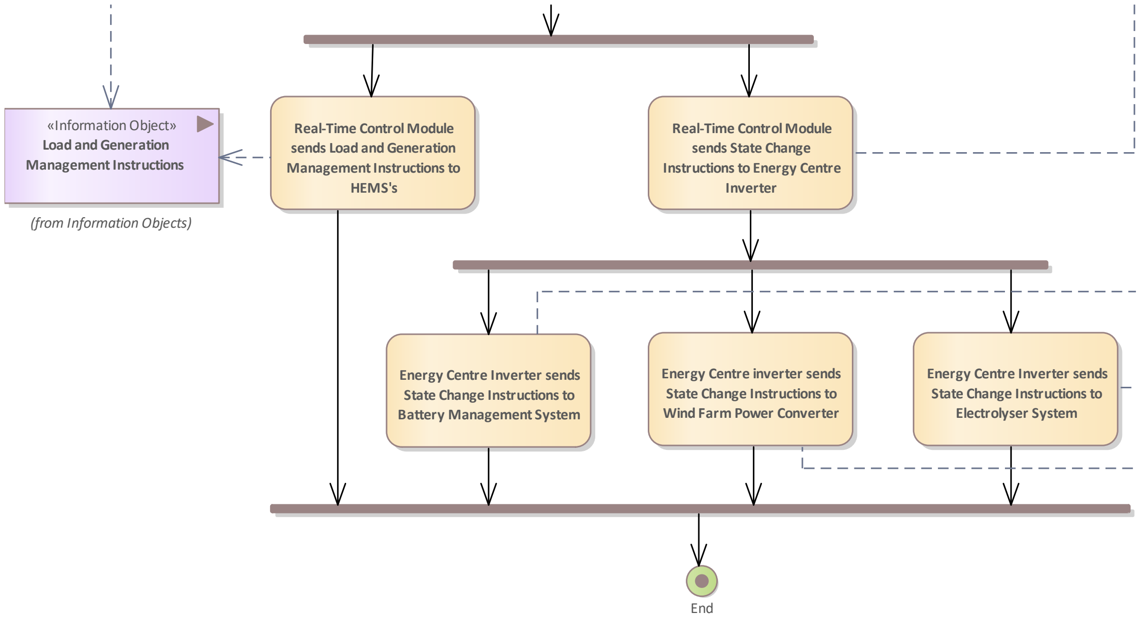

Figure 20 *Activity Diagram - Initialise the System (part 4/4).*

4.5.2 PUC – Request Market Data

As the use case Request Market Data is very similar to the use case Request Weather Data, only one of them is described here. The diagrams for the use case Request Weather Data can be found in the Appendix section. The actors and involved in the use case are presented in the Figure 21, alongside relations to other use cases.

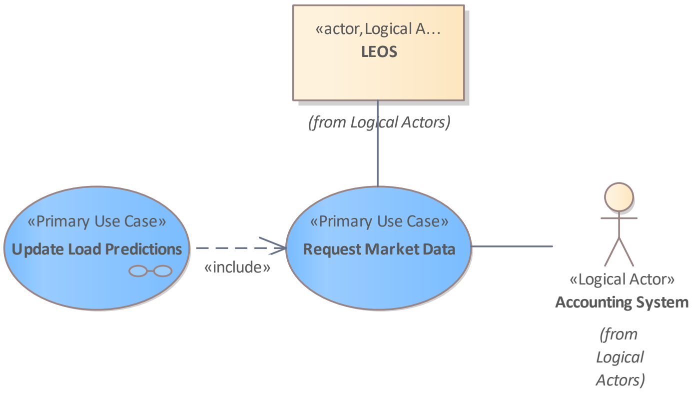

Figure 21 *PUC - Request Market Data.*

The use case is included in another use case Update Load Predictions. The use case is initialised by the LEOS, which requests a Market Data Table from the Accounting System. The Accounting System then sends LEOS the required table. This process is represented in the Figure 22 and Figure 23. Although the specific operation of the Accounting System is not the focus of this thesis, it is assumed that the Accounting System autonomously updates the Market Data Table utilising one or more market data providers.

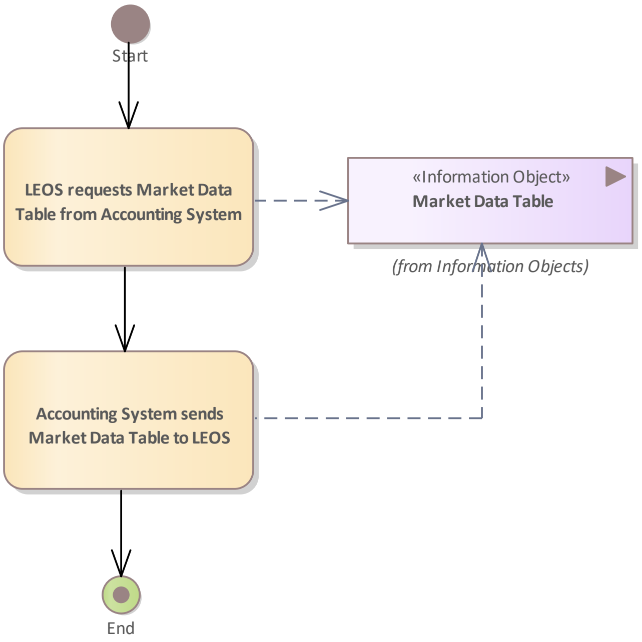

Figure 22 *Activity Diagram - Request Market Data.*

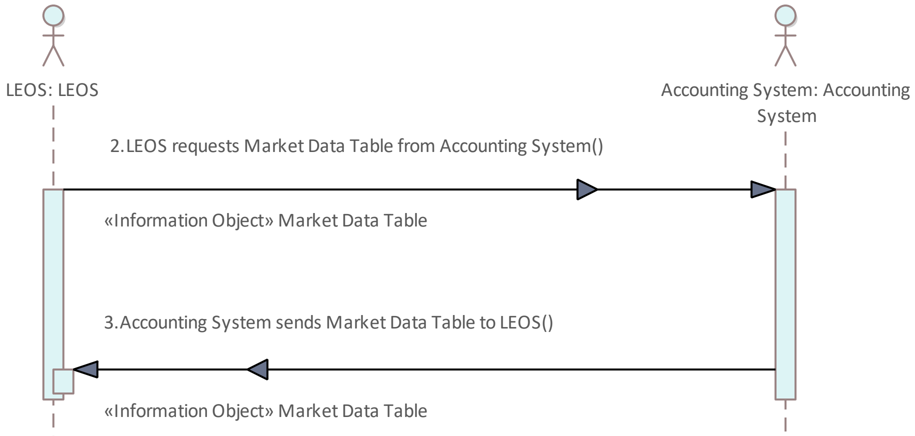

Figure 23 *Sequence Diagram - Request Market Data.*

4.5.3 PUC – Update Load Predictions

The LEOS is responsible for regularly updating the hour-ahead and day-ahead predictions for demand and production in the system, to provide estimates needed in the optimal scheduling of the system energy resources. This process is represented in the use case Update Load Predictions. The operations are carried out by the LEOS, prompted by either the System Timer or a HEMS system. Relations to other use cases are depicted in the Figure 24.

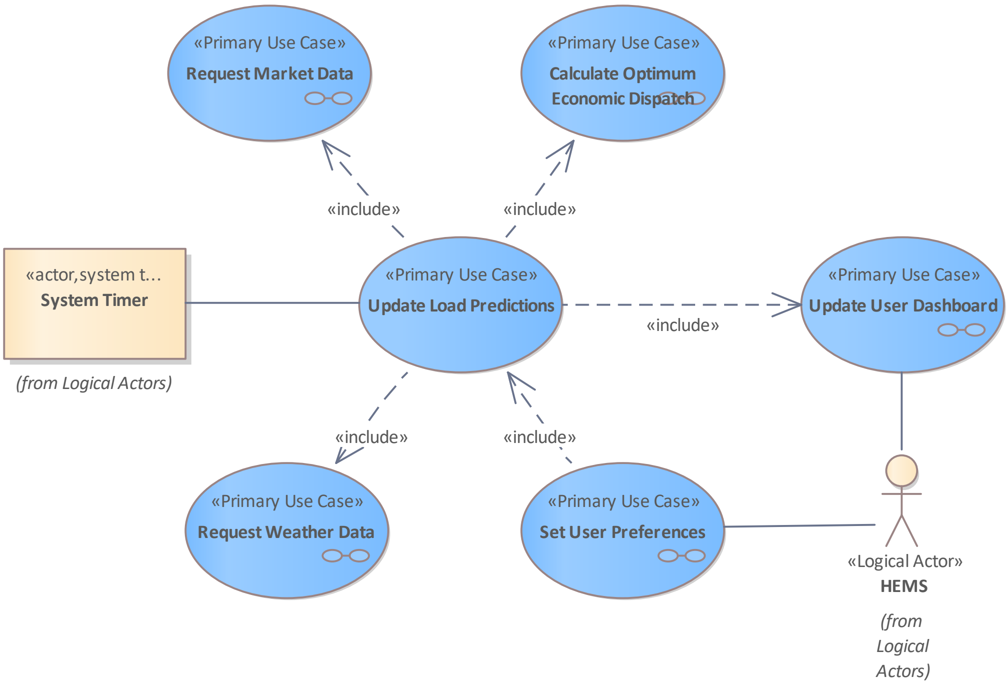

Figure 24 *PUC - Update Load Predictions.*

As shown in the Figure 25 and Figure 26, the updating the Load Predictions can either start with System Timer requesting an update from the LEOS or when a HEMS sends updated User Preferences to the LEOS. The LEOS then queries Weather and Market Data Tables and updates the newly received User Preferences in the Aggregated User Preferences. Next, the LEOS calculates the Next Hour Load Predictions and the Day Ahead Hourly Load Predictions. These calculations involve deriving household load profiles based on the weather and market data, and the aggregated user preferences. These calculations could be extended with the inclusion of stochastic or empirical models for household demand, but these or the exact algorithms used in the calculations are out of the scope of this thesis. These calculations could also be partly shared with the HEMSs, which could gather behavioural data from the household consumption and create demand predictions at the household level. However, as the exact abilities of the HEMSs are unknown in the studied scenario, for the sake of system robustness, it is assumed that the HEMSs lack this capability.

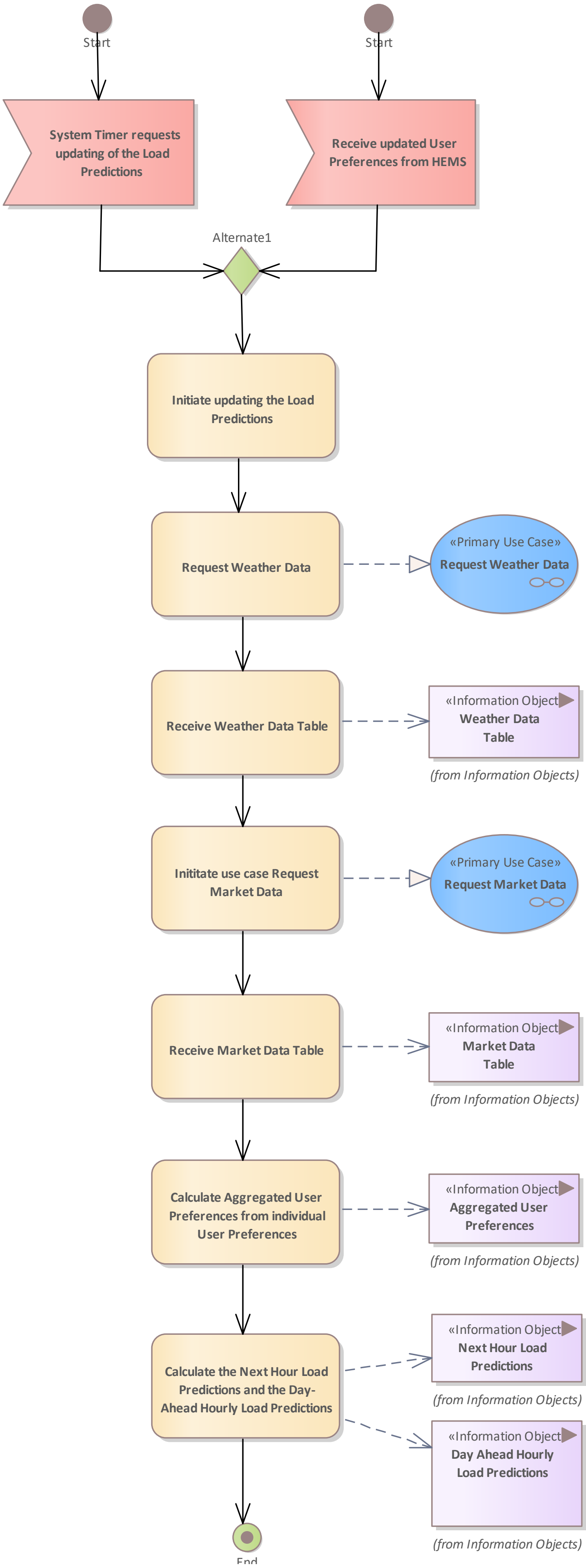

***Figure 25** Activity Diagram - Update Load Predictions.*

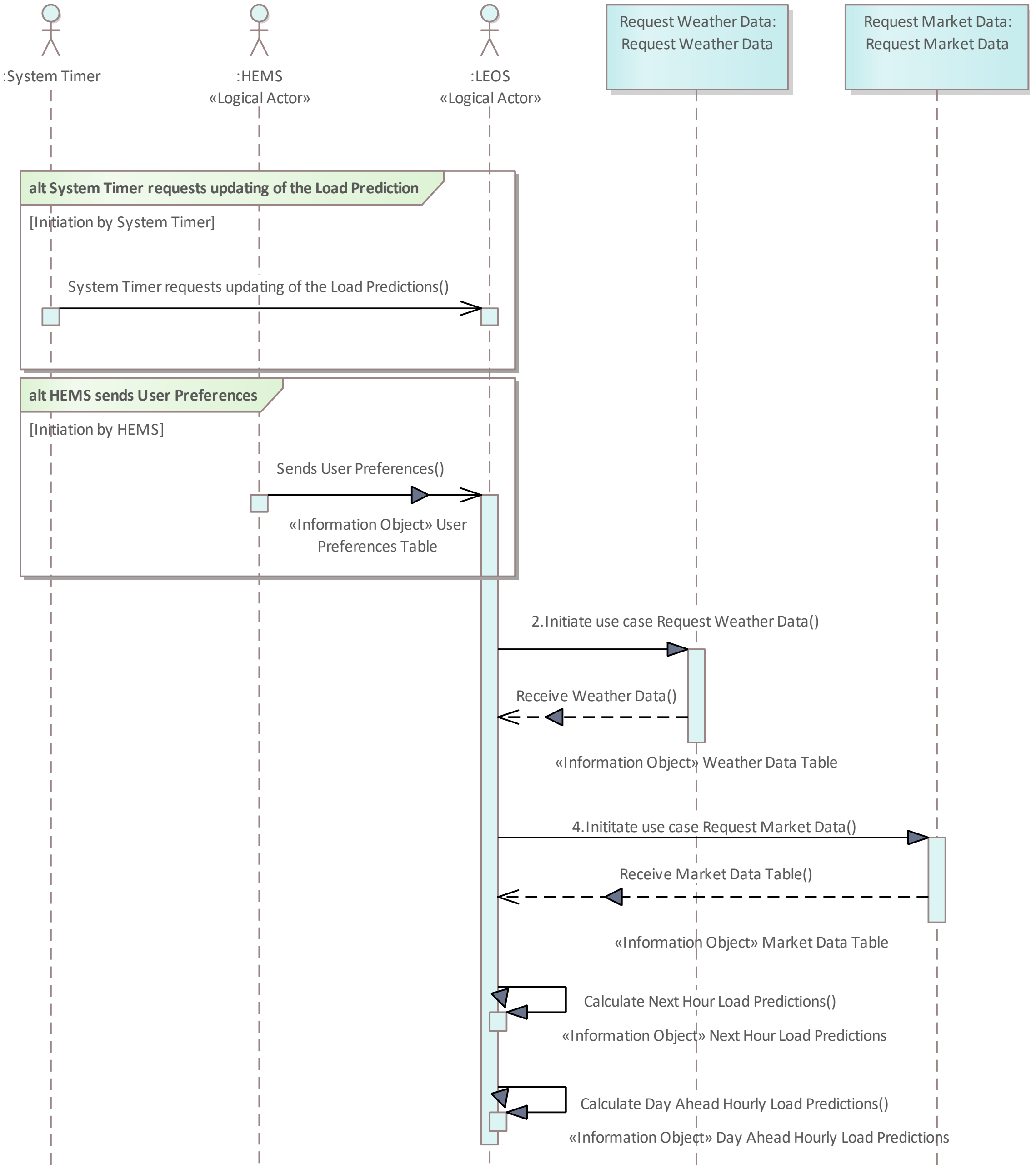

Figure 26 *Sequence Diagram - Update Load Predictions.*

4.5.4 PUC – Update User Dashboard

The HEMS provides the household an interface to visualise various system variables and user data, such as consumption history or solar PV output. This interface also allows the user to change preferences according to the load predictions and possible pricing mechanisms defined in the LEM, such as TOU. This interface, the User Dashboard, receives the up-to-date User Dashboard Data from the LEOS, which updates this information every time the Load Predictions change. The use case Update User Dashboard describes this process and is depicted in the Figure 27.

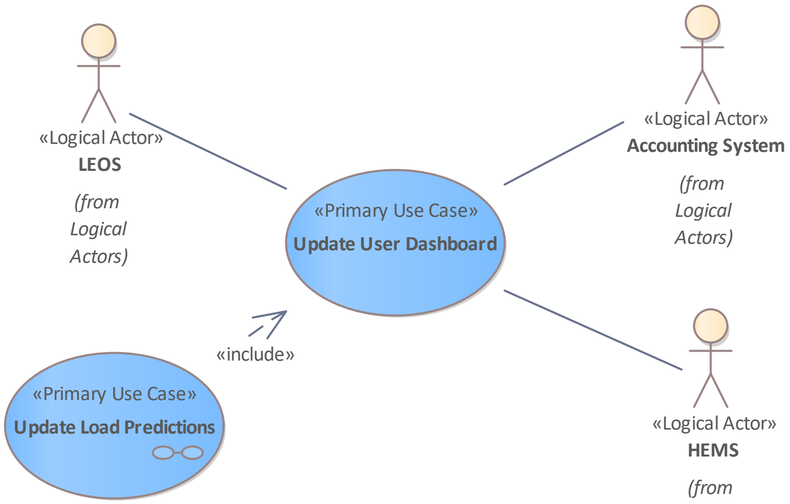

Figure 27 *PUC - Update User Dashboard.*

The updating of the User Dashboard begins with the LEOS querying Accounting Data for the household from the Accounting System. Next the LEOS uses the Accounting Data and the Optimum Economic Dispatch Plan to derive an Hourly Household Electricity Price Table, which is included in User Dashboard Data. The LEOS then sends the User Dashboard Data to the HEMS. This process is presented in the Figure 28 and Figure 29.

As the studied scenario does not take a stance on the possible ownership structure of system assets, such as the rooftop solar PV or BES systems, this thesis is unable to cover specific pricing schemes for electricity. The purpose of the User Dashboard in the HEMS is to give the households a visualisation of how the price is forecasted to evolve in time. This implies some form of time of use pricing, with the goal of guiding household behaviour towards an economically optimal consumption with price incentives. But, without a decision on the ownership and economic structure of the energy community, it is not possible to specify a detailed pricing scheme. Various options exist; the pricing may be community wide, with everyone paying the same price. Or the price might vary based on the available energy resources, such as solar PV, BES systems and even EVs on the household premises. The price paid by the community as a whole would include for example the retail electricity purchased from the Licensed Supplier, the Distribution use of System charges paid to the DNO and the marginal and maintenance costs of the community assets. However, there are many ways of dividing the total expenses among the households. Some individual households might see a subsidised price rather than the full price and some others might pay extra in compensation for particularly high consumption. In any case, price incentives can be viewed as one method of control imposed by the LEOS on the HEMS, albeit one that the households may opt to ignore. Ideally, the households can adjust how strongly the HEMS reacts to the price signals. As an example, the users might set a general rule for the HEMS to turn off water heating when the electricity price exceeds a pre-defined limit. But the users would still be able to bypass this rule if they want to. Therefore, it is important to make a distinction between the economic optimisation and the system real time control, which is introduced in the section 4.5.7. The real time control is not based on price signals, but on direct control signals from the LEOS, that the users cannot override. These include limits on solar PV production and adjustments of BES system charging and discharging.

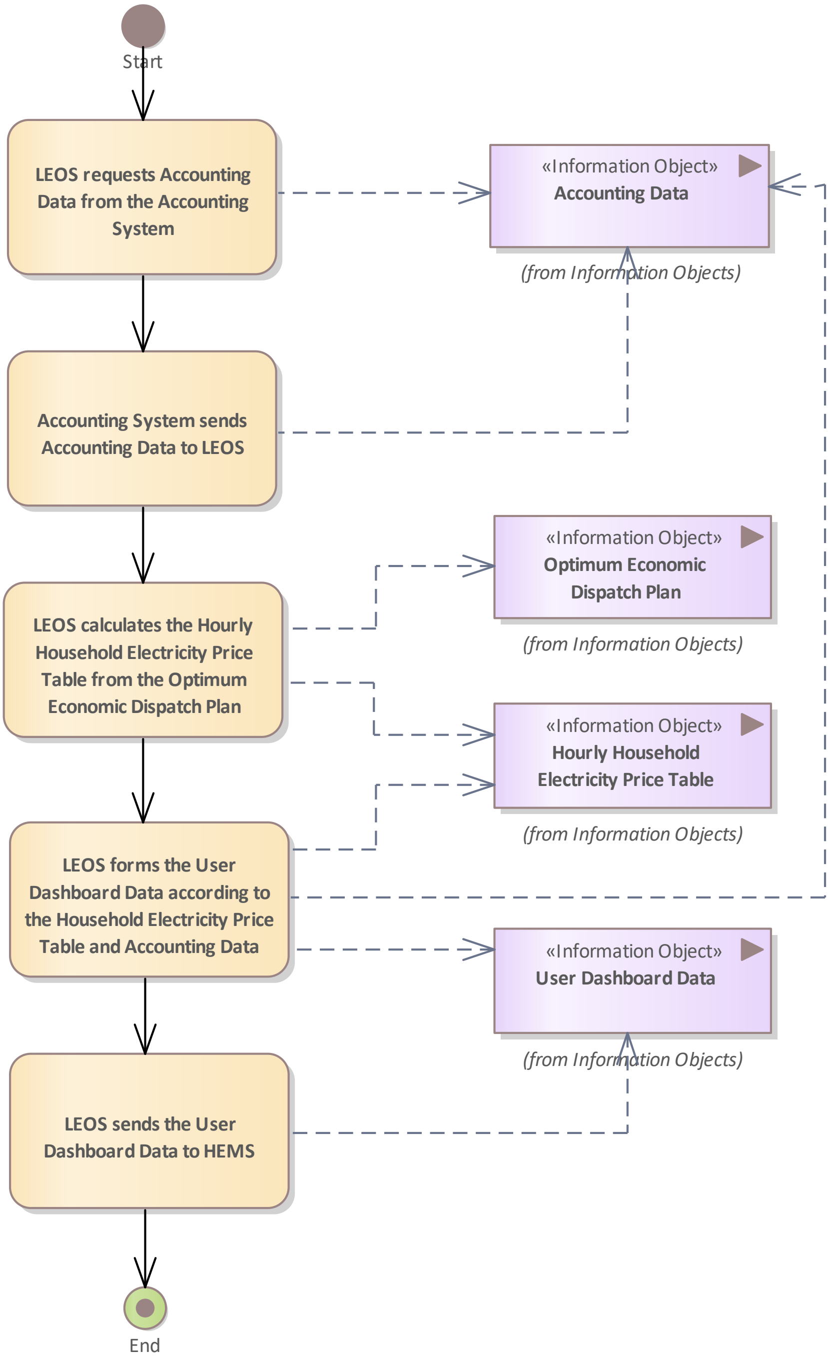

Figure 28 *Activity Diagram - Update User Dashboard.*

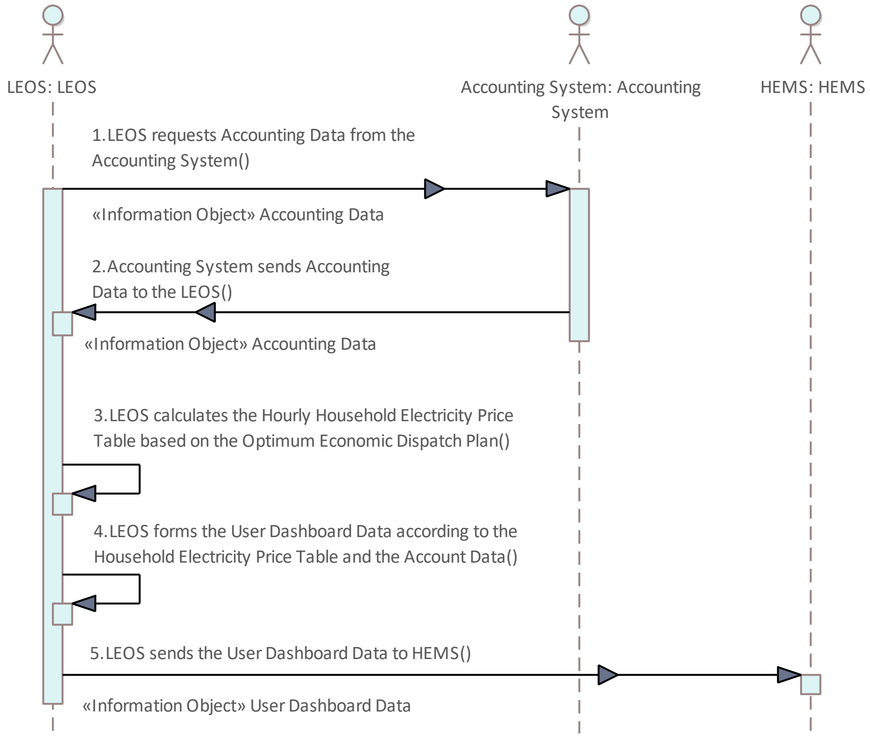

Figure 29 *Sequence Diagram - Update User Dashboard.*

4.5.5 PUC – Set User Preferences

When a household wants to adjust the HEMS User Preferences, such as the scheduling of controllable household loads, the household can access and change these preferences via the User Dashboard interface of the HEMS. The HEMS then sends the updated User Preferences to the LEOS. This process is described in the Figure 30, Figure 31 and Figure 32. As discussed in the section 4.5.3, sending updated User Preferences also invokes the updating of Load Predictions.

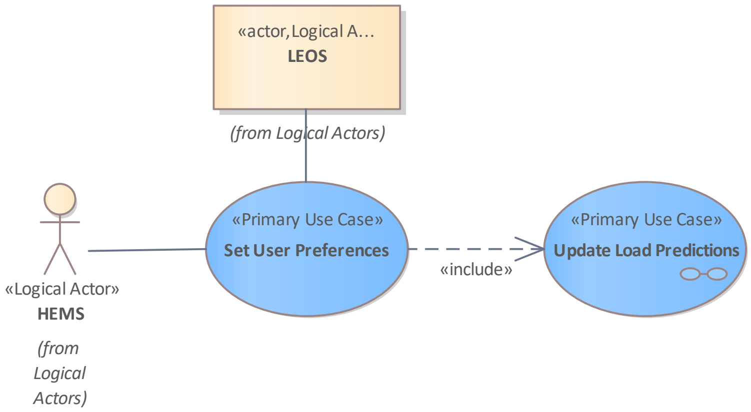

Figure 30 *PUC - Set User Preferences*

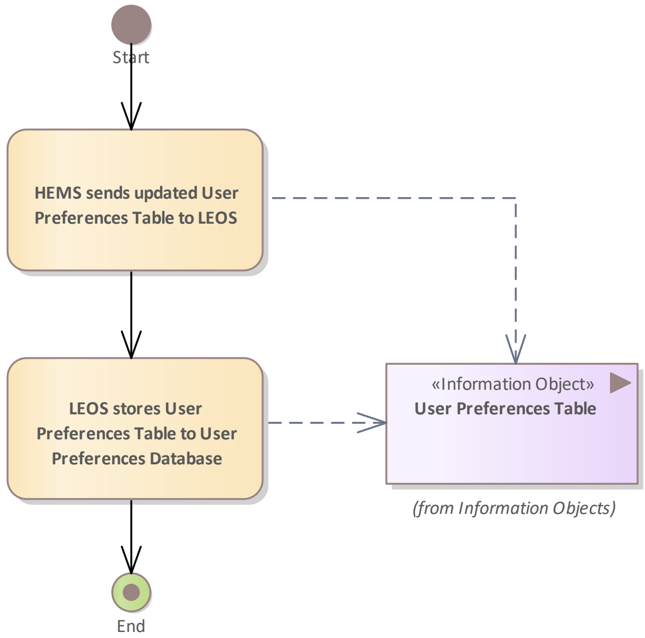

Figure 31 *Activity Diagram - Set User Preferences.*

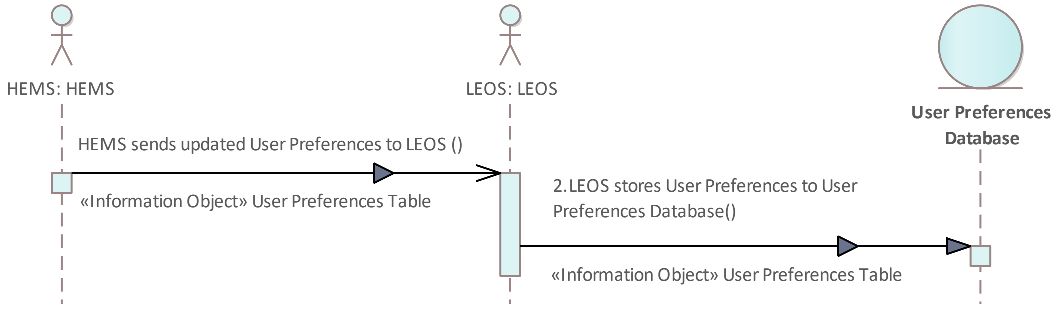

Figure 32 *Sequence Diagram - Set User Preferences.*

4.5.6 PUC – Calculate Optimum Economic Dispatch

When the system Load Predictions are updated, also the Optimum Economic Dispatch Plan requires adjustment. This use case Calculate Optimum Economic Dispatch is presented in the Figure 33. It is initiated by the LEOS and the calculations are performed by the Economic Optimisation Module. It is a sub-system of the LEOS, similar to the Real-Time Control Module. As this thesis is kept at a platform and computation independent level, the economic optimisation algorithms are not further detailed here. However, the information objects involved are defined, as shown in the Figure 34 and Figure 35. The LEOS sends the Weather Data Table, Market Data Table, Next Hour Load Predictions, Day Ahead Hourly Load Predictions, and the Aggregated User Preferences to the Economic Optimisation Module. The Economic Optimisation Module then derives an Optimum Economic Dispatch Plan and sends it to the LEOS.

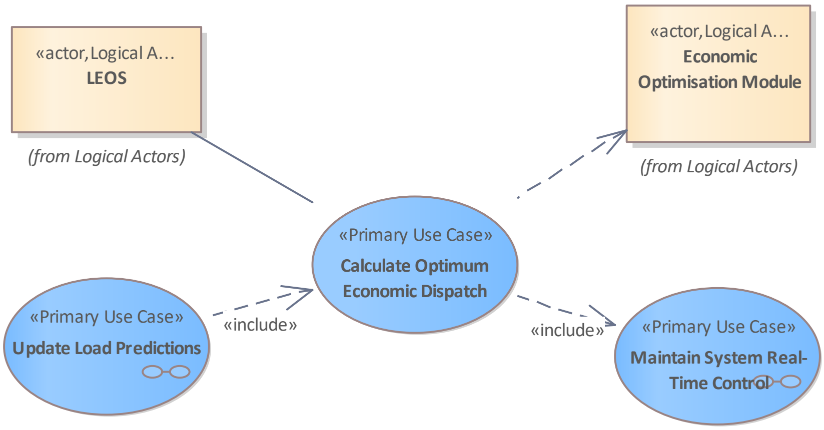

Figure 33 *PUC – Calculate Optimum Economic Dispatch.*

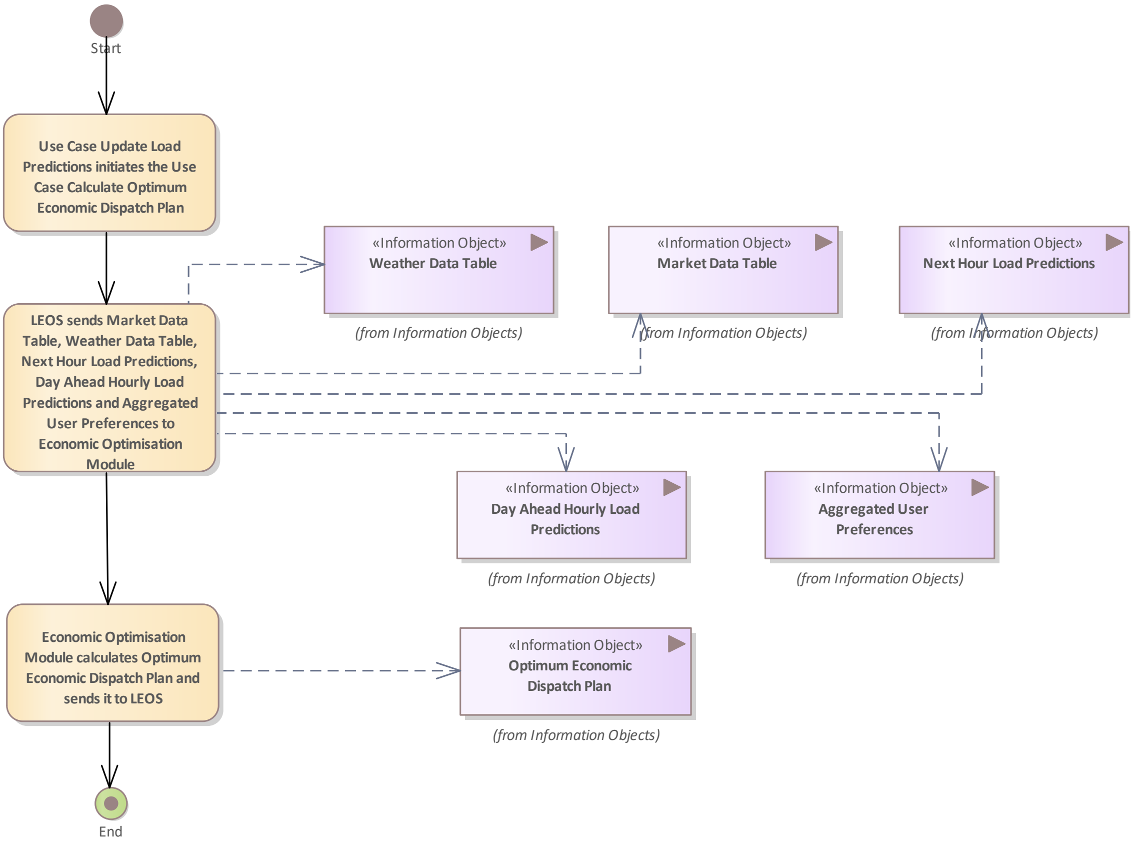

Figure 34 *Activity Diagram – Calculate Optimum Economic Dispatch.*

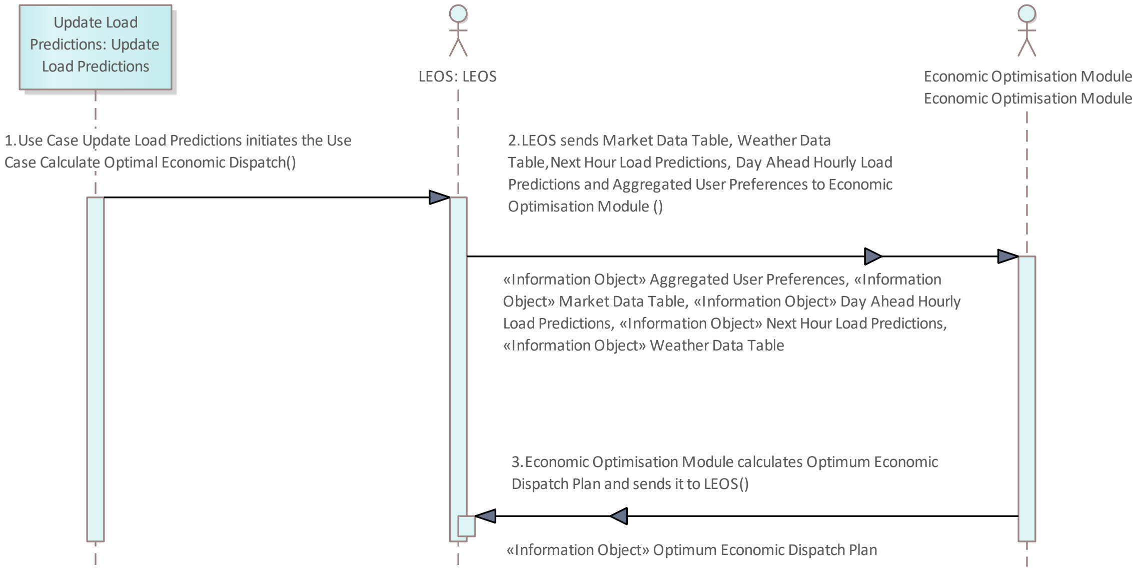

Figure 35 *Sequence Diagram - Calculate Optimum Economic Dispatch.*

4.5.7 PUC – Maintain System Real Time Control

The real-time management of power flows in the South Cornelly LV network is performed by the Real-Time Control Module, a sub-system of the LEOS. It sends control signals to system energy resources, scheduling them based on a combination of the Optimum Economic Dispatch Plan and a real-time control logic, which keeps the system within its physical power quality limits. The control logic always takes priority over the economic dispatch, and the latter is executed to the extent possible within the physical limits present at any given System State. Given the scenario set out in the section 4.1, the BES is charged only with PV and wind generation, not with electricity imported from the MV network. The control logic can be extended with additional states if a scenario with more external market interaction is explored. Additional guards linked to the Optimum Economic Dispatch Plan, specifically to the external electricity prices, should be also included in that case. The control logic depicted here prioritises the charging of the BES over the Electrolyser. Thus, the Electrolyser is only utilised when the BES state of charge is already at 100% or if the BES is being charged at nominal rate and more charging power cannot be applied.

The System States depict every possible state of balance allowed for the system in terms of demand and power flows from different DERs and the MV network. A total of 29 System States have been identified, each state is labelled according to the energy resourced utilised in the state. These are depicted in a State Machine Diagram, split into parts in Figure 36 to Figure 45 and shown as a whole in the Appendix, in the Figure 78. For each System State, all possible transitions to other states and the guard conditions for each transition are shown in the State Machine Diagram. In principle, all System States with the exception of the emergency state Risk of overvoltage, have one trigger guard condition leading to the state. Each System State defines the generation flows present in the LV network in that state. In System States where power is imported from the MV network, that imported power is used to bring the total generation to a balance with the load. In the System States, where no power is imported from the MV network, the LV network load is matched by the DERs available to the South Cornelly LEM. For each state, where power flows into or from the Energy Centre, the values of these power flows are presented in the State Machine Diagram as variables, abbreviated var. This abbreviation is not to be confused with the unit of reactive power volt-ampere reactive (var). These variables detail the amount of active power exported or imported by the Energy Centre Inverter between the South Cornelly LV network and the Energy Centre. They also show the amount of power imported from the local wind farm via the Wind Farm Power Converter, denoted as converter in the diagram. The amounts of active power generated or absorbed by the Energy Centre energy resources are also shown as variables in the System States. The Real-Time Control Module transmits the power flow values specified in the System State to the HEMSs and the Energy Centre Inverter, which in turn adjust the reference values of the DERs controlled by them.

The Figure 36 depicts the initial state of the State Machine Diagram, Network Import. This the state the system always starts in. As detailed in the section 4.5.1, during the initial state all the South Cornelly LV demand is covered by imported electricity from the MV Network. The subsequent states are introduced in Table 8 to Table 17 and the respective excerpts of the State Machine Diagram in Figure 36 to Figure 45. Some of the states contain sub-states, which have transitions between each other. In general, all of these sub-states will also transition back to the outer state and to the states linked to the outer state, when the respective trigger guards are met.

Table 8 *System States 1/10.*

State Name & Trigger Guards	**Power Flows Description**	**Transitions In From**	**Transitions Out To**
Network Import PV=0, Wind=0, SoC=0	Initial state of the system. All demand covered by imports from the MV network.	System initialisation Discharge Batteries Network Import + PV Network Import + Wind Network Import + PV + Wind	Discharge Batteries Network Import + PV Network Import + Wind Network Import + PV + Wind
Discharge Batteries PV=0, Wind=0, SoC>0	As long as battery charge available, demand covered by discharging batteries.	Network Import	Network Import

Network Import + PV 0<PV<Load, Wind=0, SoC=0	All available solar PV generation utilised. Supplemented by MV network imports.	Network Import Network + PV + Wind PV PV + Discharge Batteries	Network Import Network + PV + Wind PV

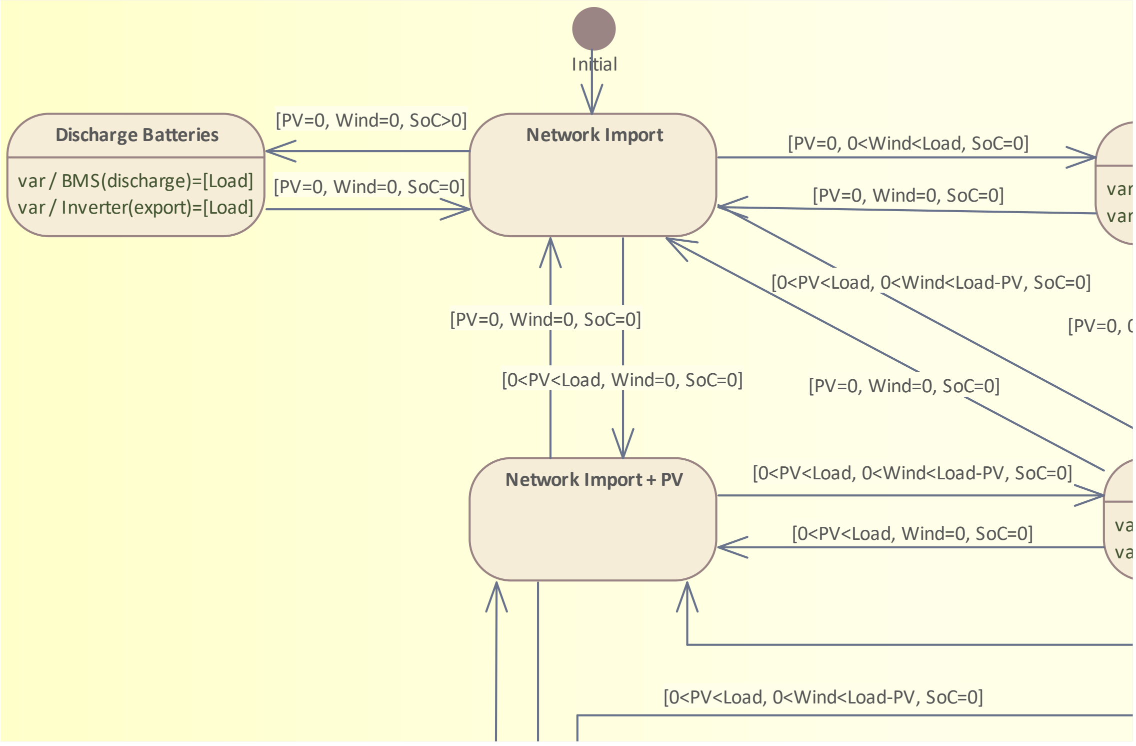

Figure 36 System States - State Machine Diagram 1/10.

Shown in the Figure 37, if wind generation is available from the local Wind Farm, the system transitions to the state Network Import + Wind. Wind power is imported via the Wind Farm Power Converter and exported to the LV network from the Energy Centre. If wind generation drops back to zero, the system transitions back to the state Network Import.

Table 9 *System States 2/10.*

State Name & Trigger Guards	Power Flows Description	Transitions In From	Transitions Out To
Network Import + Wind PV=0, 0<Wind<Load, SoC=0	All available wind generation from the local wind farm imported via the Wind Farm Power Converter. Supplemented by MV network imports.	Network Import Network + PV + Wind Wind Wind + Discharge Batteries	Network Import Network + PV + Wind Wind
Wind PV=0, Wind=Load, SoC=0	Wind generation exported via the Wind Farm Power Converter covers all demand.	Network Import + Wind PV + Wind Wind + Discharge Batteries	Network Import + Wind PV + Wind Wind + Charge Batteries

Network + PV + Wind 0<PV<Load, 0<Wind<Load-PV, SoC=0	All available wind generation from the local wind farm imported via the Wind Farm Power Converter. All available PV generation utilised. Supplemented by MV network imports.	Network Import Network Import + PV Network Import + Wind PV + Wind PV	Network Import Network Import + PV Network Import + Wind PV + Wind PV
PV + Wind PV + Wind = Load, SoC = 0	All available PV generation utilised. Supplemented by wind generation from the local windfarm imported via the Wind Farm Power Converter.	Network + PV + Wind Wind Wind + Charge Batteries PV	Network + PV + Wind Wind Wind + Charge Batteries PV

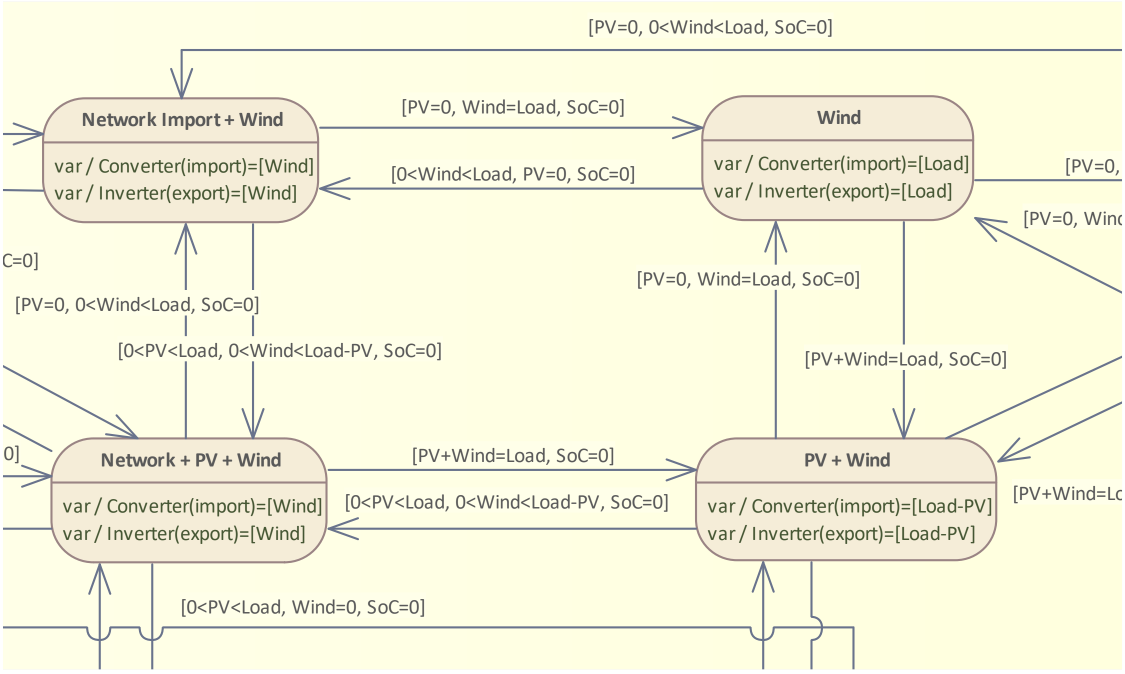

Figure 37 *System States - State Machine Diagram 2/10.*

Table 10 *System States 3/10.*

State Name & Trigger Guards	**Power Flows Description**	**Transitions In From**	**Transitions Out To**
Wind + Charge Batteries + Electrolyser PV=0, Wind>Load, SoC<100	Available wind generation significantly exceeds demand. BES charged at nominal rate. Excess generation used by Electrolysers.	Wind + Charge Batteries Wind + Electrolyser	Wind + Charge Batteries Wind + Electrolyser
Wind + Charge Batteries PV=0, Wind>Load, SoC<100	Available wind generation exceeds demand. Excess generation used to charge BES.	Wind PV + Wind Wind + Charge Batteries + Electrolyser Wind + Discharge Batteries	Wind + Charge Batteries + Electrolyser Wind + Electrolyser PV + Wind Wind + Discharge Batteries

Wind + Electrolyser PV=0, Wind>Load, SoC=100	Available wind generation exceeds demand. BES state of charge at 100%. Excess generation used by Electrolysers.	Wind + Charge Batteries + Electrolyser Wind + Charge Batteries PV + Wind + Electrolyser Risk of overvoltage	PV + Wind + Electrolyser Wind + Discharge Batteries Risk of overvoltage
Wind + Discharge Batteries PV=0, 0<Wind<Load, SoC>0	All available wind generation imported. The rest of the demand covered by discharging BES.	Wind + Charge Batteries Wind + Electrolyser PV + Wind + Electrolyser PV + Wind + Charge Batteries	Wind + Charge Batteries Network Import + Wind Wind

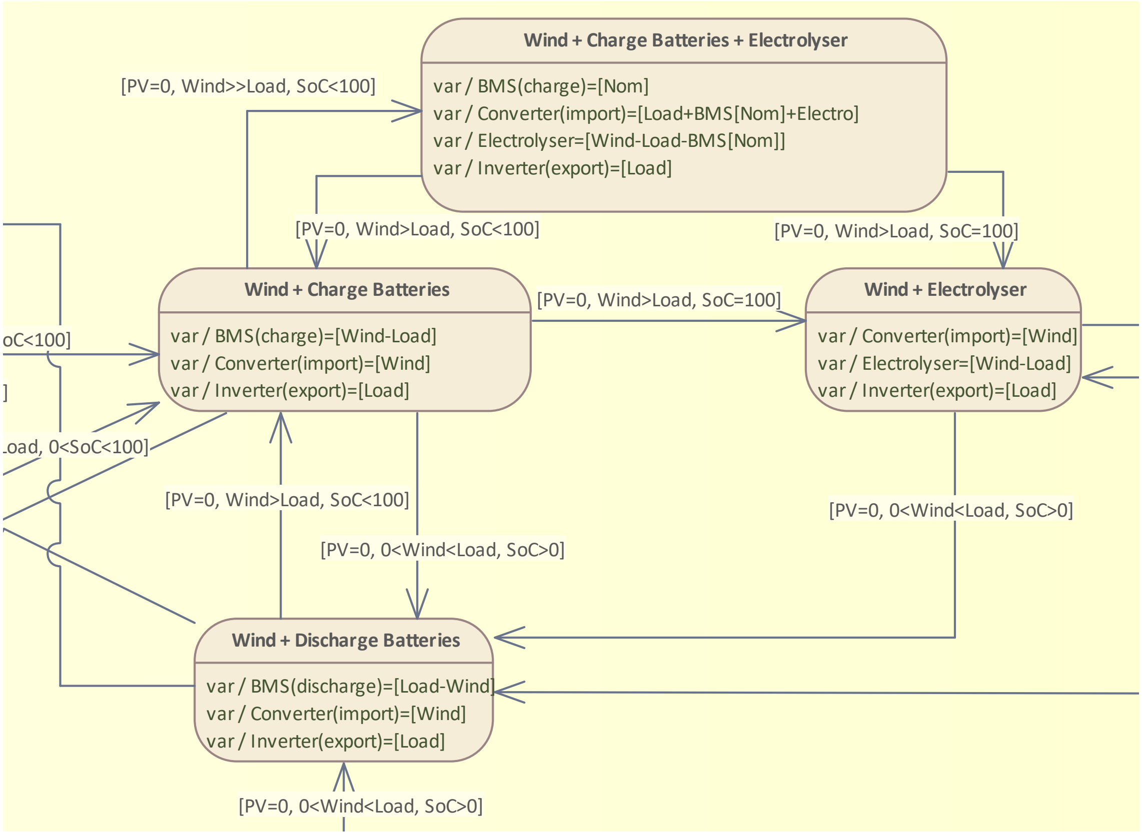

Figure 38 *System States - State Machine Diagram 3/10.*

Table 11 *System States 4/10.*

State Name & Trigger Guards	**Power Flows Description**	**Transitions In From**	**Transitions Out To**
PV PV=Load, Wind=0, SoC=0	PV generation covers all demand.	Network Import + PV Network + PV + Wind PV + Wind PV + Charge Batteries	Network Import + PV Network + PV + Wind PV + Wind PV + Charge Batteries
PV + Charge Batteries PV>Load, Wind=0, 0<SoC<100	PV generation exceeds demand. Excess power used to charge BES.	PV PV + Wind + Discharge Batteries PV + Discharge Batteries PV + Charge Batteries + Electrolyser	PV PV + Wind + Discharge Batteries PV + Discharge Batteries PV + Electrolyser PV + Charge Batteries + Electrolyser

PV + Charge Batteries + Electrolyser PV>>Load, Wind=0, 0<SoC<100	PV generation significantly exceeds demand. BES is charged at nominal rate. Excess generation used by Electrolysers.	PV + Charge Batteries	PV + Charge Batteries PV + Discharge Batteries PV + Electrolyser

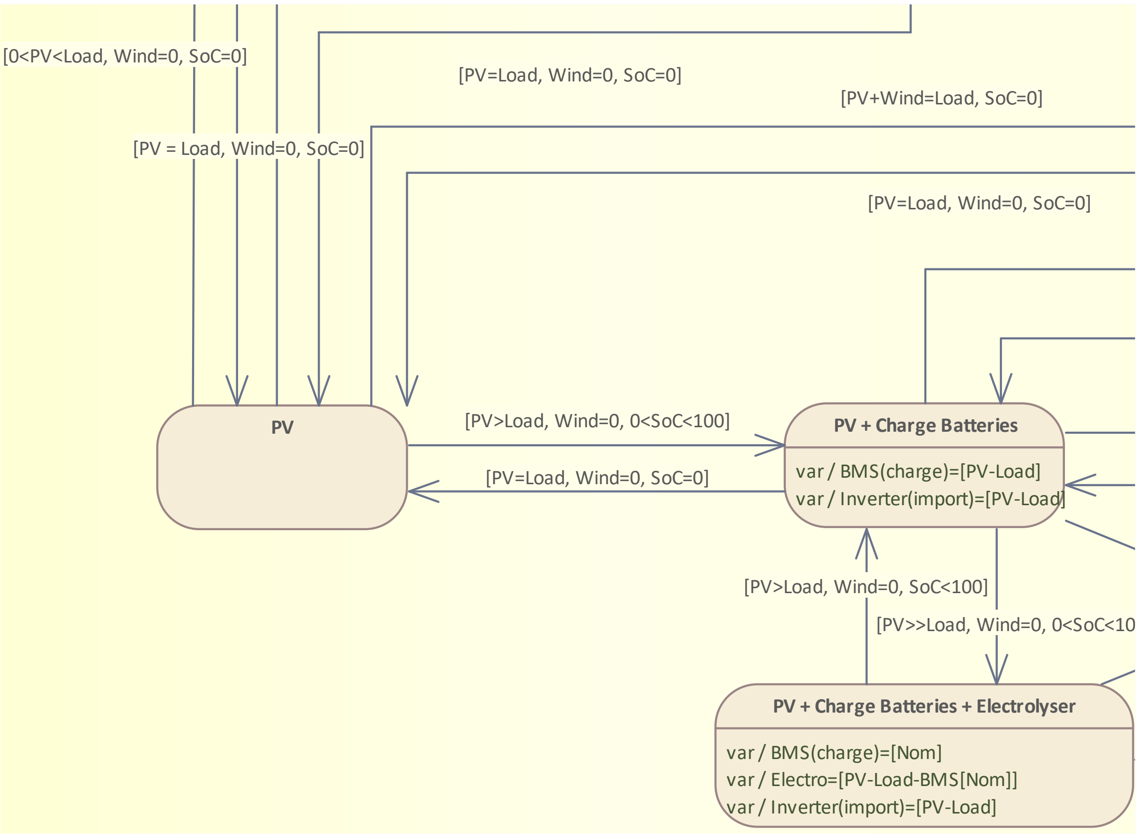

Figure 39 *System States - State Machine Diagram 4/10.*

Table 12 *System States 5/10.*

State Name & Trigger Guards	**Power Flows Description**	**Transitions In From**	**Transitions Out To**
PV + Discharge Batteries PV<Load, Wind=0, SoC>0	All available PV generation used. The rest of the demand covered by discharging BES.	PV + Charge Batteries PV + Charge Batteries + Electrolyser PV + Wind + Electrolyser PV + Wind + Charge Batteries PV + Wind + Discharge Batteries PV + Electrolyser	PV + Charge Batteries Network Import + PV PV + Wind + Discharge Batteries
PV + Wind + Discharge Batteries PV<Load, 0<Wind<Load-PV, SoC>0	All available PV generation. All available wind generation imported. The rest of the demand covered by discharging BES.	PV + Charge Batteries PV + Discharge Batteries PV + Wind + Electrolyser PV + Wind + Charge Batteries PV + Wind + Charge Batteries + Electrolyser (outer)	PV + Charge Batteries PV + Discharge Batteries PV + Wind + Charge Batteries

PV + Electrolyser PV>Load, Wind=0, SoC=100	PV generation exceeds demand. BES state of charge 100%. Excess generation used by Electrolyser.	PV + Charge Batteries PV + Charge Batteries + Electrolyser Risk of overvoltage	PV + Discharge Batteries PV + Electrolyser

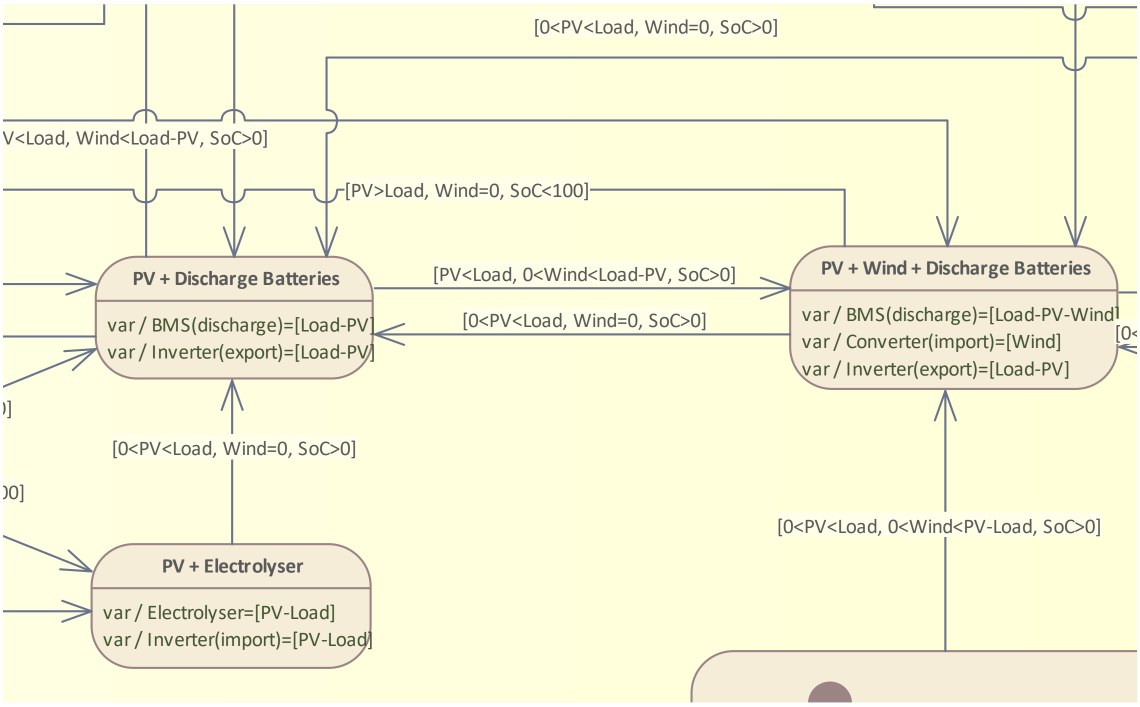

Figure 40 *System States - State Machine Diagram 5/10.*

Table 13 *System States 6/10.*

State Name & Trigger Guards	Power Flows Description	Transitions In From	Transitions Out To
PV + Wind + Charge Batteries (outer) PV+Wind>Load, SoC<100	Combined generation of PV and Wind exceeds demand. Excess generation is used to charge BES.	PV + Wind + Discharge Batteries PV + Wind + Charge Batteries + Electrolyser (outer)	PV + Wind + Discharge Batteries PV + Discharge Batteries Wind + Discharge Batteries PV + Wind + Electrolyser PV + Wind + Charge Batteries + Electrolyser
PV + Wind + Charge Batteries (inner) 0<PV<Load, Wind>Load-PV, SoC<100	Demand is higher than available PV generation. Wind generation exceeds the remaining demand. Excess wind generation is used to charge BES.	PV + Wind + Charge Batteries (outer) PV + Wind + Charge Batteries (significant PV)	Outer states PV + Wind + Charge Batteries (significant PV)
PV + Wind + Charge Batteries (significant PV) PV>Load, Wind>0, SoC<100		PV + Wind + Charge Batteries (inner)	Outer states PV + Wind + Charge Batteries (inner)

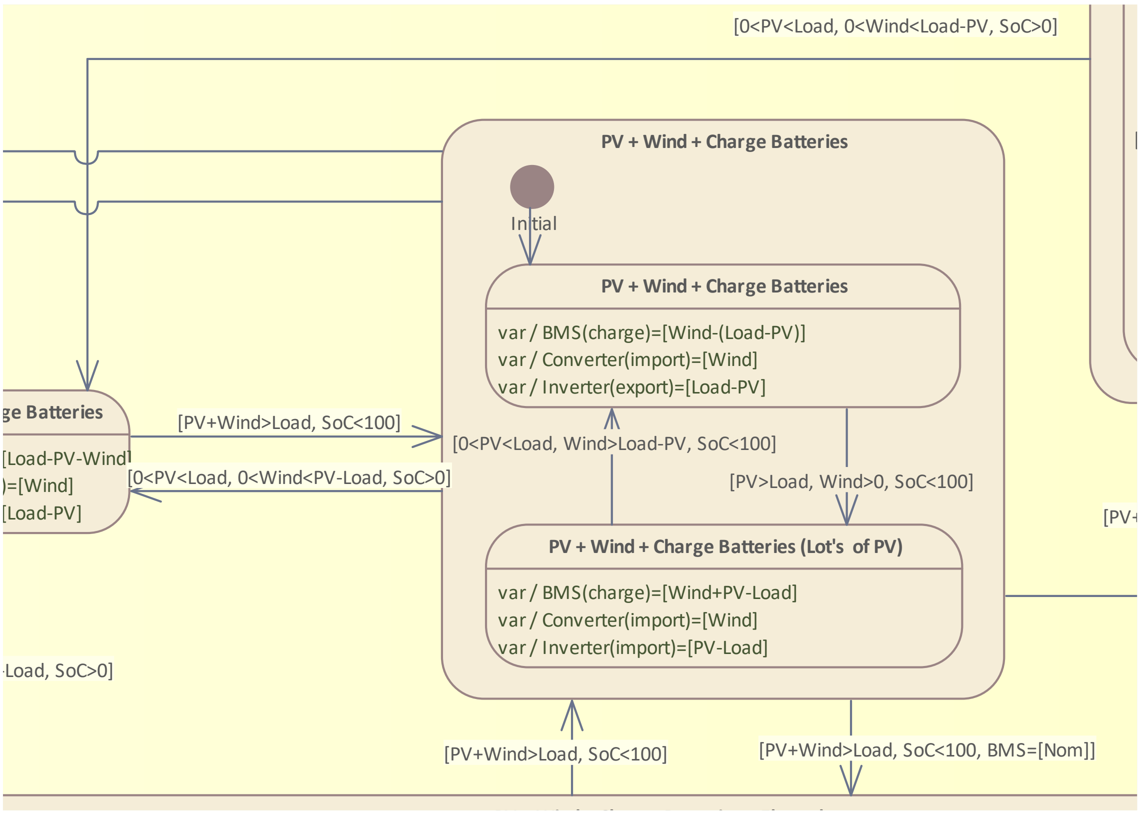

Figure 41 *System States - State Machine Diagram 6/10.*

Table 14 *System States 7/10.*

State Name & Trigger Guards	**Power Flows Description**	**Transitions In From**	**Transitions Out To**
PV + Wind + Electrolyser (outer) PV+Wind>Load, SoC=100	Combined generation of PV and Wind exceeds demand. BES state of charge is at 100%. Excess generation is used by Electrolyser.	Wind + Electrolyser PV + Wind + Charge Batteries PV + Wind + Charge Batteries + Electrolyser	Wind + Electrolyser Wind + Discharge Batteries PV + Discharge Batteries PV + Wind + Discharge Batteries
PV + Wind + Electrolyser (inner) 0<PV<Load, Wind>Load-PV, SoC=100	Demand is higher than available PV generation. Wind generation exceeds the remaining demand. BES state of charge is at 100%. Some or all excess wind generation is imported to be used by Electrolyser, depending on the inner state.	PV + Wind + Charge Batteries (outer) PV + Wind + Electrolyser (significant PV)	Outer states PV + Wind + Electrolyser (significant PV)
PV + Wind + Electrolyser < Nom PV+Wind-Load ≤ Electrolyser[Nom], SoC=100	Demand is higher than available PV generation. Wind generation exceeds the remaining demand. BES state of charge is at 100%. All excess wind generation is used by Electrolyser.	PV + Wind + Charge Batteries (inner) PV + Wind + Electrolyser=Nom	Outer states PV + Wind + Electrolyser=Nom

PV + Wind + Electrolyser = Nom PV+Wind-Load > Electrolyser[Nom], SoC=100	Demand is higher than available PV generation. Wind generation greatly exceeds the remaining demand. BES state of charge is at 100%. Excess wind generation exceeds the nominal capacity of the Electrolyser. Available wind generation is only imported to the point of reaching Electrolyser nominal capacity.	PV + Wind + Electrolyser < Nom	Outer states PV + Wind + Electrolyser < Nom
PV + Wind + Electrolyser (significant PV) PV>Load, Wind>0, SoC=100	Available PV generation exceeds demand. BES state of charge is at 100%. Excess PV generation is used by Electrolyser. Some or all available wind generation is imported to be used by Electrolyser, depending on the inner state.	PV + Wind + Electrolyser (inner)	PV + Wind + Electrolyser (inner) Outer states
PV + Wind + Electrolyser<Nom PV+Wind-Load ≤ Electrolyser[Nom]	Available PV generation exceeds demand. BES state of charge is at 100%. Excess PV generation is used by Electrolyser. All available wind generation is imported to be used by Electrolyser.	PV + Wind + Electrolyser (significant PV) PV + Wind + Electrolyser=Nom (significant PV)	PV + Wind + Electrolyser=Nom (significant PV) Outer states
PV + Wind + Electrolyser=Nom (significant PV) PV+Wind-Load > Electrolyser[Nom]	Available PV generation exceeds demand. BES state of charge is at 100%. Excess PV generation is used by Electrolyser. Available wind generation exceeds the remaining nominal capacity of the Electrolyser. Wind generation is only imported to the point of reaching Electrolyser nominal capacity.	PV + Wind + Electrolyser<Nom	PV + Wind + Electrolyser<Nom Outer states

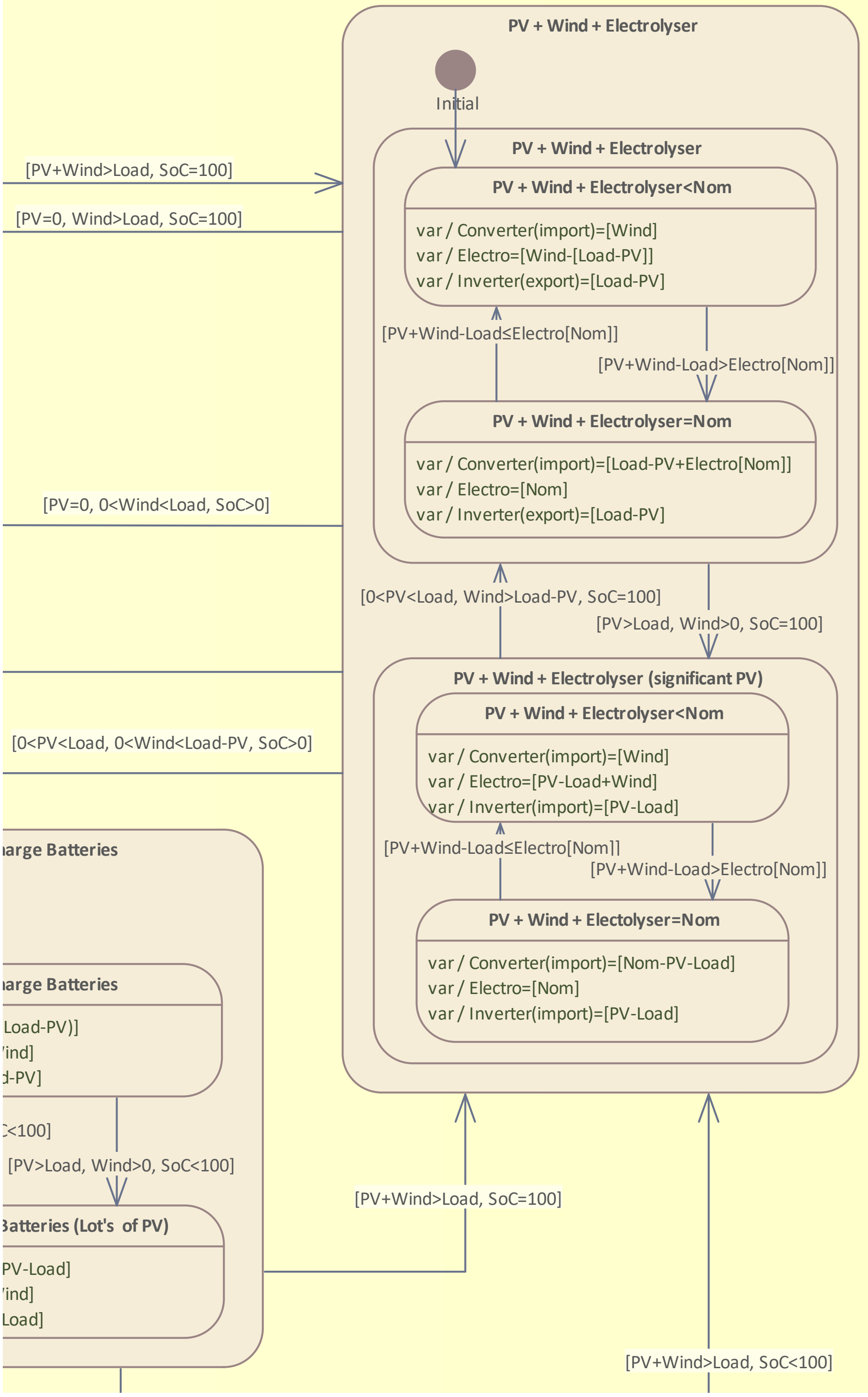

Figure 42 *System States - State Machine Diagram 7/10.*

Table 15 *System States 8/10.*

State Name & Trigger Guards	**Power Flows Description**	**Transitions In From**	**Transitions Out To**
PV + Wind + Charge Batteries +	Combined PV and wind generation exceeds the combination of demand and BES charging at a	PV + Wind + Charge Batteries	PV + Wind + Charge Batteries

Electrolyser (outer) PV+Wind>Load, SoC<100, BMS[Nom]	nominal rate. Depending on the inner state, different combinations of some or all excess generation are used by Electrolyser.		PV + Wind + Discharge Batteries
PV + Wind + Charge Batteries + Electrolyser (inner) 0<PV<Load, Wind>0, SoC<100, BMS[Nom]	Demand is higher than available PV generation. Available wind generation exceeds the combination of remaining demand and BES charging at nominal rate. All or some of the excess wind generation used by Electrolyser depending on the inner state.	PV + Wind + Charge Batteries + Electrolyser (outer) PV + Wind + Charge Batteries + Electrolyser (significant PV)	PV + Wind + Charge Batteries + Electrolyser (significant PV) Outer states
PV + Wind + Charge Batteries + Electrolyser<Nom 0<PV<Load, PV+Wind-Load-BMS[Nom] ≤ Electrolyser[Nom], SoC<100	Demand is higher than available PV generation. Available wind generation exceeds the combination of remaining demand and BES charging at nominal rate. All excess wind generation available is used by the Electrolyser.	PV + Wind + Charge Batteries + Electrolyser (inner) PV + Wind + Charge Batteries + Electrolyser = Nom	PV + Wind + Charge Batteries + Electrolyser = Nom Outer states
PV + Wind + Charge Batteries + Electrolyser=Nom 0<PV<Load, PV+Wind-Load-BMS[Nom] > Electrolyser[Nom], SoC<100	Demand is higher than available PV generation. Available wind generation exceeds the combination of remaining demand, BES charging at nominal rate and Electrolyser operating at nominal rate. Wind generation is only imported to the point of reaching BES and Electrolyser nominal capacity.	PV + Wind + Charge Batteries + Electrolyser<Nom	PV + Wind + Charge Batteries + Electrolyser<Nom Outer states

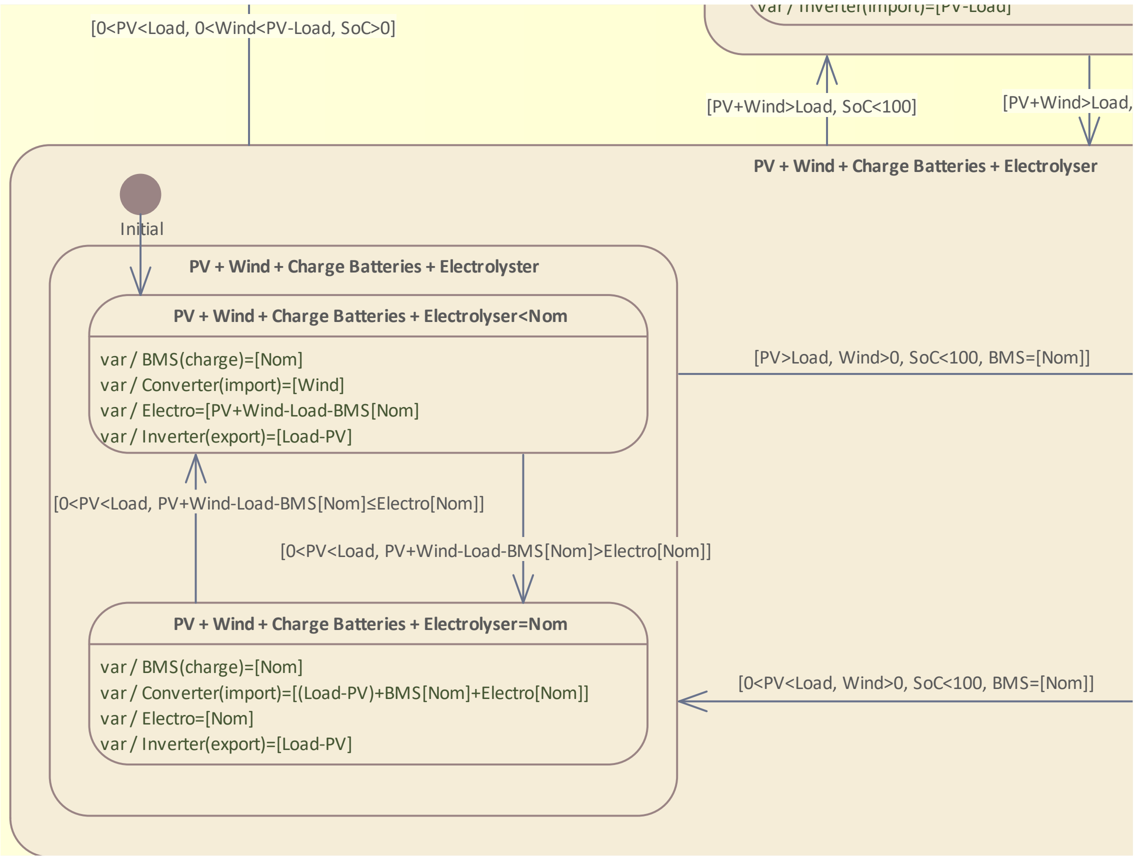

Figure 43 *System States - State Machine Diagram 8/10.*

Table 16 *System States 9/10.*

State Name & Trigger Guards	Power Flows Description	Transitions In From	Transitions Out To
PV + Wind + Charge Batteries + Electrolyser (significant PV) PV>Load, Wind>0, SoC<100, BMS[Nom]	Available PV generation exceeds demand. The combination of excess PV generation and wind generation exceeds the BES charging at nominal rate. All or some of the excess wind generation used by Electrolyser depending on the inner state.	PV + Wind + Charge Batteries + Electrolyser (inner)	PV + Wind + Charge Batteries + Electrolyser (inner) Outer states
PV + Wind + Charge Batteries + Electrolyser < Nom (significant PV) PV>Load, PV+Wind-Load-BMS[Nom] ≤ Electrolyser[Nom]	Available PV generation exceeds demand. The combination of excess PV generation and wind generation exceeds the BES charging at nominal rate. All excess wind generation used by Electrolyser.	PV + Wind + Charge Batteries + Electrolyser (significant PV) PV + Wind + Charge Batteries + Electrolyser=Nom (significant PV)	PV + Wind + Charge Batteries + Electrolyser=Nom (significant PV) Outer states
PV + Wind + Charge Batteries + Electrolyser=Nom (significant PV)	Available PV generation exceeds demand. The combination of excess PV generation and wind generation exceeds the	PV + Wind + Charge Batteries + Electrolyser < Nom (significant PV)	PV + Wind + Charge Batteries + Electrolyser < Nom (significant PV) Outer states

PV>Load, PV+Wind-Load-BMS[Nom] > Electrolyser[Nom]	combination of BES charging at nominal rate and Electrolyser operating at nominal rate. Wind generation is only imported to the point of reaching BES and Electrolyser nominal capacity.		

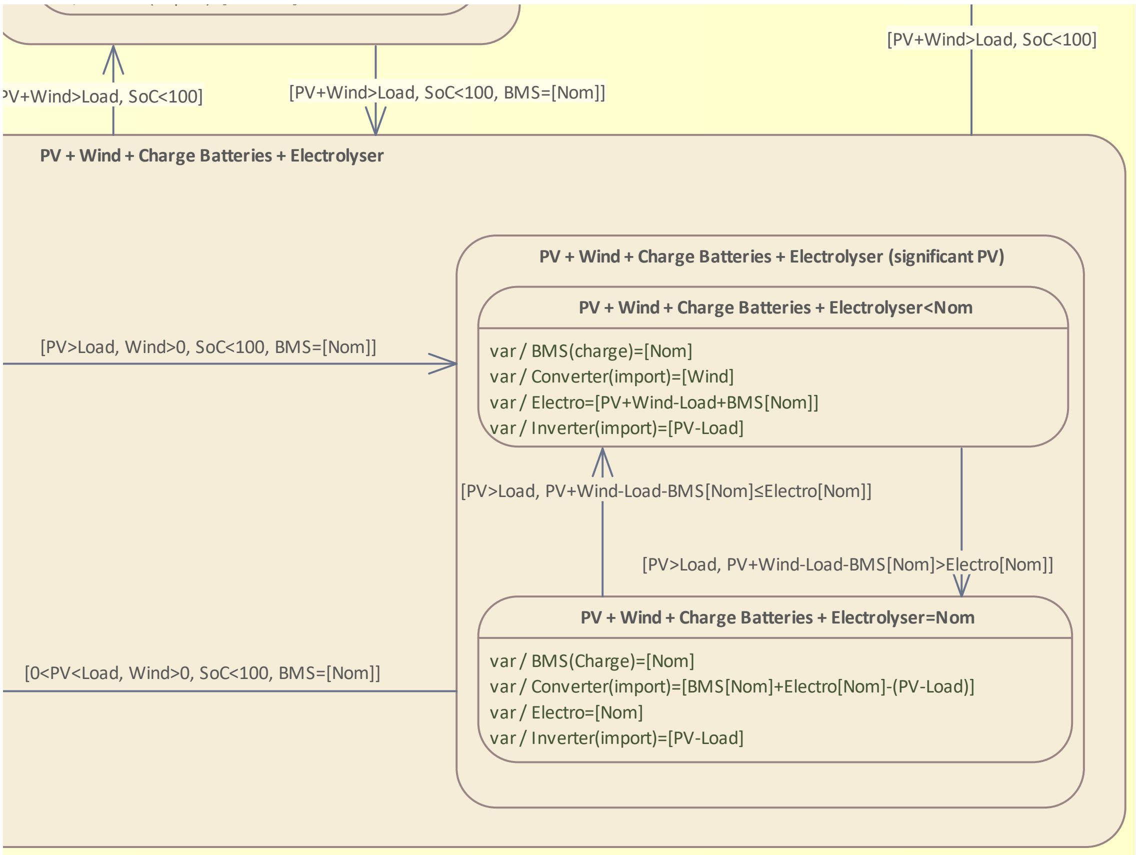

Figure 44 *System States - State Machine Diagram 9/10.*

Table 17 *System States 10/10.*

State Name & Trigger Guards	**Power Flows Description**	**Transitions In From**	**Transitions Out To**
Risk of Overvoltage PV+Wind> Load+Electro[Nom]+BMS[Nom], SoC<100 OR PV+Wind> Load+Electro[Nom], SoC=100	The combination of PV generation and available Wind generation exceeds the maximum possible system load, depending on the inner state. Wind power imports are set to 0, PV generation is limited to the maximum system load.	Normal Operation	Normal Operation
PV>Load + BMS[Nom] + Electro[Nom]	The combination of PV generation and available Wind generation exceeds the combination of demand, BES charging at nominal rate and Electrolyser operating at nominal rate. Wind imports are set	Risk of Overvoltage	PV>Load + BMS[Nom] + Electro[Nom] Normal Operation

	to 0, PV generation is limited to demand + BES at nominal charging rate + Electrolyser at nominal capacity.		
PV>Load + Electro[Nom], SoC=100	BES state of charge is 100%. The combination of PV generation and available Wind generation exceeds the combination of demand and Electrolyser operating at nominal rate. Wind imports are set to 0, PV generation is limited to demand + Electrolyser at nominal capacity.	PV>Load + BMS[Nom] + Electro[Nom]	Normal Operation

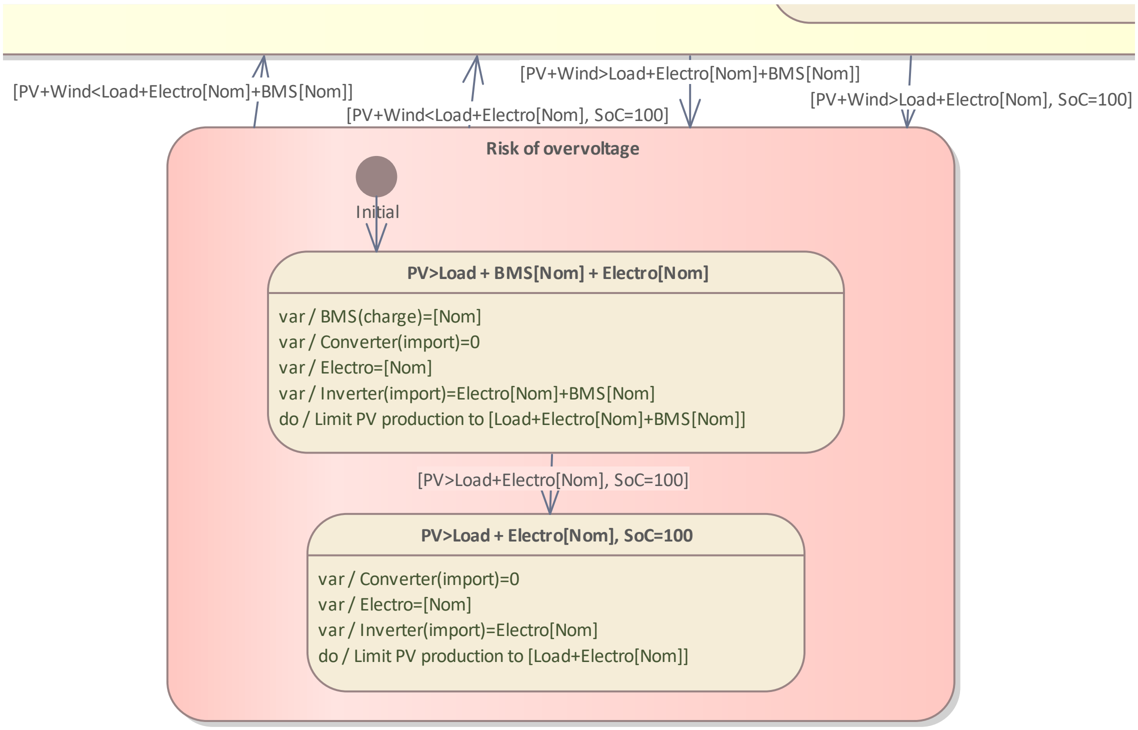

Figure 45 *System States - State Machine Diagram 10/10.*

The real-time control logic depicted in the State Machine Diagram also contains a Risk of overvoltage System State, which has sub-states containing *do* effects. These effects are activated upon entering the state and they dictate direct curtailment measures for the rooftop solar PV resources in the system. The Real-Time Control Module sends these curtailment commands to the HEMSs, and they override the HEMS's own control over the rooftop solar PV systems. This mechanism is aimed at preventing RPFs in addition to voltage deviations in grid-connected operating mode when the system is stabilised by synchronous generators and frequency deviations in islanded operating mode when the system is stabilised be power converters. As seen in the state machine, the transition to the Risk of overvoltage state can only happen, if the BES system and electrolyser cannot absorb all the excess active power in the network. This means the Real-

Time Control Module is not able to adjust the demand in the network to match the increasing generation. The guards to trigger this transition should be set so, that the transition occurs well before reaching overvoltage. It should also be made sure that these guards are set at a lower threshold than any voltage safety limits set in the solar PV inverters. This would ensure that rather than some solar PV systems disconnecting on their own, the systems are disconnected based on the curtailment commands. Whether or not all PV systems should be disconnected at the same time depends on whether there is enough other generation available in the system and on the compensation structure in place in the energy community.

The LEOS developed in this study utilises active power control to prevent overvoltage and to manage system frequency. Reactive power control is not utilised in this model, however, implementing reactive power control logic in a State Machine format is an opportunity for further research. As discussed in the section 2.4, the inclusion of reactive power control methods could optimise the utilisation of DER resources and reduce the need for active power control, in other words solar PV curtailment. In addition, the inclusion of reactive power control in the control logic would improve the network stability in islanded operating mode. Alternatively, future research could explore implementing reactive power control in an algorithmic format, as found in literature explored in the section 2.4. This approach could possibly be less complex than expanding the already extensive State Machine.

Now that formal definitions have been established for the System States and the real-time control logic, the use case Maintain System Real-Time Control can be described. The actors involved and related other use cases are depicted in the Figure 46, and the activity and sequence diagram descriptions are presented in the Figure 47, Figure 48, and Figure 49 respectively.

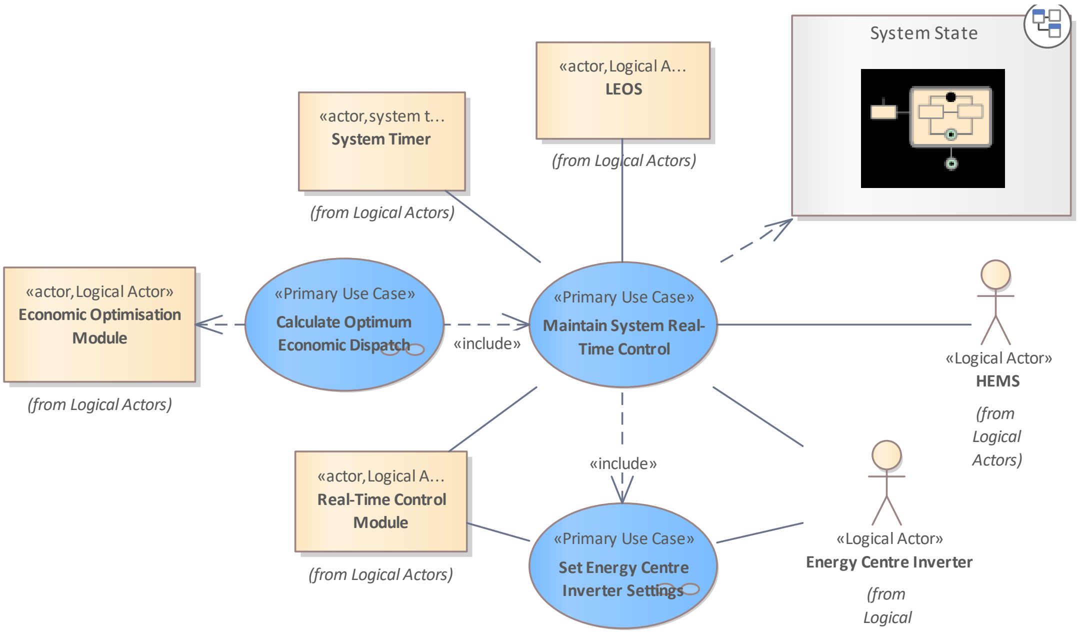

***Figure 46** PUC - Maintain System Real-Time Control.*

The use case can be initiated either by the System Timer at set time intervals, or by the Economic Optimisation Module, whenever it sends a new Optimum Economic Dispatch Plan. In principle, the System Timer should be set to constantly re-initiate the use case, to ensure responsiveness of the real-time control process. The LEOS transmits the Optimum Economic Dispatch Plan to the Real-Time Control Module. If no Optimum Economic Dispatch Plan is available, the control logic will be fully based on the State Machine. This can happen when the Economic Optimisation Module is not functioning or is unable to transmit the Optimum Economic Dispatch plan due to a communications fault. Also, if the system has been recently initialised or is recovering from a deviation or an emergency event, the control logic will follow the State Machine until the Economic Optimisation Module is able to calculate and distribute an updated Optimum Economic Dispatch Plan. The system is able to function without economic optimisation, albeit less efficiently.

The Real-Time Control Module accesses the current System Status, which defines which System State the system is in. If the Real-Time Control Module detects that the System Status deviates from the allowed System Sates in a way which is not possible to correct with the available energy resources, it initiates emergency measures. These are discussed in detail in the section 4.5.11. If the System Status is within allowed limits, the Real-Time Control Module proceeds with implementing the Optimum Economic Dispatch Plan to the extent possible within these limits. The Real-Time Control Module sends Sate

Change Instructions to the Energy Centre Inverter and Load and Generation Management Instructions to the HEMSs. The frequency of this update process determines how timely the system real-time control is.

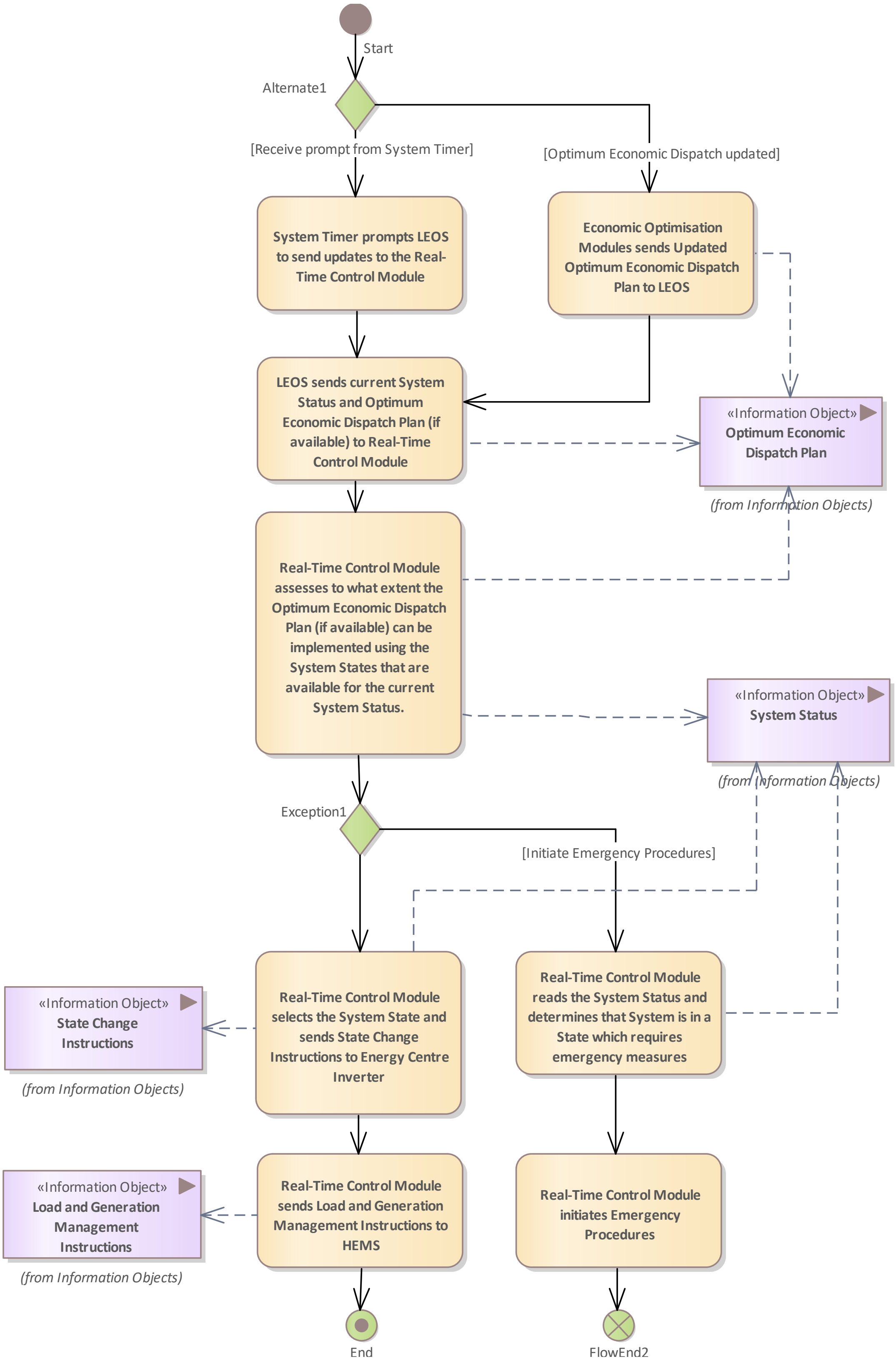

Figure 47 *Activity Diagram - Maintain System Real-Time Control.*

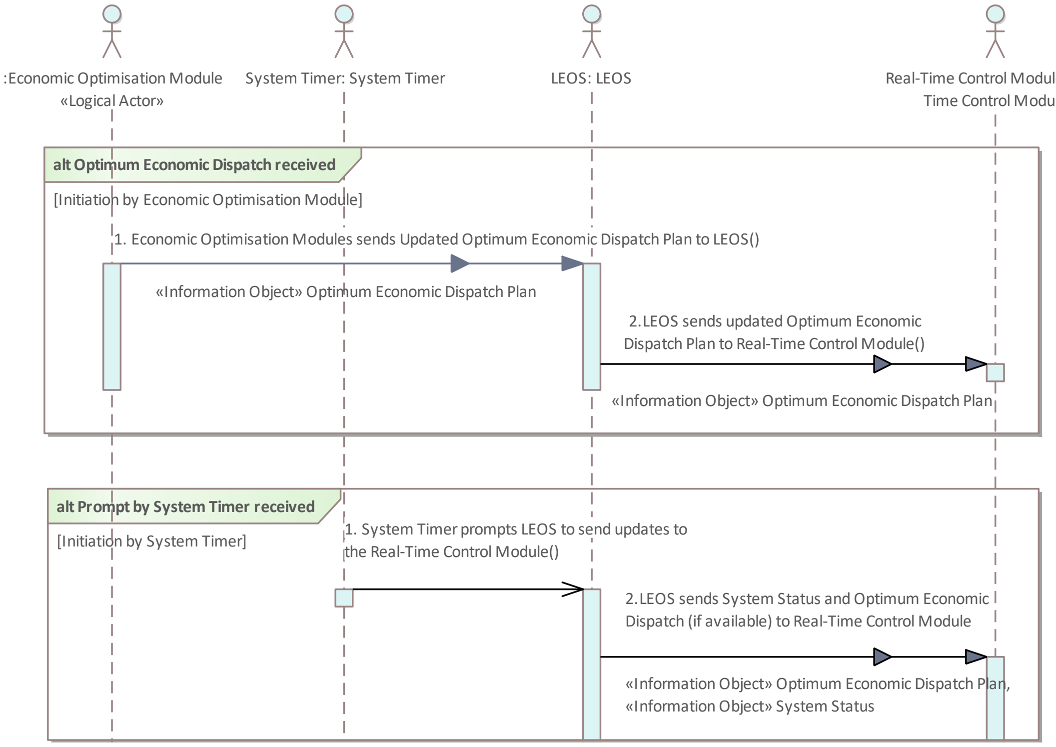

Figure 48 *Sequence Diagram - Maintain System Real-Time Control (part 1/2).*

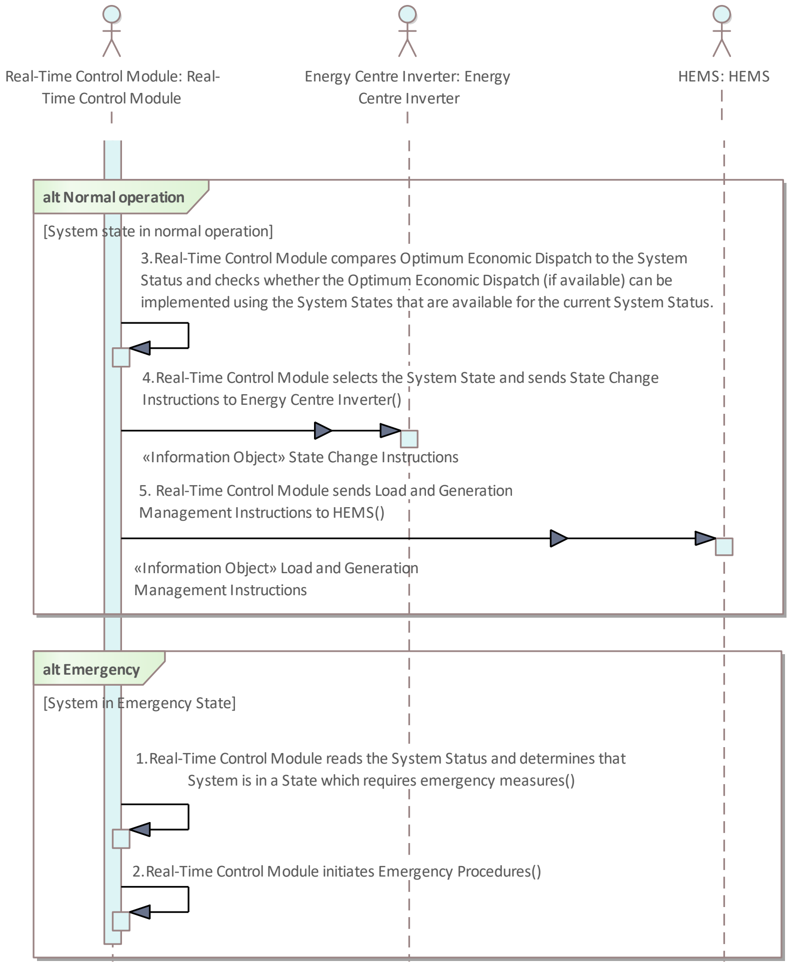

Figure 49 *Sequence Diagram - Maintain System Real-Time Contro (part 2/2).*

4.5.8 PUC – Estimate Non-LEM Households’ Consumption

As some of the South Cornelly households will likely remain outside of the LEM community, some of the demand in the network will remain invisible in the Metering Data collected by the LEOS. Therefore, it is necessary to describe a process for estimating the consumption by these Non-LEM Households. The use case is described in the Figure 50, Figure 51, and Figure 52. It is notable that the Non-LEM Households are not considered as actors in the use case, as they do not interact with the LEOS. Instead, the LEOS requests Metering Data from the Substation Transformer, to estimate the total demand in the South Cornelly LV network. Next, the LEOS compares this total demand to the aggregated LEM demand presented in the System Status. The System Status is updated every time a Metering Data Sender, such as a HEMS, sends a Metering Data information object to the LEOS. As this thesis does not cover the Communication or Component layers of the SGAM framework, the used communications protocols or communications infrastructure are not specified. However, as established in the section 2.3.1, the dispatch of DERs is perfumed at the secondary level of microgrid control, which requires a frequency of information exchange in the sub-second range. Therefore, each HEMS should send updates at least at 1 Hz frequency, if not higher. This would mean that the LEOS needs to update the System Status at least as many times per second as there are HEMSs connected. Depending on the hardware utilised for the LEOS and the communications equipment available, in a practical implementation it might be reasonable to aggregate the Metering Data instead of updating each time a new information object is received. For example, the LEOS could update the System Status each second, based on the changes received during the previous second.

As established in the section 4.1, all LEM participants are required to have either a Smart Meter or a HEMS installed. As both send Metering Data to the LEOS, the System Status provides a timely estimate on the consumption by the LEM participants. As mentioned above, the total demand in the South Cornelly LV network is based on the Metering data provided by the Substation Transformer. Given these two demand estimates, the LEOS is able to derive the Estimated Consumption by the Non-LEM Households as a deduction of the two demand values. In islanded operating mode, the LV networks total demand cannot be derived from the Substation Transformer measurements. Instead, the total demand will match the total generation in the South Cornelly LEM.

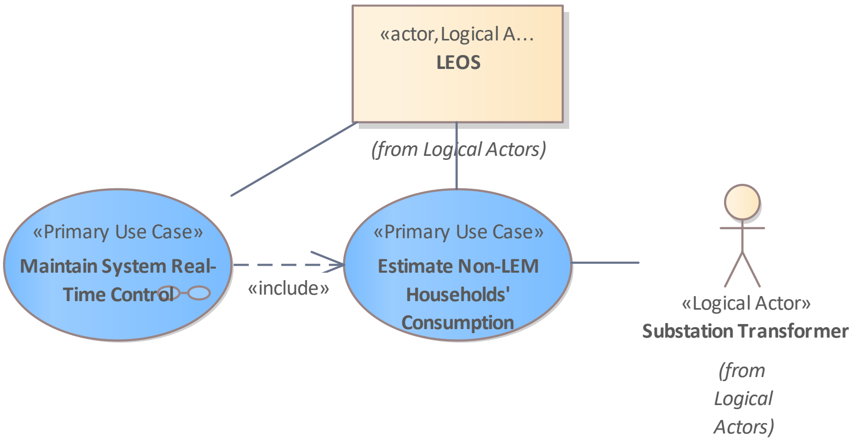

Figure 50 *Use Case Diagram - Estimate Non-HEMS Households' Consumption.*

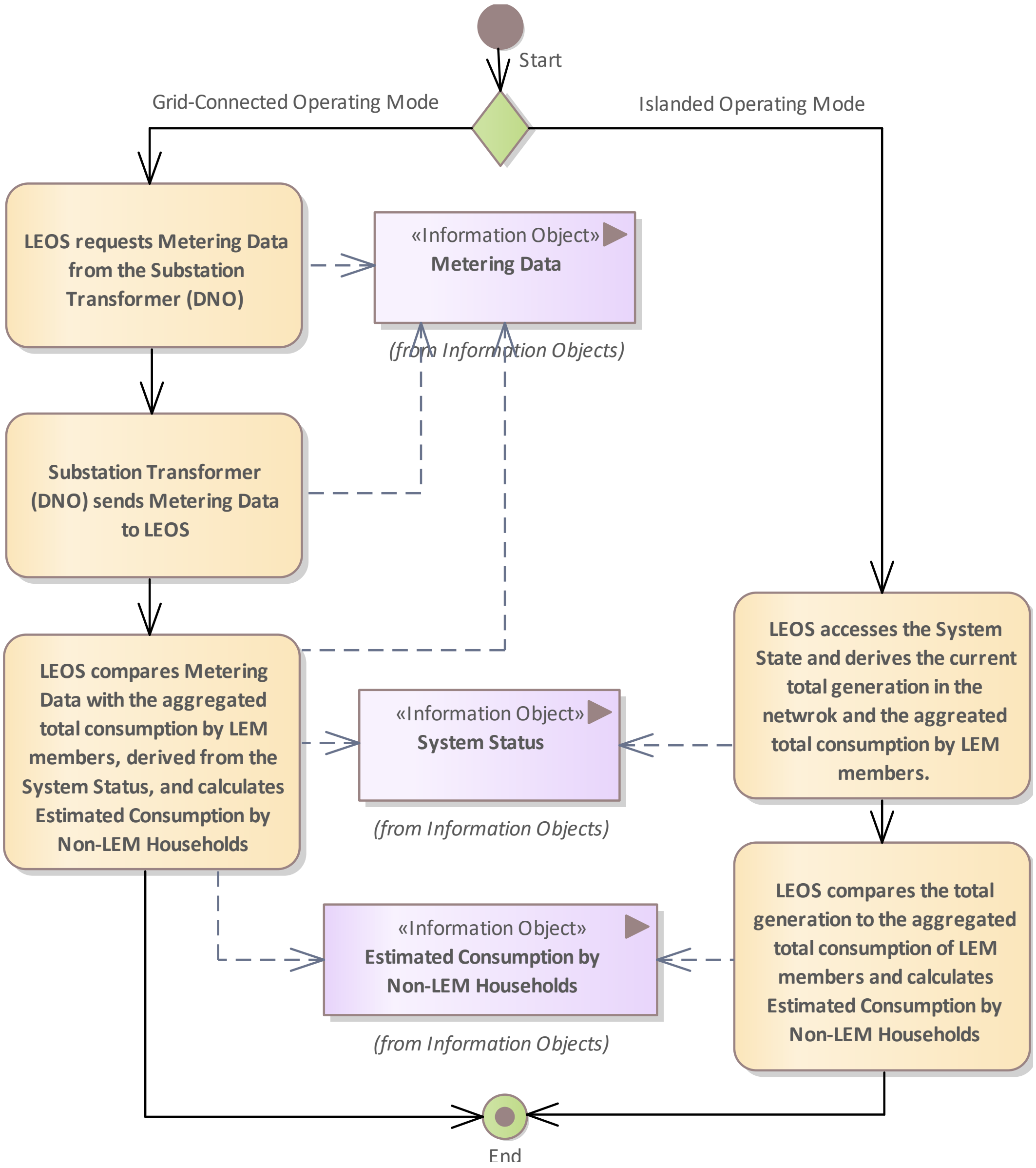

Figure 51 *Activity Diagram - Estimate Non-HEMS Households' Consumption.*

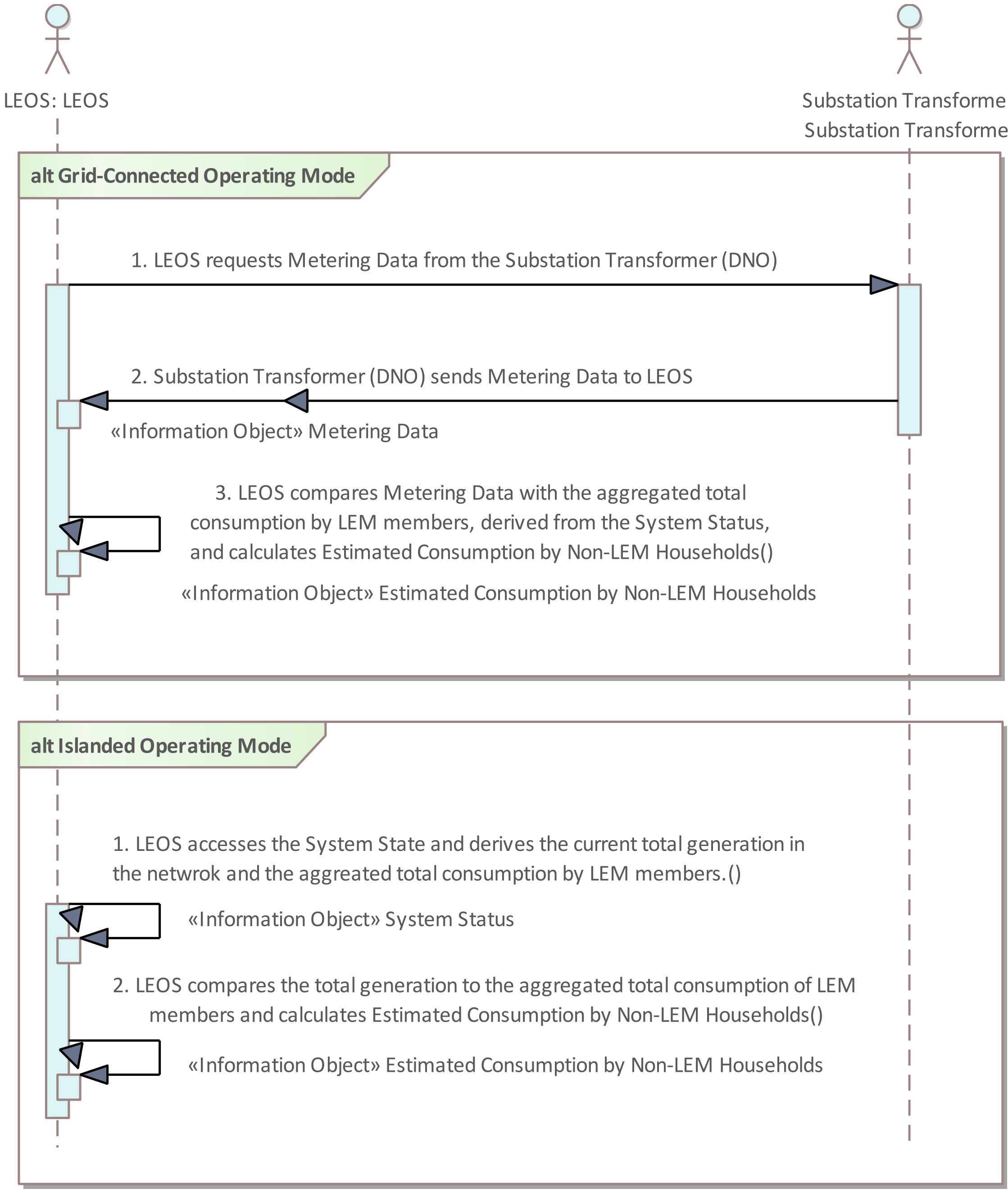

Figure 52 *Sequence Diagram - Estimate Non-HEMS Households' Consumption.*

4.5.9 PUC – Set Energy Centre Inverter Settings

Maintaining the system real-time control requires constant updating of the reference values of the DERs within the Energy Centre. As depicted in the Figure 53, Figure 54, and Figure 55, the Real-Time Control Module sends State Change Instructions to the Energy Centre Inverter, whenever a real-time control cycle is completed. The Energy Centre Inverter then adjusts these instructions and transmits them to the energy resources under its control. In terms of the hierarchical levels of control discussed in the section 2.3.1, the Energy Centre mostly operates in the secondary level of control. Therefore, a frequency of communications in the sub-second range is required. In principle, this frequency should stay constant in both grid-connected and islanded operating modes of the microgrid. However, further measures to ensure the robustness of the communications connections should be implemented for the islanded operating mode. These could, for example, consist of back up communications channels between the Energy Centre and the connected DERs and contingency procedures hardcoded in the DER controllers to be activated in case of loss of communications. A detailed analysis on the communications requirements would necessitate defining the communications protocols and hardware platforms used in the Energy Centre and in the LEOS. These decisions are therefore out of the scope of this thesis.

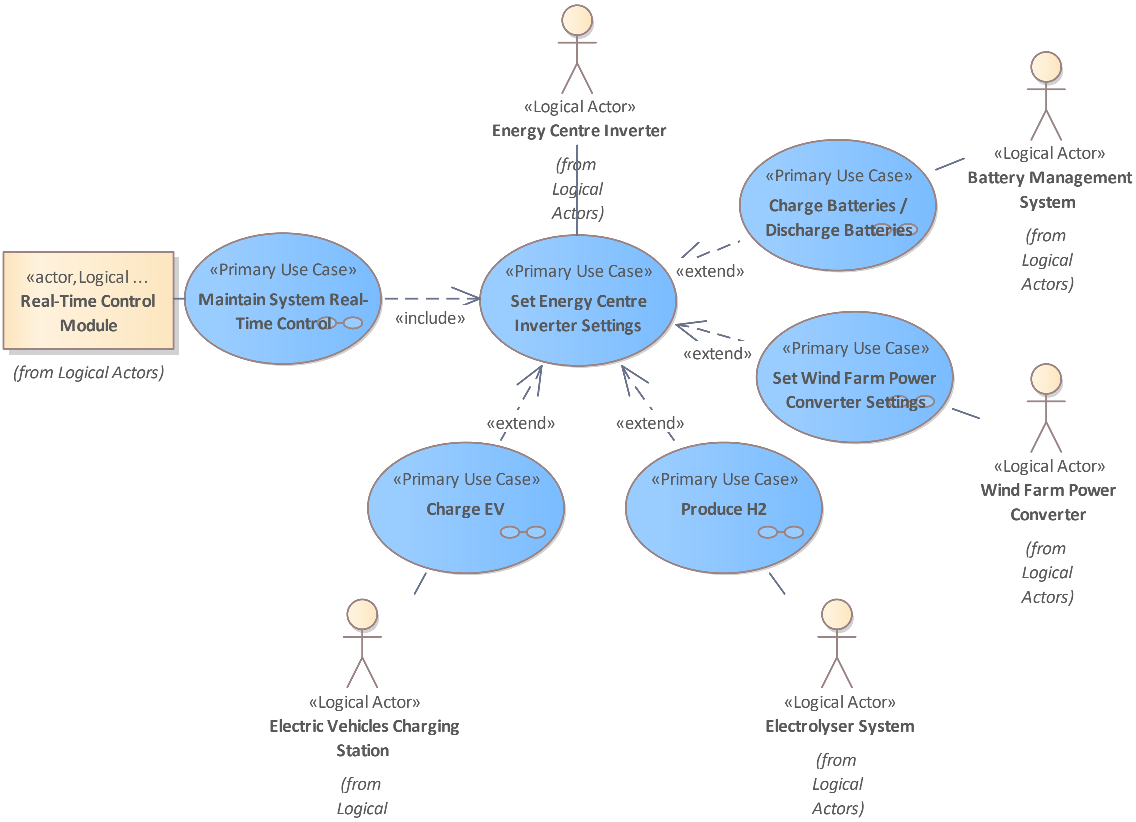

Figure 53 *PUC - Set Energy Centre Inverter Settings.*

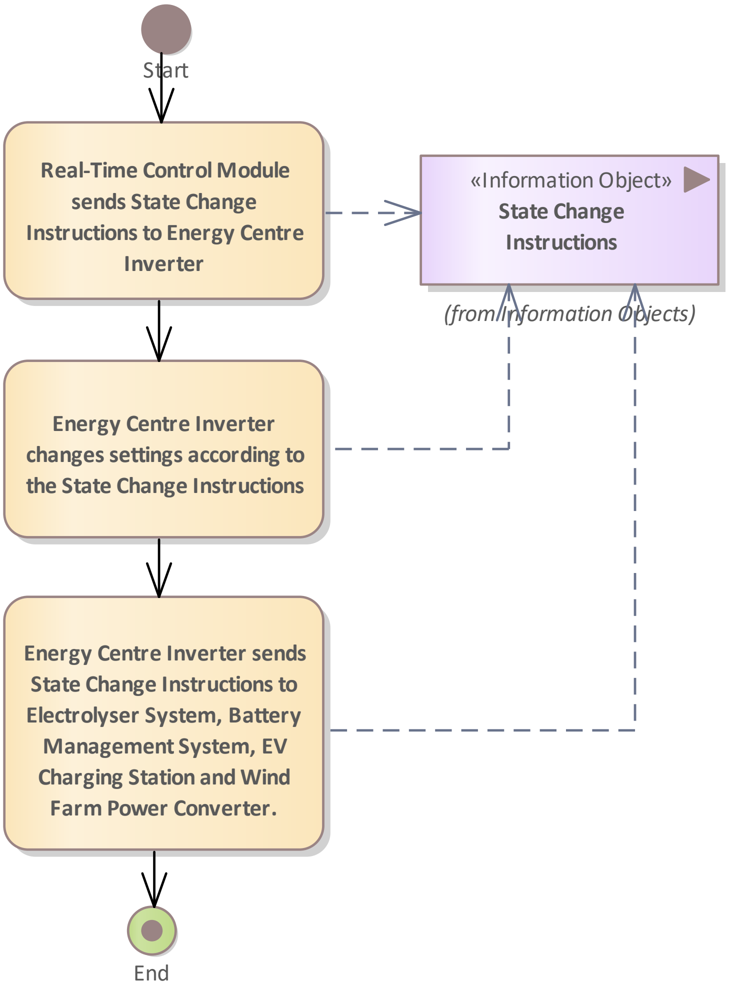

Figure 54 *Activity Diagram - Set Energy Centre Inverter Settings.*

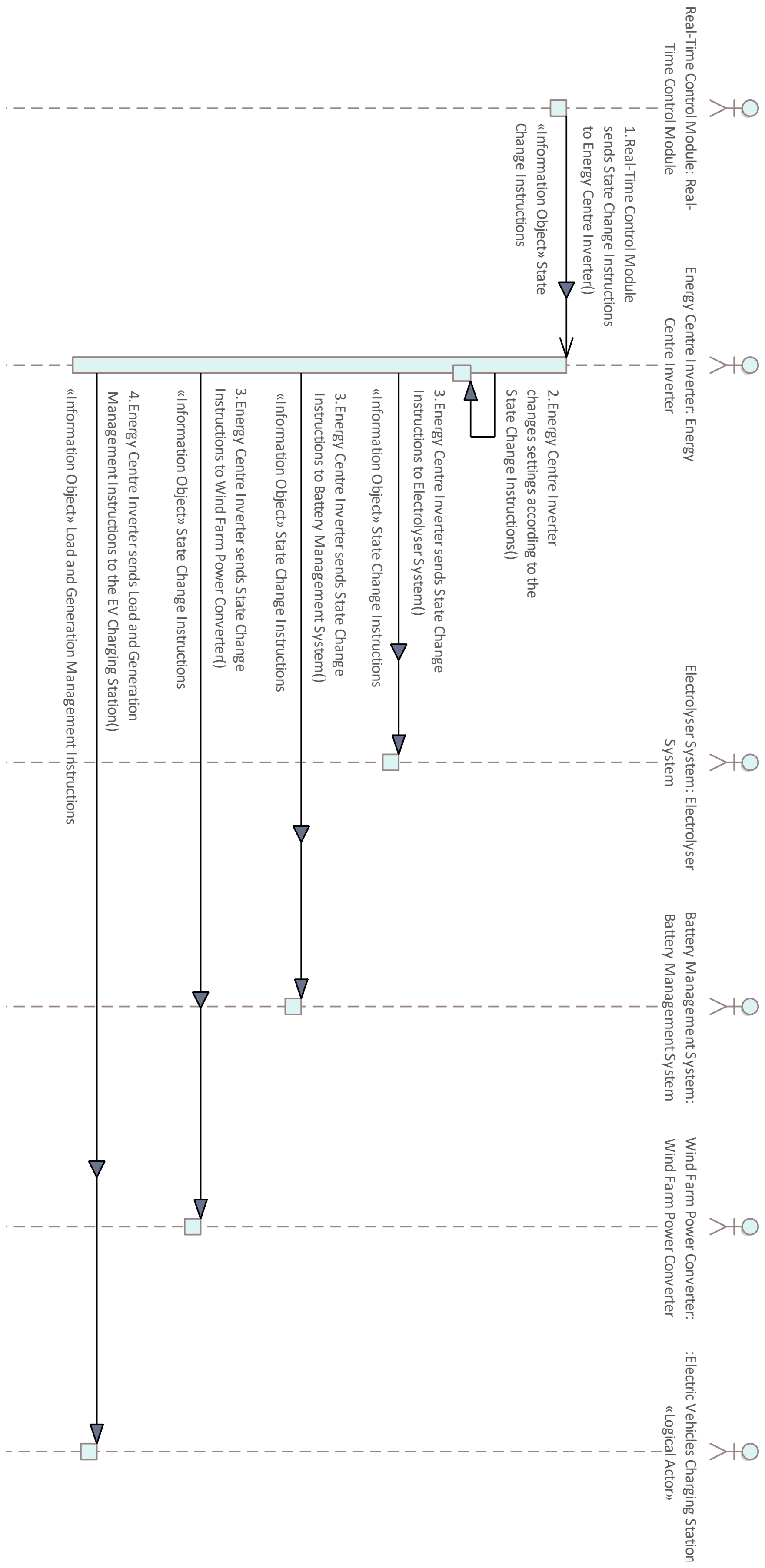

Figure 55 *Sequence Diagram - Set Energy Centre Inverter Settings.*

4.5.10 PUC – Charge Batteries / Discharge Batteries

As the use cases for adjusting the control values for the energy resources in the Energy Centre are all similar, only one of them is described in detail here. The descriptions for the use cases Set Wind Farm Power Converter Settings and Produce H2 can be found in the Appendix, in the Figure 79, Figure 80, Figure 81, Figure 82, Figure 83 and Figure 84. The use case Charge Batteries / Discharge Batteries extends the use case Set Energy Centre Inverter Settings. An extend relation is used instead of an include relation, because it is not always necessary to adjust the Battery Management System settings when the Energy Centre Inverter receives updated State Change Instructions. When the State Change Instructions affect the utilisation of the BES, the Energy Centre Inverter transmits State Change Instructions to the Battery Management System, dictating whether the BES will be charged, on standby or discharged. Also, the charging and discharging power can be adjusted.

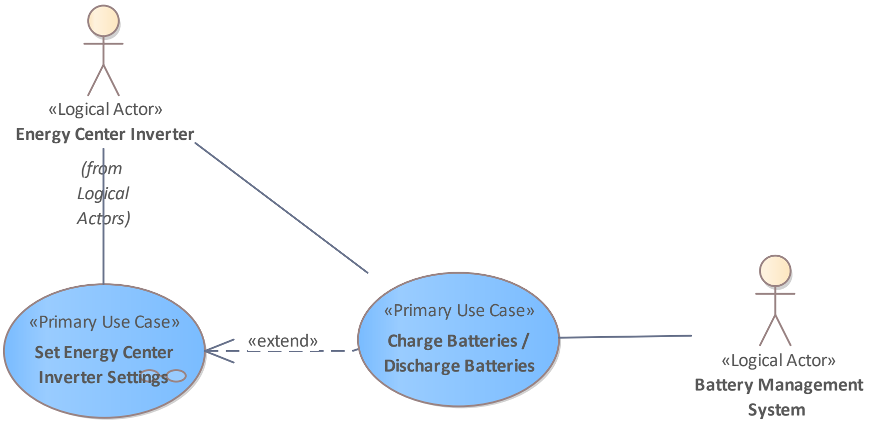

Figure 56 *PUC - Charge Batteries / Discharge Batteries.*

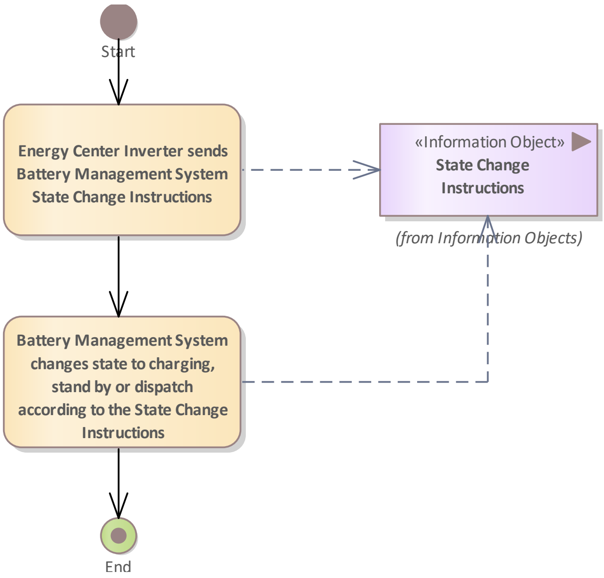

Figure 57 *Activity Diagram - Charge Batteries / Discharge Batteries.*

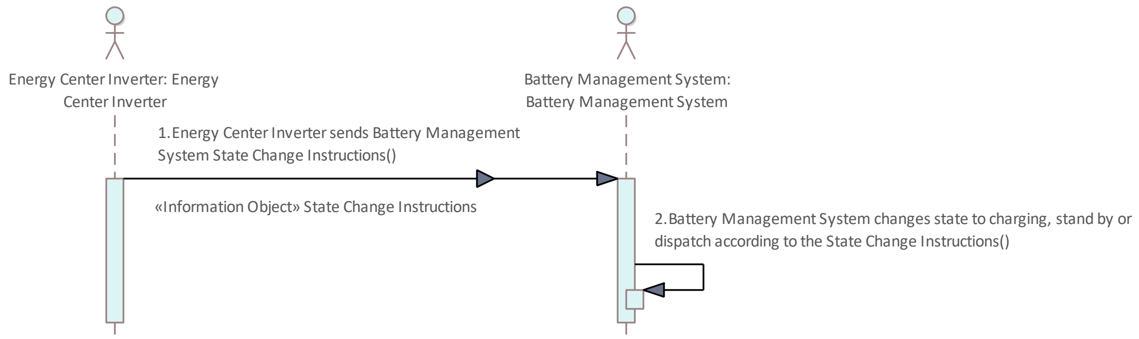

Figure 58 *Sequence Diagram - Charge Batteries / Discharge Batteries.*

4.5.11 PUC – Initiate Emergency Procedures

This thesis does not go into the detailed operation of the protection relays and algorithms used to identify irregularities such as fault currents or frequency deviations. Nevertheless, a basic assessment of archetypical fault situations and the subsequent responses is presented here, in the use case Initiate Emergency Procedures (Figure 59).

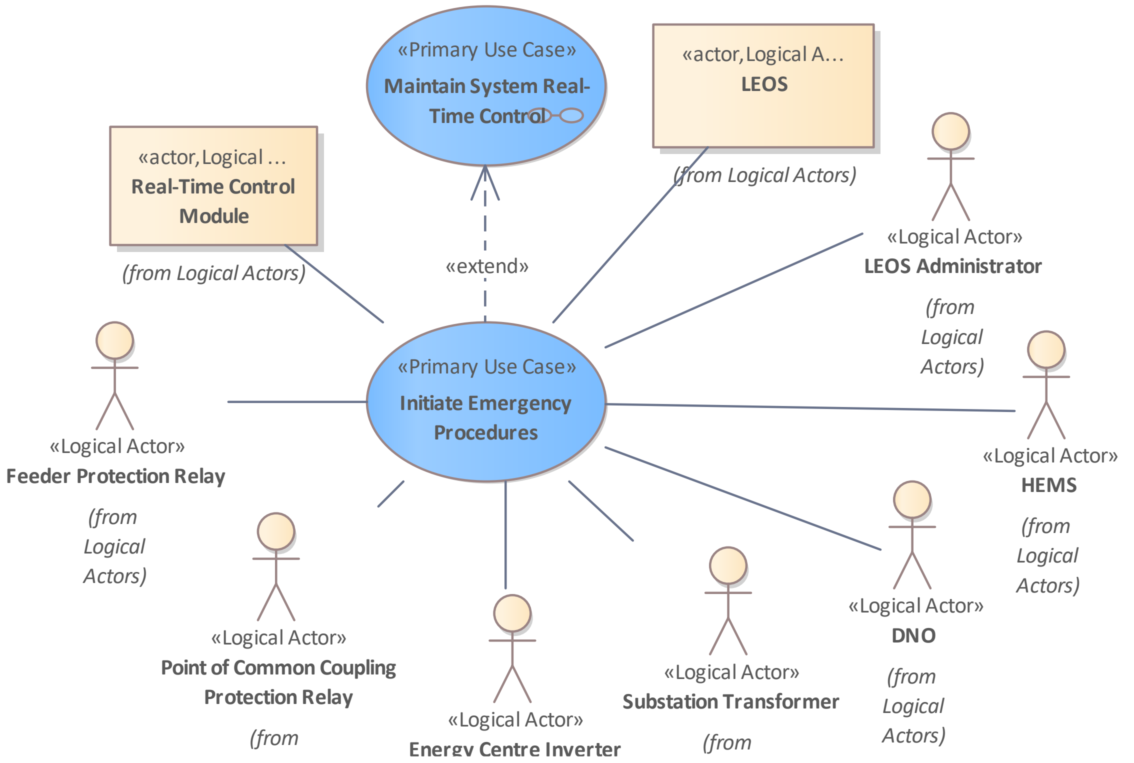

Figure 59 *PUC - Initiate Energy Procedures.*

As there are multiple different kinds of deviations and fault situations the system can enter in, the use case can be initiated in multiple ways, as shown in activity diagram split into three parts in the Figure 60, Figure 61, and Figure 62. The full activity diagram can be found in the Appendix in Figure 85. For each of the flows in the diagram, a corresponding path exists as a sequence diagram. These diagrams can be found in the appendix, in the Figure 86, Figure 87, Figure 88 and Figure 89. On the first path, the Point of Common Coupling Protection Relay detects a deviation in voltage or frequency on the MV grid side. The Point of Common Coupling Protection Relay sends a Fault-Alert to the Real-Time Control module, which in turn seeks to protect the microgrid by islanding it from the MV network. At this point there are two branching paths: either the Real-Time Control Module manages to island the microgrid, or it lacks sufficient resources to balance the load and demand in the grid and in turn powers down the grid. In general, in normal operation the Real-Time Control Module prioritises local generation if it is available. Thus, a significant import of power from the MV side implies that there is not enough local generation available to cover for the total demand. Depending on the economic optimisation objectives set, the central BES could have stored energy available, but powering a significant part of the community with just the central BES does pose high requirements for the power output rating of the BES System. The system control logic introduced in the section 4.5.7 is based on the assumption that the BES System is rated to high enough power output to at least momentarily cover the total household demand. Whether the system would be optimised for short-term frequency regulation or long-term peak shifting, however, is not addressed in this study. In conclusion, if only a small share of the local demand is covered by imports from the MV network, the emergency islanding can succeed if the local resources are capable of ramping up generation fast enough to stabilise the LV network frequency and voltage. If the emergency islanding occurs at a time of high imports from the MV network side, it is unlikely the Real-Time Control Module is able to respond fast enough and with sufficient resources, given the System States it has available. This leads to the powering down of the LV network.

To safely power down the LV network, the Real-Time Control Module first instructs the Energy Centre and the HEMSs to disconnect generation from the microgrid. After the generation is disconnected, the Real-Time Control Module sends a Fault Alert to LEOS. The LEOS in turn relays the Fault Alert to the LEOS Administrator. As all generation has been disconnected from the LV network and the LV network has been separated from the MV network, the microgrid is now in a powered down state. When the DNO confirms to the LEOS Administrator that the DNO MV grid is online and in a stable state, the microgrid can be brought online using the initialisation process described in the section 4.5.1. This thesis does not cover the possible black start restart process for the microgrid in islanded operating mode. This process would require substantial controllable generation capacity in the grid, an assumption which is not true in the studied South Cornelly LEM scenario in times with low availability of VRE resources.

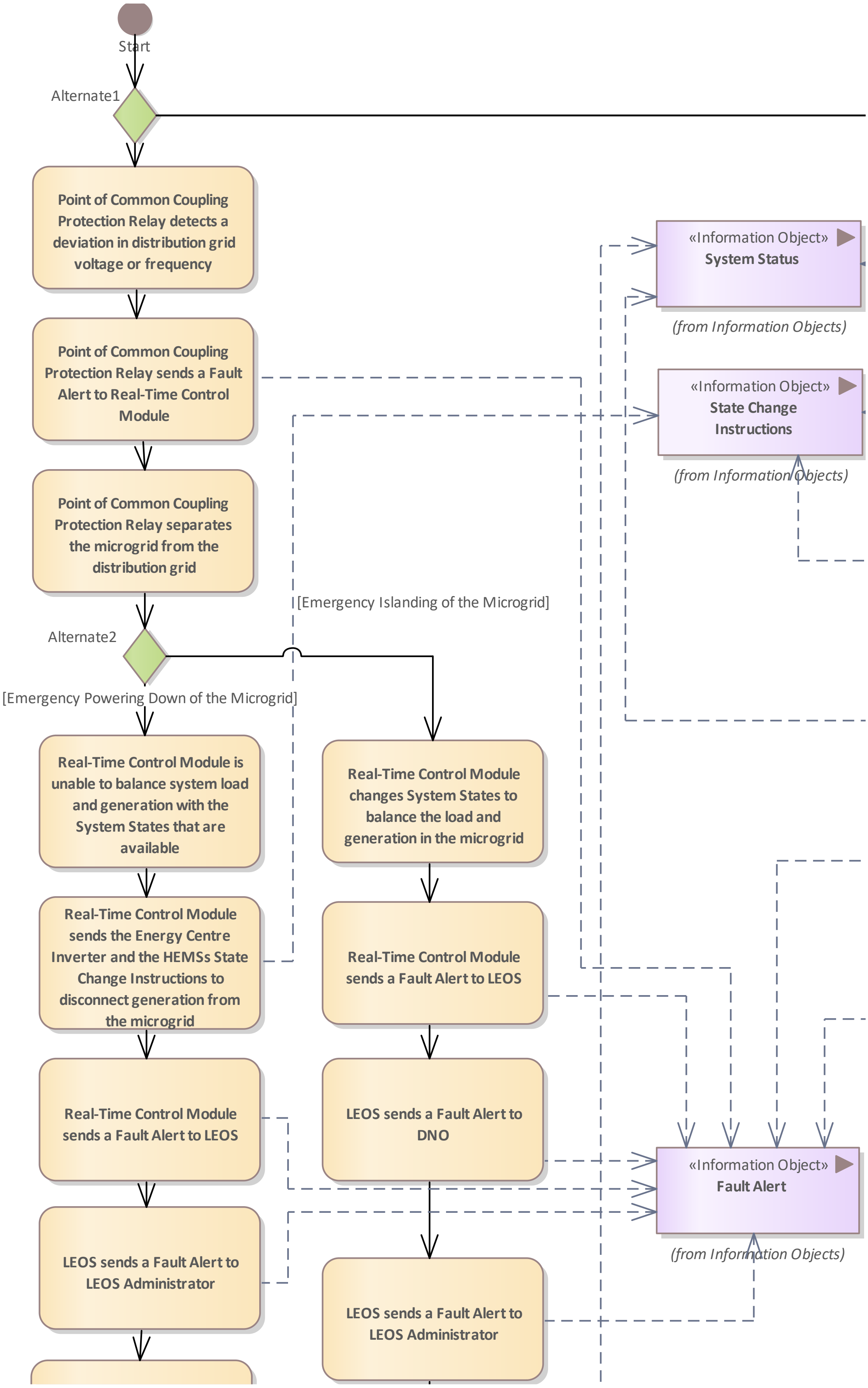

Figure 60 *Activity Diagram - Initiate Emergency Procedures 1/3.*

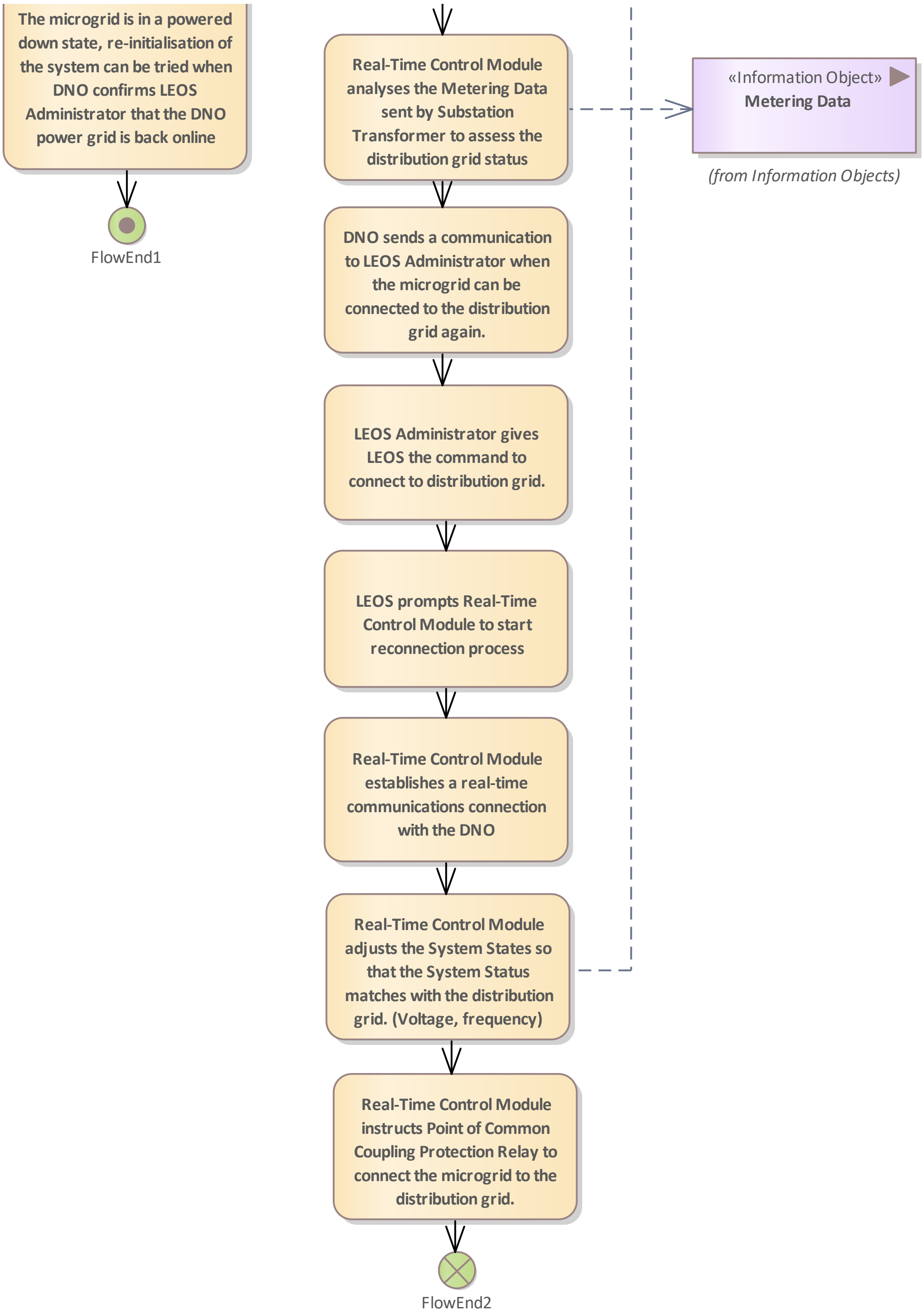

***Figure 61** Activity Diagram - Initiate Emergency Procedures 2/3.*

The second path in the use case Initiate Emergency Procedures deals with a deviation on the MV side, like the first path. However, in the second path the South Cornelly microgrid is successfully isolated from the MV distribution network and continues operation in islanded operating mode. As seen in the Figure 60, the second path splits after the Point of Common Coupling Protection Relay separates the microgrid from the MV grid.

In this path, the Real-Time Control Module is able to balance the network demand and generation using the available System States. The Real-Time Control Module sends a Fault Alert to the LEOS, which relays this Fault Alert to the DNO and the LEOS Administrator. While the microgrid continues operating in islanded mode, the Real-Time Control Module keeps analysing the Metering Data sent by the Substation Transformer to assess the MV grid status. When reconnecting with the MV network becomes possible, the DNO sends a communication to the LEOS Administrator. The LEOS Administrator then Instructs the LEOS to connect to the distribution grid. The Real-Time Control Module starts the reconnection process, by establishing a real-time communications connection with the DNO to enable swift connection at the moment the synchronisation criteria are met. This is important, as the microgrid relies on VRE resources and is therefore subject to common and difficult-to-predict frequency fluctuations. After the connection has been established, the Real-Time Control Module begins adjusting the System States to match the distribution grid voltage and frequency. When the microgrid is running in synchronised frequency and phase with the MV network, the Real-Time Control Module instructs the Point of Common Coupling Protection Relay to reconnect the microgrid with the MV network.

The third path in the use case Initiate Emergency Procedures deals with overvoltage on the microgrid side. In normal operation, the control logic of the Real-Time Control Module avoids overvoltage by managing demand in the network through adjusting the charging rate of the Battery Management System or the output of the Electrolyser System. These controls are prompted by the Real-Time Control Module and implemented by the Energy Centre Inverter. Although not directly controlled by the Real-Time Control Module, the system demand is also managed by the HEMSs, which manage household loads based on the User Preferences and the Hourly Household Electricity Price Table updated by the LEOS. The Real-Time Control Module receives continuous updates to both the Using the Optimum Economic Dispatch Plan and the System Status. By comparing the load predictions to real-time metering data, the Real-Time Control Module continuously assesses if the resources available to it are sufficient to maintain the system power balance. When the Real-Time Control Module determines that the LV network is approaching overvoltage and increasing demand is not possible, it sends the HEMSs State Change Instructions ordering them to separate PV generation from the grid. The sensitivity of triggering these curtailment measures should depend on safety margins which are tailored for the specific network hardware and load patterns. These are not explored in this study. Also, as discussed in the section 2.4.1, reactive power control is not utilised in this study, although it has potential for overvoltage prevention.

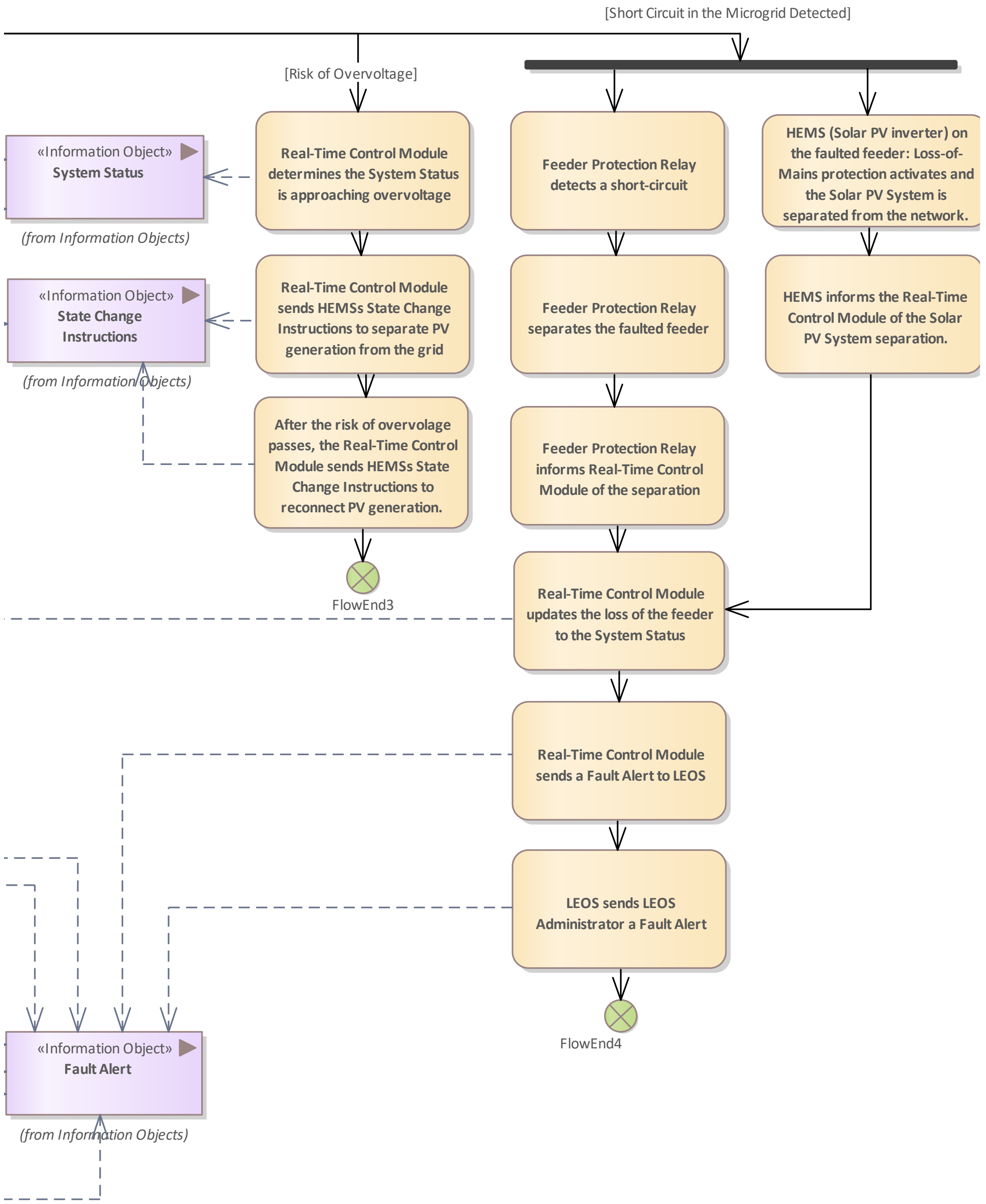

***Figure 62** Activity Diagram - Initiate Emergency Procedures 3/3.*

The fourth and last path in the use case Initiate Emergency Procedures deals with short circuits in the LV network. Each feeder in the network is equipped with a Feeder Protection Relay, which detects fault currents in the network and is able to separate the feeder from the LV network. When the Feeder Protection Relay detects a short-circuit, it separates the faulted feeder from the network and informs the Real-Time Control Module of the separation. Simultaneously, the Loss-of-Mains protection of the household solar PV systems located along the faulted feeder activates. The solar PV systems disconnect the production from the grid and the HEMS informs the Real-Time Control Module of the separation. The Real-Time Control Module updates the loss of a feeder to the System Status. Next the Real-Time Control Module sends a Fault Alert to the LEOS, which in turn sends the Fault Alert to the LEOS Administrator. The faulted feeder remains separated, until the LEOS Administrator has organised a maintenance crew to check and repair the faulted equipment. Afterwards the faulted feeder can be reconnected by undergoing the LEOS initialisation process, described in the section 4.5.1. If a fault occurs in multiple feeders at the same time, all of the affected feeders are isolated. If all feeders suffer a fault, the LV network will de facto be completely separated from the MV network.

4.5.12 PUC - Charge EV

The use case Charge EV, described in the Figure 63, is initiated by an EV Charging Customer. As shown in the Figure 64 and Figure 65, the EV Charging process starts with the EV Charging Customer requesting an EV Charging Price Table from the EV Charging Station. Next the EV Charging Station provides the customer access to the Payment Service Provider and the EV Charging Customer makes the transaction. Upon receiving validation from the Payment Service Provider, the EV Charging Station informs the EV Charging Customer, who then proceeds to connect the vehicle to the Charging Station. After the EV has been charged to the desired state of charge, the EV Charging Customer unplugs the EV.

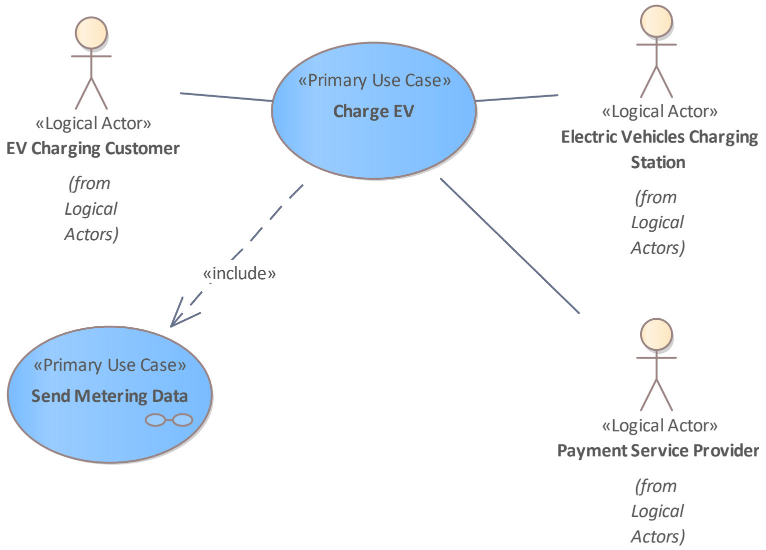

Figure 63 *PUC - Charge EV.*

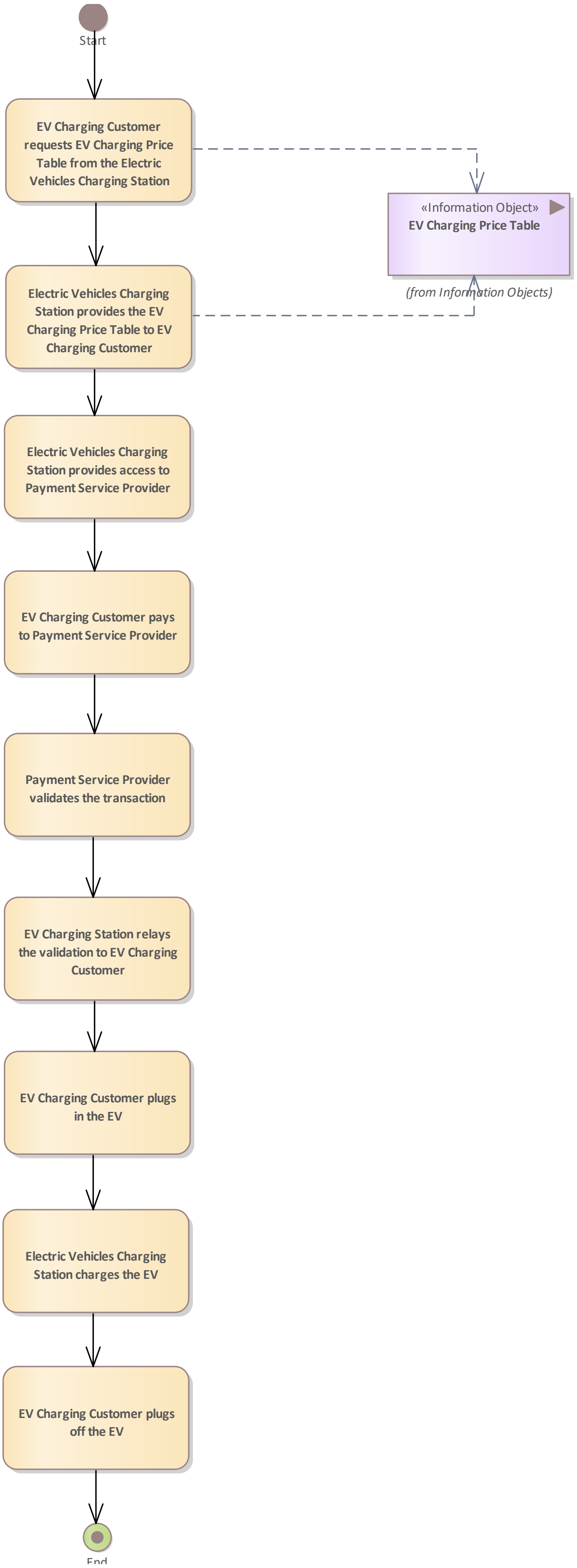

Figure 64 *Activity Diagram - Charge EV.*

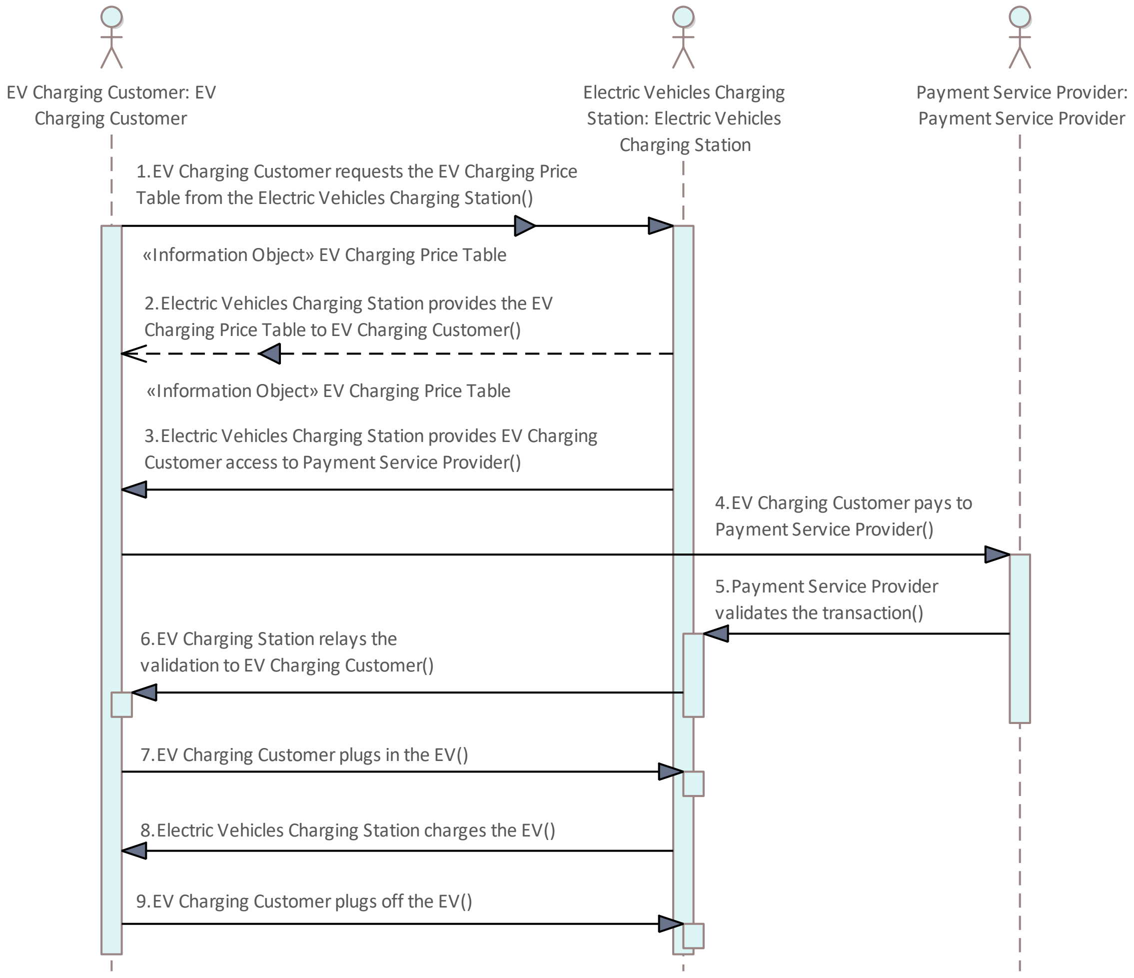

Figure 65 *Sequence Diagram - Charge EV.*

As the ownership structure of the LEM assets is not defined in the scenario studied in this thesis, the exact pricing scheme for EV charging and the formation of the EV Charging Price Table are left out of the scope of this thesis. Possible implementations are, however, explored here in a general way. In principle, the EV Charging Station would be owned and operated by the South Cornelly LEM community. Thus, there are two primary candidates for the entity which sets the EV charging prices: the LEOS and the Economic Optimisation Module. Given that the LEOS already manages the household electricity pricing, it could also set the same pricing scheme for EV charging. If vehicle to grid capability is to be utilised in the future, the EV charging would have to be managed by the LEOS. Similarly, utilising a smart charging approach, where the charging power is adjusted according to the system needs, would require the LEOS to ultimately manage the charging power. This could be implemented with the LEOS in a tertiary control role, the Energy Centre in a secondary control role and the EV Charging Station in a primary control role, or with LEOS interacting directly with the EV Charging Station. In both vehicle to grid and smart charging approaches, the pricing should incentivise the EV Charging Customer to leave the vehicle connected for a prolonged period of time instead of fast charging, as the latter provides only limited opportunities for managed charging. In addition, the customer should be compensated if providing vehicle to grid services.

In case smart charging or vehicle ton grid capabilities are not needed, the behaviour of EV Charging Customers could be guided using time of use pricing schemes. This could be managed by the Economic Optimisation Module, based on the Optimum Economic Dispatch Plan discussed in the section 4.5.6. The EV Charging Price Tables could, for example, incentivise EV charging during times of ample VRE generation. A separate question is whether to treat external EV Charging Customers differently from those which are LEM participants. Depending on the overall economic structure of the LEM and the needs of the community, the EV charging could be made free for LEM participants. Or the pricing scheme for LEM participants could be connected to other factors, such as the overall electricity consumption of the participant.

4.5.13 PUC - Send Metering Data

As the use case Store Accounting Data is very similar to the use case Send Metering Data, only one of them is described in detail here. The descriptions for the use case Store Accounting Data are found in the Appendix section, in Figure 90, Figure 91, and Figure 92. As numerous actors in the system collect metering data, the general actor Metering Data Sender is used here, as discussed in the section 4.3. Any new actor can be added to the category, realising the properties of the Metering Data Sender. The use case Send Metering Data has been kept simple, as it occurs frequently. The process, depicted in the Figure 66, Figure 67 and Figure 68, only involves the Metering Data Sender sending a Metering Data information object to the LEOS. This then prompts the LEOS to store Accounting Data. The processes are separated to allow possible extending or including the use case Store Accounting Data in other use cases.

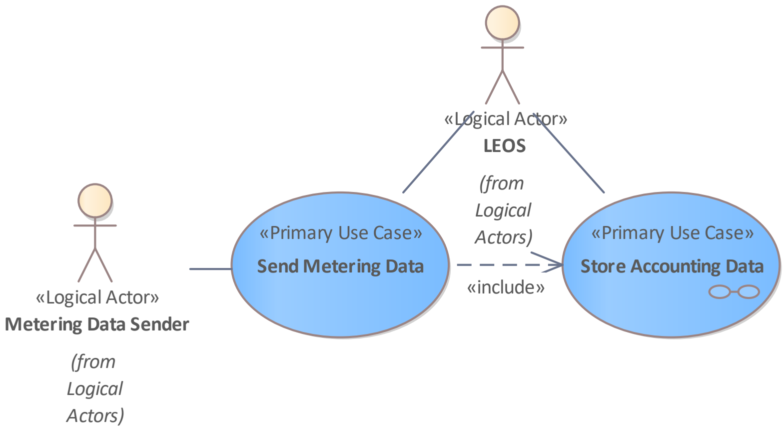

Figure 66 *PUC - Send Metering Data.*

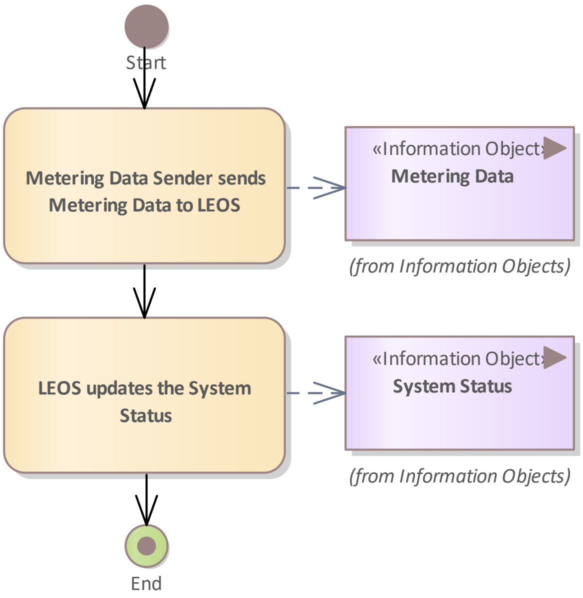

Figure 67 *Activity Diagram - Send Metering Data.*

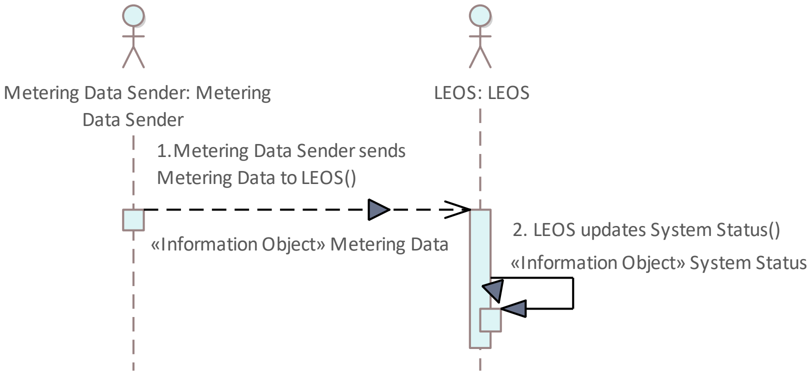

Figure 68 *Sequence Diagram - Send Metering Data.*

4.5.14 PUC – Request Accounting Data

Various external stakeholders may request access to the Accounting Data collected in the South Cornelly LEM. The specific contents of Accounting Data depend on the contractual structure adopted by the LEM community and the physical components selected, but it should at least contain the hourly or sub-hourly consumption and production figures for each household and each energy resource in the system. Likewise, the energy exported from the MV network side needs to be stored in the Accounting Data. This Accounting Data is needed to keep track of the electricity purchased from the Licensed Supplier and the electricity imported from the Wind Farm. Contrary to the current legislation in the UK, this thesis is based on a scenario where energy communities are allowed to directly share electricity between community members, without having to sell all produced electricity to the licensed supplier and to purchase electricity individually.

This is discussed in more detail in the section 1.3. In the current legislative framework, each household is encouraged to allow the installation of smart meters, operated by the electricity and gas suppliers. In the studied LEM scenario these meters are assumed to exist, and they are assumed to be used by the LEM participants who have not installed a HEMS system. It is also assumed that these smart meters are able to send data to the LEOS, in addition to sending data to the licensed supplier. In this study, it is assumed that the energy communities are allowed to purchase electricity and gas from the energy suppliers in an aggregated way, purchasing as a community rather than as individual households. In this scenario, the Accounting Data is used as a basis for these aggregated purchases. Although this thesis does not go into details of the internal pricing scheme of the energy community, the internal distribution of the costs of energy purchased would be based on the Accounting Data. There are various options for allocating these costs, which include direct allocation based on consumption, equal division between all community members or including the external electricity purchases as a component in the internal electricity pricing of the community. The latter could also be implemented in a way which would transfer the external hourly or day ahead prices of electricity to the internal pricing.

In other areas of the electricity distribution legislation, the studied scenario conforms by the current regulations in place in the UK. Thus, the LV network is assumed to be owned and ultimately manged by the DNO National Grid. This means, that distribution use of system charges are in principle billed by the DNO based on the smart meters on the premises of the individual households. However, if an agreement is reached with the DNO, the Accounting System provides an option for aggregating these charges based on the Accounting Data. Although the DNO could be considered an internal actor due to owning the LV network, organisationally it would be outside of the energy community. In addition, the energy community is assumed to have agreed with the DNO on receiving a degree of autonomous responsibility in the active network management of the LV network. Lastly, it is considered that the smart meter data collected by the DNO, and the data collected by the Accounting System are inherently separately owned datasets, even though a degree of data sharing is desirable. Given these circumstances, the DNO is considered an external actor, and it as well as the other actors mentioned inherit from the general actor External System, as presented in the Figure 70.

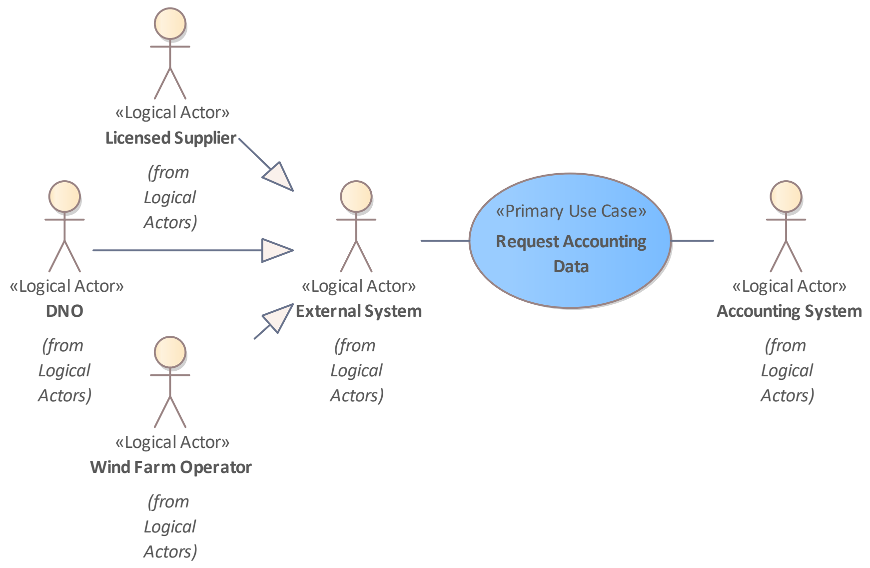

Figure 69 *PUC - Request Accounting Data.*

The use case is initiated when an External System requests Accounting Data from the Accounting System. Following the Figure 70 and Figure 71, the Accounting System then checks from the Access Rights Table, if the External System has Access Rights to the requested Accounting Data. If the External System does not have sufficient rights to access the Accounting Data, the Accounting System denies the data request made by the External System. The detailed authentication and encryption processes used are not in the scope of this study. If the External System does have rights to the data, the Accounting System sends the requested Accounting Data to the External System. The information object Accounting Data is used to represent all datasets containing accounting data, it does not specify the size or extent of the dataset shared and it does not imply that the whole database is shared. Only the data which are requested by the External System and to which the External System has sufficient access rights are shared.

As an important note, the system should not be open to public, in other words not everyone should be able to perform data requests. A public facing system would require extensive protection measures to prevent disruptions to the service, such as denial of service attacks. As the data are only intended to be available to verified users, access to the data should be provided through a private connection, such as a private web Application Programming Interface (API). A simple way to limit access to a web API is to keep the web address of the API secret for public, only sharing it with the verified stakeholders. Nevertheless, if the address is leaked, the API can be openly queried. Therefore, additional measures, such as requiring connection via a specific Virtual Private Network, should be considered. As stated before, however, this study does not take a stance on the specific cybersecurity approaches chosen.

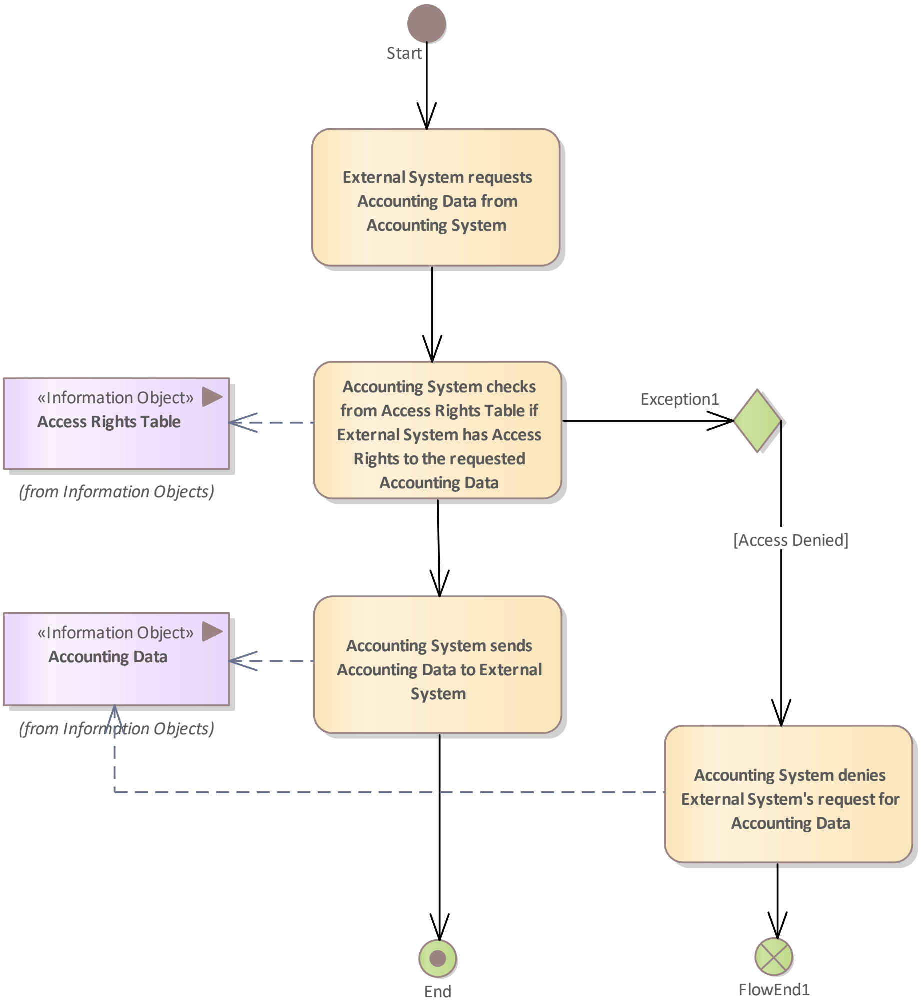

Figure 70 *Activity Diagram - Request Accounting Data.*

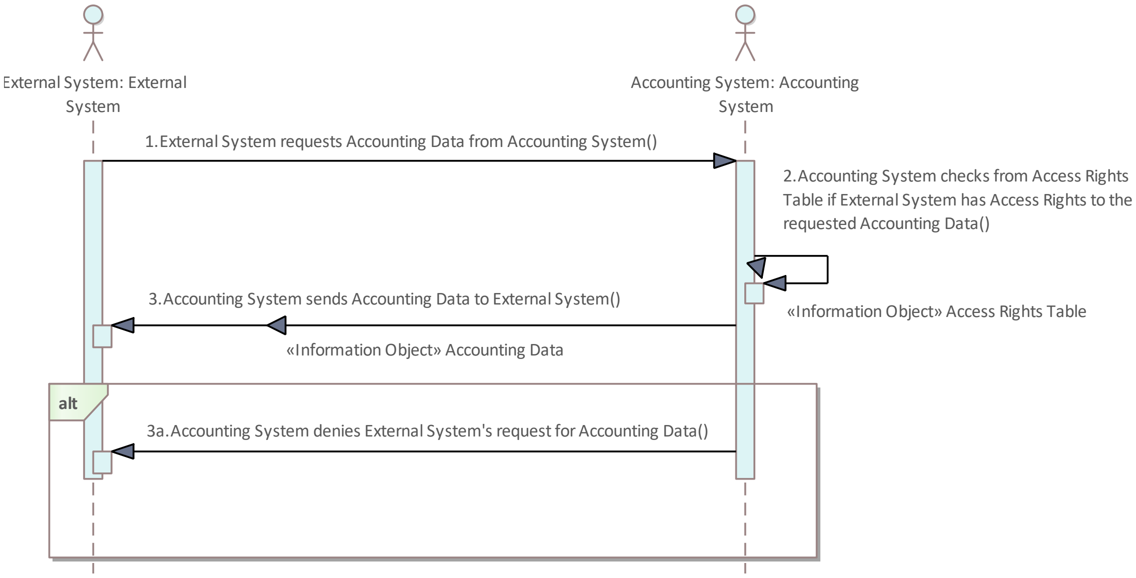

Figure 71 *Sequence Diagram - Request Accounting Data.*

5. DISCUSSION

This chapter discusses the key findings made during the development process of the LEOS model and its benefits to the South Cornelly LEM project and beyond. The main limitations of the LEOS model are also described and discussed, and possible future improvements are suggested.

The SGAM framework proved to be an apt choice for the basis of the LEOS model. The SGAM Interoperability Layers provided focus, as the Business and Function layers correspond well with the scope of this study. The SGAM Toolbox methodology separates the system level functional analysis to the System Analysis Phase and the design and solution level analysis to the System Architecture Phase. The computation independent approach of the System Analysis Phase was well suited for describing the LEOS functionality and further contributed to focusing this study. The SGAM Toolbox also provided versatile concepts for mapping the LEOS functionality and actors. These include the UML diagrams, which have been used both for mapping the business goals of the South Cornelly LEM actors to practical use cases and then for describing these use cases in detail.

With the actors and use cases mapped, and the use cases described in activity and sequence diagrams, the LEOS model provides a comprehensive overview of the LEOS functionality and the activity and communications involved. The model shows the extent of systems required to operate a microgrid in South Cornelly and provides a map to understand the interoperability and interconnections needed between different LEOS and LEM actors. Thus, the model is essential in assessing the feasibility and resource requirements of developing a LEOS and establishing a LEM in South Cornelly.

The activity and sequence diagrams developed act as a backbone for possible future implementations of the LEOS, providing a starting point for software development in the UML format commonly used in software engineering. They model also allows further development of the system architecture into the design and solution levels by expanding the model to the SGAM Communication, Information and Component layers. New functionality can also be added to the model, taking advantage of use case modularity and actor generalisations. In addition, the state machine developed for real-time control provides a template for system power flow control logic, although it would need to be algorithmically tested for possible dead ends.

Although developed for the South Cornelly LEM scenario described in the section 4.1, the LEOS model provides insights beyond the South Cornelly LEM project. The functionalities described in general use cases provide a reference for other energy community projects and energy management systems. As actor generalisation is used when defining the use cases, different resources and stakeholders can be added to the use case models. In addition, the modularity of the LEOS leaves room for adding or changing modules as needed.

Even so, not all aspects of the LEOS model are easily reusable in other projects. Some of the approaches taken are affected by the constraints and goals of the South Cornelly LEM scenario. These are less applicable to projects with different objectives. The South Cornelly specific requirements include the need of full backfeed prevention and some high-level architecture choices, such as introducing the Energy Centre concept. These are reflected in the responsibilities and grouping of the LEOS modules. Nevertheless, the information and communications architectures of the LEOS are left undefined, to allow for a multitude of different implementations. Similarly, subsystems that require defining the LEM ownership structure or internal and external pricing schemes, are left as “black box” modules. Thus, the internal functionalities of modules such as the Accounting System or Economic Optimisation Module are not defined in this thesis. General links for information object exchange between modules are proposed and general data collection responsibilities assigned. Although these choices are tailored for the South Cornelly LEM scenario, no position is taken on the possible contractual frameworks implemented in the community.

The microgrid control strategy implemented in the LEOS model is, however, highly specific to the South Cornelly LEM scenario. The real-time control logic and the interactions between different modules, such as the LEOS, the Real-Time Control Module, the Energy Centre, and the HEMSs are designed specifically for the scenario studied in this thesis. There is no easy way to fit these designs into other projects. Although the LEOS control strategy can be used as a general reference, a project with different set of constraints and resources would need significant modifications to the control logic. It can even be argued, that the microgrid control strategy should always be tailored to the requirements of the practical case study or project in question. Therefore, the parts of the LEOS model which deal with the real-time control of the microgrid are not very applicable to other research and energy community projects. Nevertheless, even if not directly applicable to projects with differing limitations and goals, the documented development process of the LEOS model provides guidelines and references for future projects aiming to establish or improve microgrid energy management systems.

The main limitation of this study is the strict focus on the system level functional analysis. Analysis on practical solutions and design has been limited and the SGAM Communication, Information and Component layer modelling has been excluded from this study. The two main factors behind this decision are the preliminary status of the South Cornelly LEM project itself and the extensive work required in model development. At the time of initialising this study, the LEM project was on the preliminary stages of establishing the LEOS concept. The availability of resources and therefore the specifics of the solution proposed were still under planning, so the focus of this study was set at the system and functional level and the study was based on a South Cornelly LEM scenario which may not reflect the eventual progress of the South Cornelly LEM project. The model development proved to be time consuming and the created diagrams extensive, which contributed to the need of strictly focusing the study on the functional level. Going beyond functional level analysis would have required selecting a specific focus in one system aspect or module, as analysing the whole system on a solution level granularity would have not been possible in the span of a master's thesis. To name two significant exclusions due to being outside of scope, the economic optimisation methodology used by the Economic Optimisation Module is not defined in this study and the cybersecurity aspects of the system are left for further analysis of the Communication, Information and Component levels.

Some limitations have also been implemented in the functional analysis. Although the SGAM Toolbox methodology includes mapping the use cases to SGAM zones and domains, this was excluded from this study in order to leave more space for the activity and sequence diagrams, which are part of the main output of this study. As the South Cornelly LEM scenario is mostly confined within a limited number of SGAM domains and zones, and only considers Business and Function layers, mapping individual use cases in this way was deemed of minor additional value for the study. However, if the study were to be expanded onto the Information and Communication layers, this mapping would provide an important basis on which to start building the system information and automation architectures.

The lack of information on the eventual physical characteristics of the system also imposes limitations for the analysis. The LEOS model focuses on the management of active power flows and does not consider reactive power control, although the latter has been identified as an effective solution in the literature. This decision has been made due to lack of information on the actual power converter equipment available for the possible future implementation of the South Cornelly LEM. Without knowledge on the share of rooftop solar PV systems in South Cornelly, the possible reactive power production and absorption capacities of these solar PV inverters, and the capacities of the Energy Centre energy resources, it is difficult to assess the feasibility of reactive power management. Therefore, the LEOS model has been based on active power management using BES systems and electrolysers, but with the system stability ensured by the option of curtailing solar PV output and importing power from the DNO MV grid. An option for islanded operation has been included for emergency purposes in situations where sufficient DER resources are available, but black start capability in islanded mode has been excluded, as it would require a significant amount of controllable energy resources to be available in the system.

There are various ways in which the model can be developed further, many of which go beyond functional analysis. Although the SGAM Toolbox utilises UML diagrams, the toolbox can be considered an example of a domain specific language, which implements general purpose UML concepts on a specific domain. In the future SysML (Systems modelling language) could be used to compliment the UML concepts with SysML specific Requirement Diagrams. These would allow for more formal capturing and specifying of the system performance requirements and constraints, such as latency requirements for system components.

If the LEM participants of South Cornelly are willing to invest in sufficient solar PV inverter capacity, or if funding is available from other sources, reactive power control may become highly effective option for reducing solar PV curtailment and improving security of supply and power quality. However, a simulation on the possible grid losses incurred in the real South Cornelly network should be performed before committing to this method. As pointed out in the literature, the reactive power control is especially well suited for higher levels of PV penetration [123]. In the LEOS model, reactive power control could be implemented in a distributed way as a volt-var droop control at the primary and secondary levels of control, with the primary controllers of each energy resource implementing the droop control and the HEMSs and the Energy Centre Inverter providing corrections for possible deviations. If a more centralised approach would be considered, it could be implemented within the Real-Time Control Module, for example in the state machine for the system control logic. However, the state machine is already complex and adding reactive power control there might make it unnecessarily convoluted. Instead, a hybrid approach of including algorithms inside the states and possibly breaking the control logic into multiple different but interconnected state machines could be explored.

Another possible improvement to the Real-Time Control Module and the state machine could be the inclusion of controllable loads in the central power flow management logic. The LEOS model developed in thesis leaves the scheduling of household loads to the

HEMSs, which make decisions based on the user preferences and the Household Electricity Prices Table updated to the HEMSs by the LEOS as part of the User Dashboard Data. Essentially, this is a price-based demand response mechanism, which provides a great degree of flexibility for the end users but is not always optimally efficient for the system as a whole. As people tend to form habits that require dedicated effort to change, it is expected that even with moderate price incentives, some households would not change consumption patterns. More behavioural changes may be achieved with more extreme price incentives, but there is likely a limit to the maximum prices the community would be willing to set.

Instead of the price-based, voluntary approach to demand response, more centralised control could also be given to the LEOS. In this kind of scenario, the LEOS would set more direct instructions for load shifting and the HEMS would follow these more rigidly. While this approach could increase the overall system efficiency, the community members would likely not prefer giving up all control over the household load scheduling. A voluntary hybrid approach could be implemented by allowing the households to turn on direct price-based control at the HEMS's end. In this approach, the LEOS would still send HEMS price signals instead of direct control signals, but the HEMS's own control logic would automatically adjust consumption based on the price signals, instead of following user set consumption schedules and time bands. Regardless of the approach chosen, the demand response capacity available at household premises is typically limited to a small number of schedulable loads, such as water heaters, dishwashers and washing machines. This capacity could, however, be significantly increased with the introduction of heat pumps and air conditioning units, smart EV charging and BES systems.

When it comes to enforcing system stability and improving active network management in islanded mode, the LEOS model could be expanded by including a grid-forming power converter as an actor. The current model positions the Energy Centre Inverter as the best suited holder of this role, but the state machine diagram could be edited to allow for changing the grid forming converter based on the generation capacity available. More detailed control logic for the grid forming converter would also improve the black start capability of the system and could be part of implementing such a function in the future, alongside a more robust process for synchronising with and reconnecting to the DNO MV grid.

Additionally, the contractual and practical microgrid management challenges rising from a mixture of LEM participants and non-participants in the same network could be explored further. The non-LEM households benefit from the network in the form of power quality and resilience. As the non-LEM households do not have similar incentives to shift and manage consumption as the LEM participants, the community may need to import electricity from the grid to cover for the higher consumption. Although the non-participants have separate contracts with licenced suppliers and pay for their consumption, this complicates the management and scheduling of the system energy resources.

Another complicating aspect is the division of system costs between the participants. This is a significant factor in the economic optimisation of the system, as the initial premise is not to export electricity over the MV substation the DNO side and to purchase as little imported electricity as possible. Even if the interaction with the outside electricity market can be minimal during times of high VRE generation, the Distribution Use of System Charges paid to the DNO for using the South Cornelly LV network ensure that there are costs involved in using locally produced electricity too. Thus, reassessing the goal of limiting purchases from the external electricity market could actually reduce the electricity costs for the community members who do not have solar PV at their premises. At times of high VRE generation, the market prices may be competitive with the locally produced electricity when the high round-trip costs incurred from the Distribution of Use of System Charges are counted in. As solar PV and BES systems cannot be installed at every household premises, a degree of sharing would be needed even in a system with a high self-sufficiency of DER resources. A near self-sufficient DER based system would also require considerable investments. This can make it notably less appealing option to the community, compared to a hybrid approach where electricity is purchased from the market when cost effective.

Whether the Distribution Use of System charges are divided between all LEM participants and an hourly aggregate price is set for everyone or whether the participants pay different prices based on their individual consumption behaviour will affect both the scheduling decisions made by the HEMSs and the optimal economic dispatch plans set by the Economic Optimisation module. Some houses are better suited for rooftop solar PV or BES installation and some households are keener to install these systems than others. If these differences are accounted for in the LEM internal electricity pricing scheme, they will also affect the optimal economic dispatch plans. Finally, some kind of contractual or accounting measures might be needed between the LEM, the non-participants, and the licensed suppliers. If the non-participants consume locally produced electricity at a time of high solar PV output, and no electricity is imported to the LV network from outside, the Distribution Use of System Charges are incurred to the LEM while nothing is purchased from the licensed suppliers. The Distribution Use of System Charges thus pose one additional limitation for LEM projects in the UK. With the current charges in place, significant portion of the system planning, and optimisation has to go into minimising any excess flows between different energy resources in the system. This implies prioritising the consumption of solar PV generation at the premises of the producing household or storing the excess in a local BES system. Storing excess production in the central BES system at the Energy Centre would be an especially costly option and therefore possibly underutilised except for times of peak consumption or production. These round-trip costs of sharing energy between community members limit the initial goal of optimising the local production and consumption and sharing the resources among community members. Additionally, this study relies on the local wind farm to supplement solar PV generation. The wind farm is assumed to give the community preferential access to the wind generation whenever needed, at a reasonable price. This may not be a realistic expectation from a power purchase agreement. Thus, different contractual options should be explored for the private wire wind generation contract, and this should be taken into account in the overall economic planning.

This study does not engage in estimating the economic viability of the studied energy community model. The purpose of this study is to provide an understanding of the general functionality required to realise such a model. Before any practical implementation of the LEOS is planned, the contractual and economic dimensions of the studied scenario should be mapped in depth, in a regulatory framework grounded on a realistic outlook on the current legislative direction.

In addition, introducing a novel active network management system with islanding capacity would require significant additional design work on top of the general functional description of the LEOS presented in this thesis. This would include acquiring the exact topography of the existing LV network infrastructure in South Cornelly and building a simulation model with the expected demand and generation in place. The scenarios of minimum and maximum network load should be estimated, within the thermal limits of the feeders and existing network equipment. These estimates should be used in defining the performance requirements for new network equipment and the communications infrastructure. A system capable of stable and safe islanded operating mode based on purely inverter output from DERs requires significant emphasis on the robust real-time communication between different DER systems. This thesis lays down a basic real-time control logic based on system states. This basic control logic is only the first step among many in a practical implementation of a real-time microgrid control system. It maps the principles for tertiary level control, which need to be implemented by secondary and primary level solutions. Given that the primary control level would need to operate in the milliseconds range, a great deal of planning needs to go into finding a suitable control approach, as discussed in the section 2.3. The choice of control approach among droop-control, virtual synchronous generators, centralised master-slave control, or other similar approaches will define the fundamental requirements for not only the communications infrastructure, but also for the power converter and metering hardware used.

6. CONCLUSIONS

The world is embroiled in era-defining environmental, social, and economic changes. Swift actions are needed in combating the impacts of the human induced climate change and the social and economic challenges brought with it. To rapidly deploy low carbon energy sources and to mitigate the adverse effects of the climate the change, this thesis recommends the establishment of energy communities. When based on distributed renewable energy resources, these communities exhibit resilience to disruptions in the wider energy system and supply chains. In addition to improving self-sufficiency, the energy communities open new social and economic opportunities for the community members.

This thesis has built on the groundwork laid by the Belgian energy specialist company Challoch Energy in the South Cornelly LEM project, which aims to establish a low carbon energy community in South-Wales. Under the guidance of Mike Parr, this thesis has continued the work in identifying the relevant actors, the business and community goals, and the business and physical restrictions of the South Cornelly LEM scenario. Various challenges in microgrid deployment were identified, with the control and optimal management of the microgrid energy resources deemed as one of the most critical. The main research question of this thesis is, how to present and define the functionality of a central LEOS, which interacts with HEMSs and other microgrid assets, in a standardised manner? In other words, this thesis seeks to develop a functional description of the LEOS. In addition, this thesis aims to model the mentioned functionality in a universal manner, using standards which a diverse range of stakeholders can understand. Additionally, a key objective behind the LEOS is a modular and universal approach, inspired by similar architecture found in computer operating systems. The goal is to create a flexible platform with standardised interfaces for different assets.

To answer the questions posed, this thesis presents a functional description of a LEOS using the SGAM framework. The framework has been chosen due to its fit with the European technological and regulatory ecosystems and its ability to formally identify and describe actors and functionality. The availability of the SGAM Toolbox extension for the software Enterprise Architect was an additional contributing factor, as it significantly accelerated the model development process. The SGAM framework fulfils the objective of unified approach well. The SGAM Toolbox provides the UML diagrams required to model the LEOS functionality in a standardised way, widely used and understood across the fields of systems and software engineering.

The scope of this study is defined using the SGAM Layers of Interoperability and the phases described in the SGAM Toolbox. The System Analysis Phase covering the development of the Business and Function Layers is selected, as this platform independent approach suits the LEOS functional description well. The System Architecture Phase describing the Community, Information and Component Layers is left out. Thus, the possible information, communication and automation infrastructures employed to realise the LEOS are not covered. The communication and control between the LEOS and other system assets is detailed on a functional level, fulfilling the initial research question. From an implementation perspective, however, completely separating the System Analysis phase from the Architecture Phase in this way may be counterproductive. Although the Function Layer should in principle set the requirements for the system architecture, it is unlikely that all architecture choices will be equally viable. Adjusting the Function Layer models may be needed along the implementation process, as the architecture choices are explored, and the most suitable solution is selected.

In accordance with the objectives set, the LEOS model entails a degree of universality and modularity in the forms of actor generalisation and modularisation of different system functionalities. However, as discussed in the section 5, the control strategy selected is specific to the South Cornelly LEM scenario and mostly not applicable to other projects. In addition, the South Cornelly LEM scenario includes concepts such as the Energy Centre, which also break the principle of universality. All in all, the LEOS model only partially reaches the objective of general applicability and extendibility. It can be argued that in most cases the control strategy of a microgrid management system should be tailored to the specific performance requirements and environment in each project. Alluding to the computer operating system reference which the LEOS concept draws from, the operating system needs dedicated drivers for each component in order to effectively utilise them.

Another feature of computer operating systems originally intended to be applied to the LEOS is the use of standardised interfaces. The generalisation of actors partly implements this in the LEOS model, but the main realm for standardisation and interoperability lies on the Communication and Information Layers. Therefore, additional design work would be needed to ensure the interoperability of different assets envisioned for the LEOS. This is one of the identified avenues for future research. By combining tailored control strategies and existing universal standards, general purpose interfaces could be provided for various microgrid resources. As an example, this could mean a common interface for all types of DER generation, realised in the back end using control software similar in principle to the drivers on computer platforms.

Given the practical economic, regulative, and physical constraints discussed in chapter 5, significant changes to the goals and structuring of the LEM project may be needed to ensure day-to-day economic viability, realistic investment costs and a reliable microgrid control system. Nevertheless, the LEOS provides a basis for further expansion into the SGAM Communication, Information and Component layers.

Possible future additions to the model and opportunities for further studies include using the SGAM framework to analyse and implement economic optimisation methodology, and pricing and contractual frameworks which are fair for all community members while incentivising optimal use of energy. Another avenue for future research is developing general purpose interfaces for microgrid assets, transforming the LEOS to a modular and universal platform similar to a computer operating system. This kind of platform would benefit from improved scalability and lower threshold for deployment, improving the user experience of communities using the platform and reducing the technical skill level needed to manage the system. Additionally, cybersecurity measures should be developed to protect the LEOS software, and the network and household hardware. These are vital for the reliable and secure operation of any energy system. Furthermore, different solutions for integrating reactive power control into the LEOS could be explored to improve the system performance and stability and reduce the need for solar PV curtailment. Lastly, the interaction between the microgrid and the DNO MV network could be further explored to realise efficiency benefits for both and to improve the islanding and reconnection capabilities of the microgrid. This could involve developing more robust communication and control strategies for the islanded operating mode, including the utilisation of multiple power converters capable of switching in and out of the grid forming role as needed.

REFERENCES

[1] C. Free and A. Hecimovic, “Global supply chains after COVID-19: the end of the road for neoliberal globalisation?,” *Accounting, Audit. Account. J.*, vol. 34, no. 1, pp. 58–84, Jan. 2021.

[2] J. Nayak, M. Mishra, B. Naik, H. Swapnarekha, K. Cengiz, and V. Shanmuganathan, *An impact study of COVID-19 on six different industries: Automobile, energy and power, agriculture, education, travel and tourism and consumer electronics*, vol. 39, no. 3. 2022.

[3] European Commission, “REPowerEU: Joint European Action for more affordable, secure and sustainable energy,” 2022. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A230%3AFIN&qid=1653033742483

[4] The White House, “FACT SHEET: United States Bans Imports of Russian Oil, Liquefied Natural Gas, and Coal.” Accessed: Oct. 18, 2023. Available: https://www.whitehouse.gov/briefing-room/statements-releases/2022/03/08/fact-sheet-united-states-bans-imports-of-russian-oil-liquefied-natural-gas-and-coal/

[5] WMO, “2021 one of the seven warmest years on record, WMO consolidated data showsitle.” Accessed: Oct. 18, 2023. Available: https://public.wmo.int/en/media/press-release/2021-one-of-seven-warmest-years-record-wmo-consolidated-data-shows

[6] IPCC, “Climate Change 2022 - Impacts, Adaptation and Vulnerability - Summary for Policymakers,” 2546. Available: https://report.ipcc.ch/ar6wg2/pdf/IPCC_AR6_WGII_SummaryForPolicymakers.pdf

[7] UN Office for Disaster Risk Reduction and Centre for Research on the Epidemiology of Disasters, “Human Cost of Disasters - An overview of the last 20 years 2000-2019,” 2020.

[8] United Nations, *The Paris Agreement*. United Nations, 2015. Available: https://unfccc.int/sites/default/files/english_paris_agreement.pdf

[9] IEA, “Net Zero by 2050: A Roadmap for the Global Energy Sector,” 2021. Available: https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c-10b13d840027/NetZeroby2050-ARoadmapfortheGlobalEnergySector_CORR.pdf

[10] UNEP, IRENA, and UNESCAP, “Theme Report On Eenergy Transition - Towards The Achievement Of SDG 7 and Net-Zero Emissions,” 2021. Available: https://www.un.org/sites/un2.un.org/files/2021-twg_2-062321.pdf

[11] IRENA, *World Energy Transitions Outlook 2022: 1.5°C Pathway*. Abu Dhabi: IRENA, 2022. Available: https://www.irena.org/publications/2022/Mar/World-Energy-Transitions-Outlook-2022

[12] D. McCauley and R. Heffron, “Just transition: Integrating climate, energy and environmental justice,” *Energy Policy*, vol. 119, pp. 1–7, Aug. 2018.

[13] S. Abram *et al.*, “Just Transition: A whole-systems approach to decarbonisation,” *Clim. Policy*, vol. 22, no. 8, pp. 1033–1049, 2022.

[14] B. Galgóczi, “From a ‘just transition for us’ to a ‘just transition for all,’” *Transf. Eur. Rev. Labour Res.*, vol. 28, no. 3, pp. 349–366, Aug. 2022.

[15] X. Wang and K. Lo, “Just transition: A conceptual review,” *Energy Res. Soc. Sci.*, vol. 82, Dec. 2021.

[16] International Renewable Energy Agency, “Renewable power generation costs in 2021,” 2022. Available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Jul/IRENA_Power_Generation_Costs_2021.pdf?rev=34c22a4b244d434da0accde7de7c73d8

[17] J. G. Rendon and D. M. López González, “Opportunities and challenges of mainstreaming distributed energy resources towards the transition to more efficient and resilient energy markets,” *Renew. Sustain. Energy Rev.*, vol. 157, no. December 2021, p. Article 111751, 2022.

[18] M. Pagliaro and F. Meneguzzo, “Distributed Generation from Renewable Energy Sources : Ending Energy Poverty across the World,” *Energy Technol.*, vol. 8, no. 7, pp. 1–7, 2020.

[19] T. Jin, T. Shi, and T. Park, “The quest for carbon-neutral industrial operations: renewable power purchase versus distributed generation,” *Int. J. Prod. Res.*, vol. 56, no. 17, pp. 5723–5735, 2018.

[20] V. Brummer, “Community energy – benefits and barriers: A comparative literature review of Community Energy in the UK, Germany and the USA, the benefits it provides for society and the barriers it faces,” *Renewable and Sustainable Energy Reviews*, vol. 94. Elsevier Ltd, pp. 187–196, Oct. 01, 2018.

[21] T. R. B. Kushal and M. S. Illindala, “Decision Support Framework for Resilience-

Oriented Cost-Effective Distributed Generation Expansion in Power Systems," *IEEE Trans. Ind. Appl.*, vol. 57, no. 2, pp. 1246–1254, Mar. 2021.

[22] R. Poudineh and T. Jamasb, "Distributed generation, storage, demand response and energy efficiency as alternatives to grid capacity enhancement," *Energy Policy*, vol. 67, pp. 222–231, 2014.

[23] A. Hussain, V. H. Bui, and H. M. Kim, "Microgrids as a resilience resource and strategies used by microgrids for enhancing resilience," *Applied Energy*, vol. 240. Elsevier Ltd, pp. 56–72, Apr. 15, 2019.

[24] Y. Wen, Y. Dai, X. Zhou, and F. Qian, "Multiple roles coordinated control of battery storage units in a large-scale island microgrid application," *IEEJ Trans. Electr. Electron. Eng.*, vol. 12, no. 4, pp. 527–535, 2017.

[25] X. Liu, E. G. O'Rear, W. E. Tyner, and J. F. Pekny, "Purchasing vs. leasing: A benefit-cost analysis of residential solar PV panel use in California," *Renew. Energy*, vol. 66, pp. 770–774, 2014.

[26] ENTSO-E, "Options for the design of European Electricity Markets in 2030," 2021. Available: https://eepublicdownloads.entsoe.eu/clean-documents/Publications/Market Committee publications/210331_Market_design 2030.pdf

[27] Energinet, Fingrid, Statnett, and Svenska Kraftnät, "Solutions Report 2020," 2020. Available: https://www.fingrid.fi/globalassets/dokumentit/fi/tiedotteet/sahkomarkkinat/2020/solutions-report-2020-3-april-2020-updated-figure.pdf

[28] A. G. Zamani, A. Zakariazadeh, and S. Jadid, "Day-ahead resource scheduling of a renewable energy based virtual power plant," *Appl. Energy*, vol. 169, pp. 324–340, 2016.

[29] Institute of Electrical and Electronics Engineers, *IEEE PC62.62/D3, November 2017 : IEEE Approved Draft Standard Test Specifications for Surge-Protective Devices (SPDs) for Use on the Load Side of the Service Equipment in Low-Voltage (1000 V and Less) AC Power Circuits.* IEEE, 2018.

[30] International Electrotechnical Commission, *IEC TS 62898-1:2017 - Microgrids. Part 1, Guidelines for microgrid projects planning and specification*. 2017.

[31] European Parliament and Council of the European Union, *Directive (EU) 2019/944 on Common Rules for the Internal Market for Electricity and Amending Directive 2012/27/EU*, no. L 158. 2019, p. 18. Available:

http://www.omel.es/en/files/directive_celex_32019l0944_en.pdf

[32] Council of European Energy Regulators, “Regulatory Aspects of Self-Consumption and Energy Communities, CEER Report C18-CRM9_DS7-05-03,” 2019. Available: https://www.ceer.eu/documents/104400/-/-/8ee38e61-a802-bd6f-db27-4fb61aa6eb6a

[33] UK Department of Energy & Climate Change (DECC), “Community Energy Strategy: Full Report,” 2014. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/275163/20140126Community_Energy_Strategy.pdf

[34] I. Savelli and T. Morstyn, “Better together: Harnessing social relationships in smart energy communities,” *Energy Res. Soc. Sci.*, vol. 78, no. February, p. 102125, 2021.

[35] S. Moroni, V. Antoniucci, and A. Bisello, “Energy sprawl , land taking and distributed generation : towards a multi-layered density,” *Energy Policy*, vol. 98, pp. 266–273, 2016.

[36] European Commission, “State of the Energy Union 2021 – Contributing to the European Green Deal and the Union’s recovery,” pp. 1–30, 2021.

[37] Community Energy England, Community Energy Wales, and Community Energy Scotland, “Community Energy State of the Sector Report 2021 Working together towards net zero,” 2021. Available: https://communityenergyengland.org/files/document/523/1624438045_UKSOTSReport.pdf

[38] European Commission, “European Commission Communication: Europe’s moment: Repair and Prepare for the Next Generation,” 2020. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0456&from=EN

[39] United Nations, *TRANSFORMING OUR WORLD: THE 2030 AGENDA FOR SUSTAINABLE DEVELOPMENT*, no. October. 2015.

[40] International Energy Agency, International Renewable Energy Agency, United Nations Statistics Division, The World Bank, and World Health Organization, “Tracking SDG7 - The energy progress report 2021,” 2021. Available: https://trackingsdg7.esmap.org/data/files/download-documents/2021_tracking_sdg7_report.pdf

[41] F. Lombardi, F. Riva, M. Sacchi, and E. Colombo, “Energy for Sustainable

Development Enabling combined access to electricity and clean cooking with PV-microgrids : new evidences from a high-resolution model of cooking loads," *Energy Sustain. Dev.*, vol. 49, pp. 78–88, 2019.

[42] V. S. K. V Harish, N. Anwer, and A. Kumar, "Applications , planning and socio-techno-economic analysis of distributed energy systems for rural electrification in India and other countries : A review," *Sustain. Energy Technol. Assessments*, vol. 52, no. PA, p. 102032, 2022.

[43] D. Kollanyi, A. Bharadwaj, and P. Weston, "PRODUCTIVE USE OF ENERGY IN AFRICAN MICRO-GRIDS : TECHNICAL AND BUSINESS CONSIDERATIONS," 2018. Available: https://www.nrel.gov/docs/fy18osti/71663.pdf

[44] V. Motjoadi, P. N. Bokoro, and M. O. Onibonoje, "A Review of Microgrid-Based Approach to Rural Electrification in South Africa : Architecture and Policy Framework," *Energies*, vol. 13, no. 2193, pp. 1–23, 2020.

[45] S. C. Bhattacharyya and D. Palit, "Mini-grid based off-grid electrification to enhance electricity access in developing countries : What policies may be required ?," *Energy Policy*, vol. 94, pp. 166–178, 2016.

[46] Y. Wang, H. Li, B. Sun, H. Chen, H. Li, and Y. Luo, "Drought Impacts on Hydropower Capacity Over the Yangtze River Basin and Their Future Projections under 1.5/2°C Warming Scenarios," *Front. Earth Sci.*, vol. 8, no. September, pp. 1–13, 2020.

[47] J. Doss-Gollin, D. J. Farnham, U. Lall, and V. Modi, "How unprecedented was the February 2021 Texas cold snap?," *Environ. Res. Lett.*, vol. 16, no. 6, p. 64056, 2021.

[48] F. H. Jufri, V. Widiputra, and J. Jung, "State-of-the-art review on power grid resilience to extreme weather events: Definitions, frameworks, quantitative assessment methodologies, and enhancement strategies," *Appl. Energy*, vol. 239, no. January, pp. 1049–1065, 2019.

[49] G. Mutani, S. Santantonio, G. Brunetta, O. Caldarice, and M. Demichela, "An energy community for territorial resilience: Measurement of the risk of an energy supply blackout," *Energy Build.*, vol. 240, Jun. 2021.

[50] National Grid ESO, TNEI, and SP Energy Networks, "Energy restoration for tomorrow Project progress report December 2021," 2021. Available: https://www.nationalgrideso.com/document/226946/download

[51] P. E. Bett and H. E. Thornton, "The climatological relationships between wind and

solar energy supply in Britain," *Renew. Energy*, vol. 87, pp. 96–110, 2016.

[52] B. Aylott, J. Pecinovsky, and J. Laveyne, "REScoop VPP - D3.1 Final design/specification," 2020. Available: https://uploads.strikinglycdn.com/files/5134c203-ac31-4567-bf7a-7d7992b40218/D3.1 Final design_specification.pdf

[53] D. Katsaprakakis and I. Dakanali, "Comparing electricity storage technologies for small insular grids," *Energy Procedia*, vol. 159, pp. 84–89, 2019.

[54] D. Parra *et al.*, "An interdisciplinary review of energy storage for communities: Challenges and perspectives," *Renew. Sustain. Energy Rev.*, vol. 79, no. March, pp. 730–749, 2017.

[55] G. Barbose and D. Naïm, "Tracking the Sun - Pricing and Design Trends for Distributed Photovoltaic Systems in the United States - 2019 Edition," 2019.

[56] A. J. Pimm, T. T. Cockerill, and P. G. Taylor, "The potential for peak shaving on low voltage distribution networks using electricity storage," *J. Energy Storage*, vol. 16, pp. 231–242, 2018.

[57] J. M. Aberilla, A. Gallego-Schmid, L. Stamford, and A. Azapagic, "Design and environmental sustainability assessment of small-scale off-grid energy systems for remote rural communities," *Appl. Energy*, vol. 258, no. November, p. 114004, 2020.

[58] M. F. Zia, E. Elbouchikhi, and M. Benbouzid, "Microgrids energy management systems: A critical review on methods, solutions, and prospects," *Appl. Energy*, vol. 222, pp. 1033–1055, Jul. 2018.

[59] International Electrotechnical CommissionInternational Electrotechnical Commission.Technical Committee 8, *IEC TS 62898-2:2018 - Microgrids. Part 2, Guidelines for operation*. 2018. Available: https://webstore.iec.ch/preview/info_iects62898-2%7Bed1.0%7Den.pdf

[60] Z. Tang, D. J. Hill, and T. Liu, "A Novel Consensus-Based Economic Dispatch for Microgrids," *IEEE Trans. Smart Grid*, vol. 9, no. 4, pp. 3920–3922, 2018.

[61] K. Sirviö, K. Kauhaniemi, A. A. Memon, H. Laaksonen, and L. Kumpulainen, "Functional analysis of the microgrid concept applied to case studies of the sundom smart grid," *Energies*, vol. 13, no. 6, Aug. 2020.

[62] CEN-CENELEC-ETSI Smart Grid Coordination Group, "CEN-CENELEC-ETSI Smart Grid Coordination Group - Smart Grid Reference Architecture," 2012.

Accessed: May 04, 2023. Available: https://www.cencenelec.eu/media/CEN-CENELEC/AreasOfWork/CEN-CENELEC_Topics/Smart Grids and Meters/Smart Grids/reference_architecture_smartgrids.pdf

[63] Institute of Electrical and Electronics Engineers, *IEEE Guide for Smart Grid Interoperability of Energy Technology and Information Technology Operation with the Electric Power System (EPS), End-Use Applications, and Loads*. 2011.

[64] R. Babaei, D. S. K. Ting, and R. Carriveau, “Optimization of hydrogen-producing sustainable island microgrids,” *Int. J. Hydrogen Energy*, vol. 47, no. 32, pp. 14375–14392, 2022.

[65] L. Huang, W. Sun, Q. Li, W. Li, and H. Zhang, “Distributed adaptive secondary control for microgrids with time delay and switching topology,” *Electr. Power Syst. Res.*, vol. 210, Sep. 2022.

[66] M. Y. Divani, M. Najafi, A. Ghaedi, and H. Gorginpour, “Security-constrained optimal scheduling and operation of island microgrids considering demand response and electric vehicles,” *Int. Trans. Electr. Energy Syst.*, vol. 31, no. 12, pp. 1–26, 2021.

[67] C. Lee and M. Tuegeh, “Optimal optimisation-based microgrid scheduling considering impacts of unexpected forecast errors due to the uncertainty of renewable generation and loads fluctuation,” vol. 14, pp. 321–331, 2020.

[68] Q. Zhang, J. Ding, W. Shen, J. Ma, and G. Li, “Multiobjective Particle Swarm Optimization for Microgrids Pareto Optimization Dispatch,” vol. 2020, 2020.

[69] D. E. Olivares *et al.*, “Trends in microgrid control,” *IEEE Trans. Smart Grid*, vol. 5, no. 4, pp. 1905–1919, 2014.

[70] F. Gao, R. Kang, J. Cao, and T. Yang, “Primary and secondary control in DC microgrids: a review,” *J. Mod. Power Syst. Clean Energy*, vol. 7, no. 2, pp. 227–242, Mar. 2019.

[71] I. Serban, S. Cespedes, C. Marinescu, C. A. Azurdia-Meza, J. S. Gomez, and D. S. Hueichapan, “Communication requirements in microgrids: A practical survey,” *IEEE Access*, vol. 8, pp. 47694–47712, 2020.

[72] O. Palizban and K. Kauhaniemi, “Hierarchical control structure in microgrids with distributed generation: Island and grid-connected mode,” *Renew. Sustain. Energy Rev.*, vol. 44, pp. 797–813, 2015.

[73] M. Uslar *et al.*, “Applying the smart grid architecture model for designing and

validating system-of-systems in the power and energy domain: A European perspective," *Energies*, vol. 12, no. 2. MDPI AG, Jan. 15, 2019.

[74] S. P. Menci, J. Le Baut, J. M. Domingo, G. L. López, R. C. Arín, and M. P. Silva, "A novel methodology for the scalability analysis of ICT systems for smart grids based on SGAM: The InteGrid project approach," *Energies*, vol. 13, no. 15, Aug. 2020.

[75] Challoch Energy, "Challoch Energy - Projects." Accessed: May 07, 2023. Available: https://www.challoch-energy.com/projects

[76] Bridgend County Borough Council, "Bridgend County Borough Council - Low Carbon Communities." Accessed: May 07, 2023. Available: https://www.bridgend.gov.uk/residents/housing/low-carbon-communities/

[77] Ofegem, "Supply licence guide : Introduction to the supply licences," 2019, Available: https://www.ofgem.gov.uk/sites/default/files/docs/2019/02/introduction_to_the_supply_licences_0.pdf

[78] C. Coutinho, *Energy Bill [HL] - As Amended - Report Stage: Tuesday 5 September 2023*, no. September. House of Commons, 2023. Available: https://publications.parliament.uk/pa/bills/cbill/58-03/0340/amend/energy_day_rep_0905.pdf

[79] J. Lowitzsch, C. E. Hoicka, and F. J. van Tulder, "Renewable energy communities under the 2019 European Clean Energy Package – Governance model for the energy clusters of the future?," *Renew. Sustain. Energy Rev.*, vol. 122, Apr. 2020.

[80] European Commission, *Communication from the Commission to the European Parliament, Council, The European Social Committee and the Committee of the Regions: Smart Grids: from innovation to deployment*. European Union, 2011. Available: http://ec.europa.eu/energy/gas_electricity/smartgrids/doc/expert_group1.pdf.

[81] Directorate-General for Energy - European Commission, *Standardization Mandate to European Standardisation Organisations (ESOs) to support European Smart Grid deployment*. European Union, 2011. Available: https://energy.ec.europa.eu/system/files/2014-11/2011_03_01_mandate_m490_en_0.pdf

[82] G. Locke and P. D. Gallagher, "NIST Special Publication 1108 NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 1.0," 2010.

Available: https://www.nist.gov/system/files/documents/smartgrid/FinalSGDoc2010019-corr010411-2.pdf

[83] Institute of Electrical and Electronics Engineers, *IEEE Application Guide for IEEE Std 1547 - IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems*. 2003.

[84] Institute of Electrical and Electronics Engineers, *IEEE Std 2030.9-2019 IEEE Recommended Practice for the Planning and Design of the Microgrid*. IEEE, 2019. Available: https://sagroups.ieee.org/scc21/standards/2030-9-2019/

[85] International Electrotechnical Commission, *IEC SRD 63200 Systems Reference Deliverable - Definition of extended SGAM smart energy grid reference architecture model*. 2021. Available: https://webstore.iec.ch/preview/info_iecsrd63200%7Bed1.0%7Den.pdf

[86] European Parliament and European Council, *Regulation (EU) No 1025/2012 of the European Parliament and of the Council of 25 October 2012 on European standardisation*. European Union, 2015. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32012R1025#:~:text=Regulation %28EU%29 No 1025%2F2012 of the European Parliament,and of the Council Text with EEA relevance

[87] European Committee for Electrotechnical Standardization, “European Standards.” Accessed: May 01, 2023. Available: https://www.cencenelec.eu/european-standardization/european-standards/

[88] M. Valdes, X. Ren, S. Sapre, M. Trivette, and S. Meiners, “Reviewing equipment standards: Differences between the IEC and IEEE electrical equipment standards,” *IEEE Ind. Appl. Mag.*, vol. 20, no. 1, pp. 16–32, 2014.

[89] European Committee for Electrotechnical Standardization, “About CENELEC - The Frankfurt Agreement.” Accessed: May 01, 2023. Available: https://www.cencenelec.eu/about-cenelec/cenelec-and-iec-cooperation/

[90] European Committee for Electrotechnical Standardization, *CENELEC GUIDE 13 IEC-CENELEC Agreement on Common planning of new work and parallel voting*. 2016. Available: https://www.cencenelec.eu/media/Guides/CLC/13_cenelecguide13.pdf

[91] European Commission, “E02892-Smart Grids Task Force Abbreviation: SGTF Policy Area: Energy Lead DG: ENER-DG Energy,” 2023. Available:

https://circabc.europa.eu/ui/group/f5b849d3-26ae-4cba-b9f9-6bc6688c5f58/library/605cef0a-ee4d-402d-

[92] CEN-CENELEC-ETSI Smart Grid Coordination Group, “CEN-CENELEC-ETSI Smart Grid Coordination Group-Framework Document,” 2012. Available: https://www.cencenelec.eu/media/CEN-CENELEC/AreasOfWork/CEN-CENELEC_Topics/Smart Grids and Meters/Smart Grids/smartgrids_frameworkdocument.pdf

[93] GridWise Architecture Council, “GridWise® Interoperability Context-Setting Framework The GridWise Architecture Council,” 2008. Available: https://gridwiseac.org/pdfs/GridWise_Interoperability_Context_Setting_Framework.pdf

[94] National E-Health Transition Authority of Australia, “Towards an Interoperability Framework,” 2005. Available: http://www.providersedge.com/ehdocs/ehr_articles/towards_an_interoperability_framework.pdf

[95] Institute of Electrical and Electronics Engineers, *2030.2-2015 - IEEE Guide for the Interoperability of Energy Storage Systems Integrated with the Electric Power Infrastructure*.

[96] Institute of Electrical and Electronics Engineers, *2030.2.1-2019 - IEEE Guide for Design, Operation, and Maintenance of Battery Energy Storage Systems, both Stationary and Mobile, and Applications Integrated with Electric Power Systems*. IEEE, 2019.

[97] CEN-CENELEC-ETSI Smart Grid Coordination Group, “SG-CG/ M490/F_ Overview of SG-CG Methodologies,” 2014. Available: https://www.cencenelec.eu/media/CEN-CENELEC/AreasOfWork/CEN-CENELEC_Topics/Smart Grids and Meters/Smart Grids/2_sgcg_methodology_overview.pdf

[98] I. Zečević, P. Bjeljac, B. Perišić, V. Maruna, and D. Venus, “Domain-Specific Modeling Environment for Developing Domain Specific Modeling Languages as Lightweight General Purpose Modeling Language Extensions,” in *Recent Advances in Information Systems and Technologies*, Springer, Cham, 2017, pp. 872–881.

[99] Object Management Group, *OMG Unified Modeling Language (OMG UML) Version 2.5.1*. 2017. Available:

https://www.omg.org/spec/UML/20161101/PrimitiveTypes.xmi

[100] Object Management Group, *OMG Systems Modeling Language (OMG SysML) Version 1.6*. 2019. Available: https://www.omg.org/spec/SysML/20181001/sysmldi.xmi

[101] International Electrotechnical Commission., *International Standard: Use case methodology - Part 2: Definition of the templates for use cases, actor list and requirements list*. 2015. Available: https://webstore.iec.ch/preview/info_iec62559-2%7Bed1.0%7Db.pdf

[102] International Electrotechnical Commission, "SyC Smart Energy - Supporting Documents." 2021. Available: https://www.iec.ch/dyn/www/f?p=103:227:307016111229633::::FSP_ORG_ID,FSP_LANG_ID:11825,25

[103] CEN-CENELEC-ETSI Smart Grid Coordination Group, "SG-CG/M490/K_ SGAM usage and examples SGAM User Manual-Applying, testing & refining the Smart Grid Architecture Model (SGAM)," 2014. Available: https://www.cencenelec.eu/media/CEN-CENELEC/AreasOfWork/CEN-CENELEC_Topics/Smart Grids and Meters/Smart Grids/4_sgcg_methodology_sgamusermanual.pdf

[104] A. Gopstein, C. Nguyen, C. O'Fallon, N. Hastings, and D. Wollman, "NIST framework and roadmap for smart grid interoperability standards, release 4.0," Gaithersburg, MD, Feb. 2021. Available: https://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.1108r4.pdf

[105] A. Estebsari, L. Barbierato, A. Bahmanyar, L. Bottaccioli, E. Macli, and E. Patti, "A SGAM-based test platform to develop a scheme for wide area measurement-free monitoring of smart grids under high PV penetration," *Energies*, vol. 12, no. 8, Apr. 2019.

[106] CEN-CENELEC-ETSI Smart Grid Coordination Group, "SG-CG/M490/I_Smart Grid Interoperability - Methodologies to facilitate Smart Grid system interoperability through standardization, system design and testing," 2014. Available: https://www.cencenelec.eu/media/CEN-CENELEC/AreasOfWork/CEN-CENELEC_Topics/Smart Grids and Meters/Smart Grids/6_sgcg_interoperability_report.pdf

[107] Salzburg University of Applied Sciences, "SGAM Toolbox - Modelling aid for the Smart Grid Architecture Model." Accessed: May 06, 2023. Available: https://sgam-

toolbox.org/

[108] Sparx Systems, “Sparx Systems - Products - Enterprise Architect,” 2023. Accessed: May 06, 2023. Available: https://sparxsystems.com/products/ea/index.html

[109] Christian Neureiter, “Introduction to the „SGAM Toolbox“,” Salzburg, 2014. Available: https://sgam-toolbox.org/downloads/Introduction-to-SGAM-Toolbox.pdf

[110] A. Dimeas, A. Tsikalakis, G. Kariniotakis, and G. Korres, “Microgrid Control Issues,” in *Microgrids: Architectures and Control*, 1st ed., N. Hatziargyriou, Ed., John Wiley & Sons, Incorporated, 2014, pp. 25–80.

[111] A. J. Veronica and N. S. Kumar, “Control strategies for frequency regulation in microgrids: A review,” *Wind Eng.*, vol. 45, no. 1, pp. 107–122, Feb. 2021,.[112] M. Fusero, A. Tuckey, A. Rosini, P. Serra, R. Procopio, and A. Bonfiglio, “A comprehensive inverter-bess primary control for AC microgrids,” *Energies*, vol. 12, no. 20, Oct. 2019.

[113] K. Monteiro, M. Marot, and H. Ibn-Khedher, “Review on microgrid communications solutions: A named data networking - Fog approach,” *2017 16th Annu. Mediterr. Ad Hoc Netw. Work. Med-Hoc-Net 2017*, no. June, 2017.

[114] M. Castilla, A. Camacho, J. Miret, M. Velasco, and P. Martí, “Local Secondary Control for Inverter-Based Islanded Microgrids with Accurate Active Power Sharing under High-Load Conditions, *IEEE Trans. Ind. Electron.*, vol. 66, no. 4, pp. 2529–2539, Apr. 2019.

[115] H. Han, X. Hou, J. Yang, J. Wu, M. Su, and J. M. Guerrero, “Review of power sharing control strategies for islanding operation of AC microgrids,” *IEEE Trans. Smart Grid*, vol. 7, no. 1, pp. 200–215, Jan. 2016.

[116] D. Chathurangi, U. Jayatunga, S. Perera, A. P. Agalgaonkar, and T. Siyambalapitiya, “A nomographic tool to assess solar PV hosting capacity constrained by voltage rise in low-voltage distribution networks,” *Int. J. Electr. Power Energy Syst.*, vol. 134, no. April 2021, p. 107409, 2022.

[117] D. Almeida, J. Pasupuleti, and J. Ekanayake, “Comparison of reactive power control techniques for solar pv inverters to mitigate voltage rise in low-voltage grids,” *Electron.*, vol. 10, no. 13, pp. 1–17, 2021.

[118] J. P. Holguin, D. C. Rodriguez, and G. Ramos, “Reverse Power Flow (RPF) Detection and Impact on Protection Coordination of Distribution Systems,” *IEEE*

Trans. Ind. Appl., vol. 56, no. 3, pp. 2393–2401, 2020.

[119] Electric Power Research Institute, “Stochastic Analysis to Determine Feeder Hosting Capacity for Distributed Solar PV,” 2012.

[120] N. C. Tang and G. W. Chang, “A stochastic approach for determining PV hosting capacity of a distribution feeder considering voltage quality constraints,” in *Proceedings of International Conference on Harmonics and Quality of Power, ICHQP*, IEEE Computer Society, Jun. 2018, pp. 1–5.

[121] S. Fan, C. Li, Z. Wei, T. Pu, and X. Liu, “Method to determine the maximum generation capacity of distribution generation in low-voltage distribution feeders,” *J. Eng.*, vol. 2017, no. 13, pp. 944–948, Jan. 2017.

[122] J. F. B. Sousa, C. L. T. Borges, and J. Mitra, “PV hosting capacity of LV distribution networks using smart inverters and storage systems: A practical margin,” *IET Renew. Power Gener.*, vol. 14, no. 8, pp. 1332–1339, 2020.

[123] S. Hashemi and J. Østergaard, “Efficient Control of Energy Storage for Increasing the PV Hosting Capacity of LV Grids,” *IEEE Trans. Smart Grid*, vol. 9, no. 3, pp. 2295–2303, 2018.

[124] Object Management Group, “Model Driven Architecture (MDA) MDA Guide rev. 2.0,” 2014. Available: http://www.omg.org/mda/

[125] International Electrotechnical Commission, *IEC 62559-2: Use case methodology. Part 2, Definition of the templates for use cases, actor list and requirements list*. 2015. Available: https://webstore.iec.ch/preview/info_iec62559-2%7Bed1.0%7Db.pdf

[126] Sparx Systems, “UML 2 Tutorial - State Machine Diagram.” Accessed: May 15, 2023. Available: https://sparxsystems.com/resources/tutorials/uml2/state-diagram.html

[127] Draw.io, “Draw.io.” Accessed: May 15, 2023. Available: https://www.drawio.com/

[128] Microsoft, “Microsoft Power Point.” Accessed: May 15, 2023. Available: https://www.microsoft.com/en-ww/microsoft-365/powerpoint

[129] SolarVenti International, “SolarVenti.” Accessed: May 16, 2023. Available: https://www.solarventi.com/

[130] International Organisation for Standardisation and International Electrotechnical Commission, *ISO/IEC 7498-1:1994 Information technology - Open Systems Interconnection - Basic Reference Model: The Basic Model*. 1994. Available:

https://www.iso.org/obp/ui/#iso:std:iso-iec:7498:-1:ed-1:v2:en

[131] European Telecommunications Standards Institute, “Digital cellular telecommunications system (Phase 2+) - Specification of the Subscriber Identity Module-Mobile Equipment (SIM-ME) interface; (GSM 11.11) ETSI,” 1996. Available: https://www.etsi.org/deliver/etsi_gts/11/1111/05.03.00_60/gsmts_1111v050300p.pdf

[132] International Electrotechnical Commission, “61850-1 - Technical Report - Communication Networks and Systems for Power Utility Automation,” 2013.

[133] Institute of Electrical and Electronics Engineers, “2030.7-2017 - IEEE Standard for the Specification of Microgrid Controllers,” 2018.

APPENDIX A: LEOS DIAGRAMS

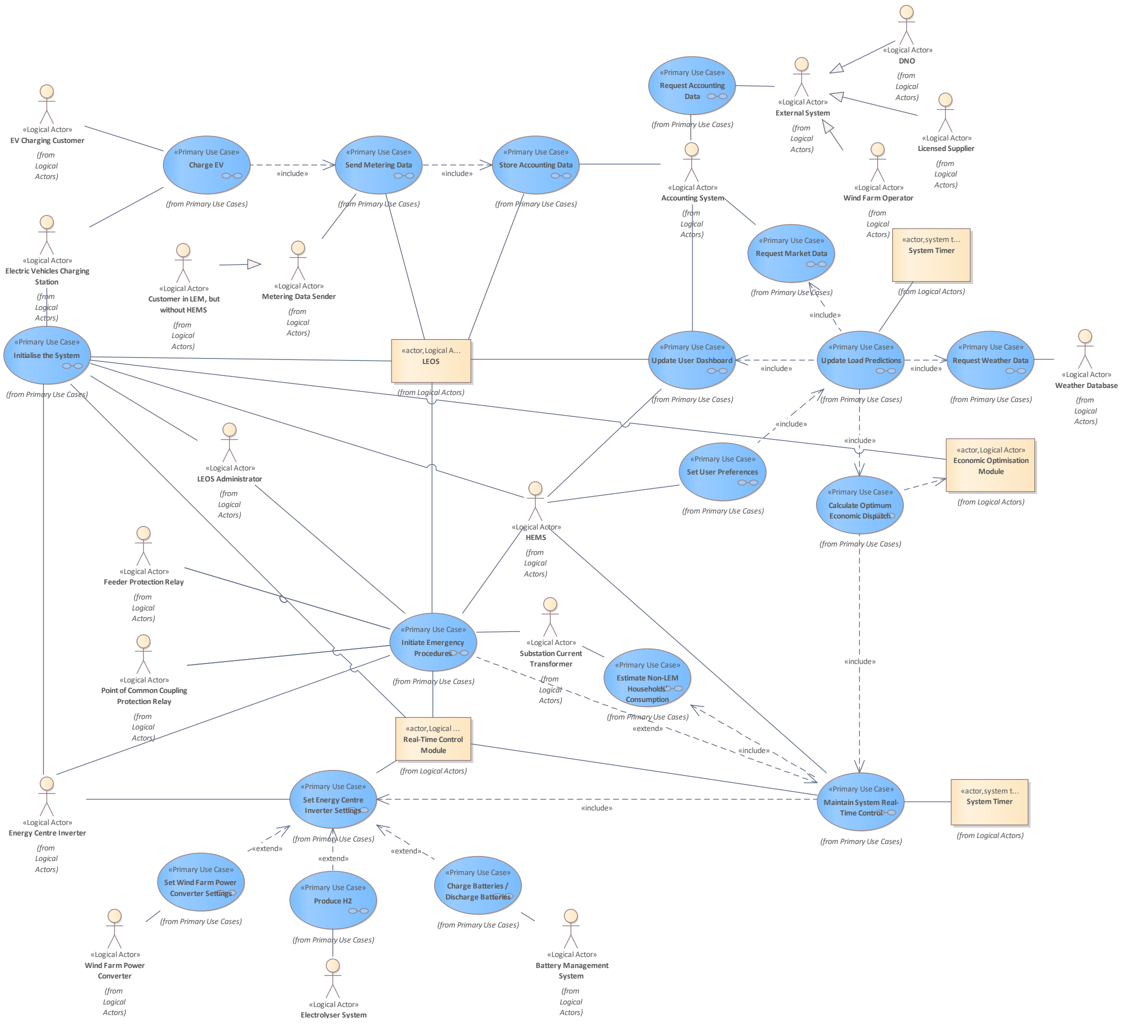

Figure 72 *HLUC Model - Utilise Local Energy Operating System.*

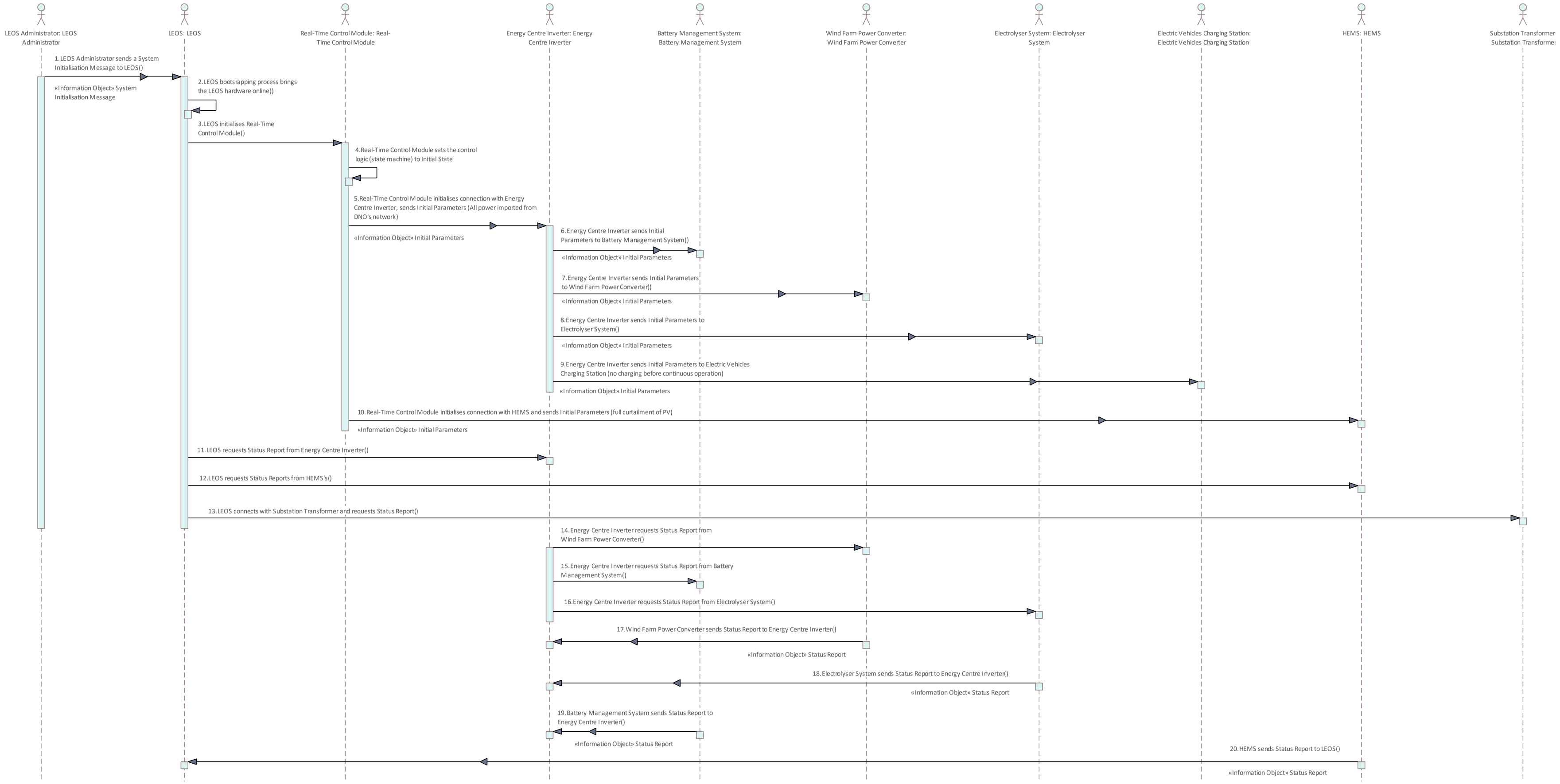

***Figure 73** Sequence Diagram - Initialise the System (part 1/2).*

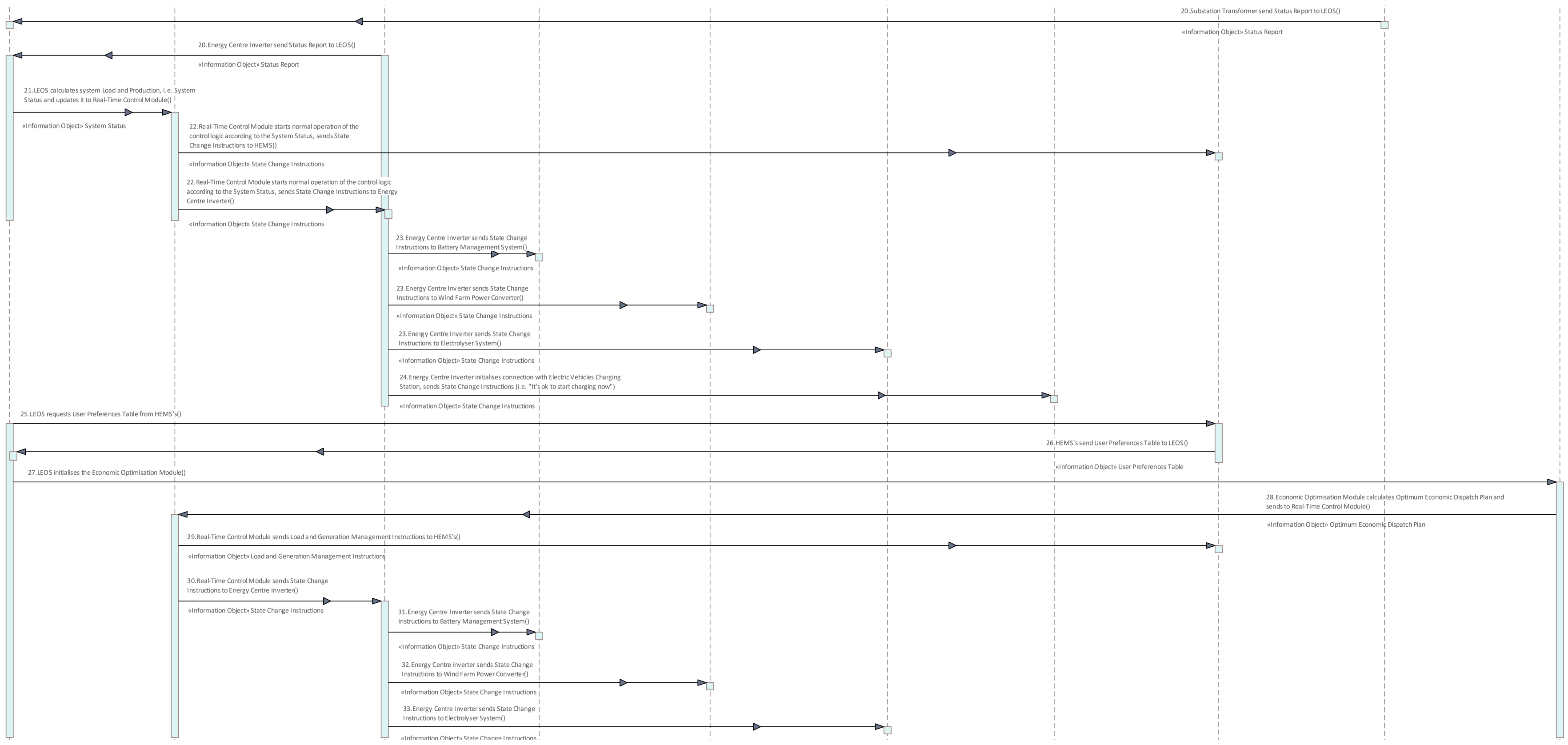

Figure 74 *Sequence Diagram - Initialise the System (part 2/2).*

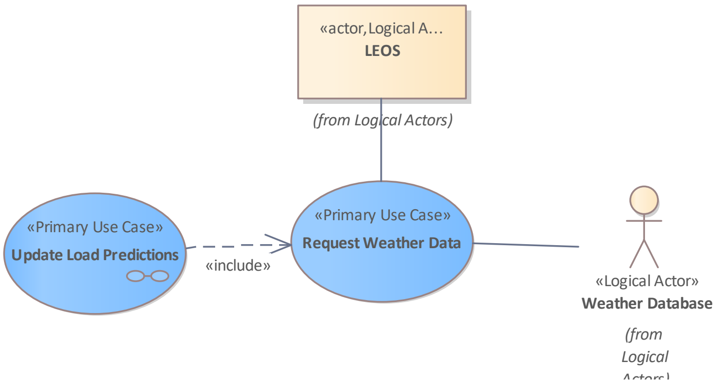

Figure 75 *PUC - Request Weather Data.*

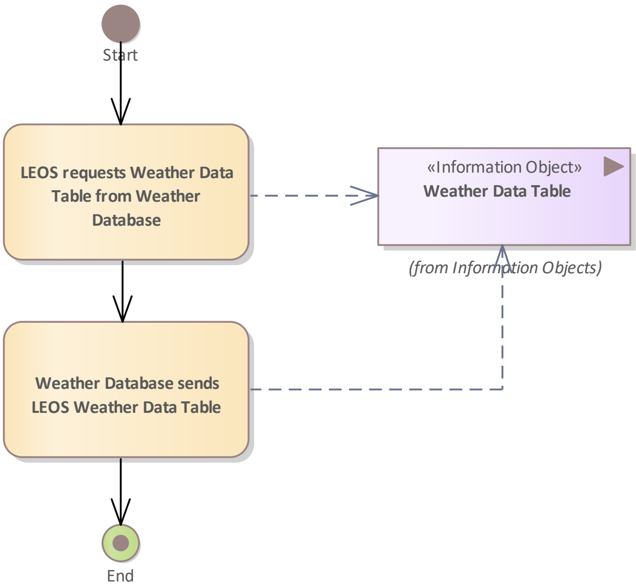

Figure 76 *Activity Diagram - Request Weather Data*

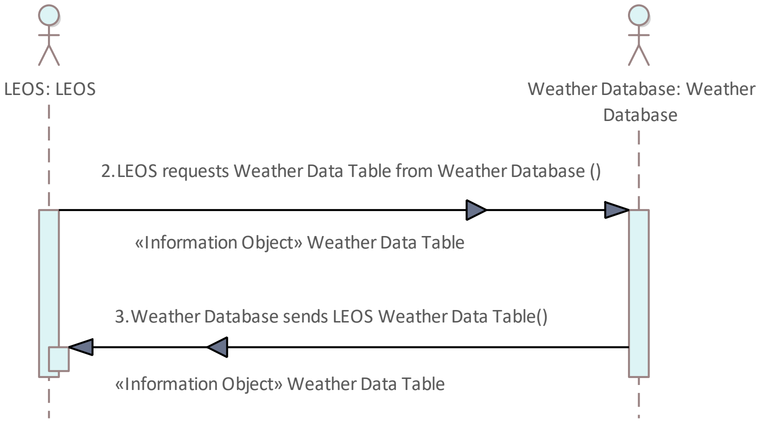

Figure 77 *Sequence Diagram - Request Weather Data.*

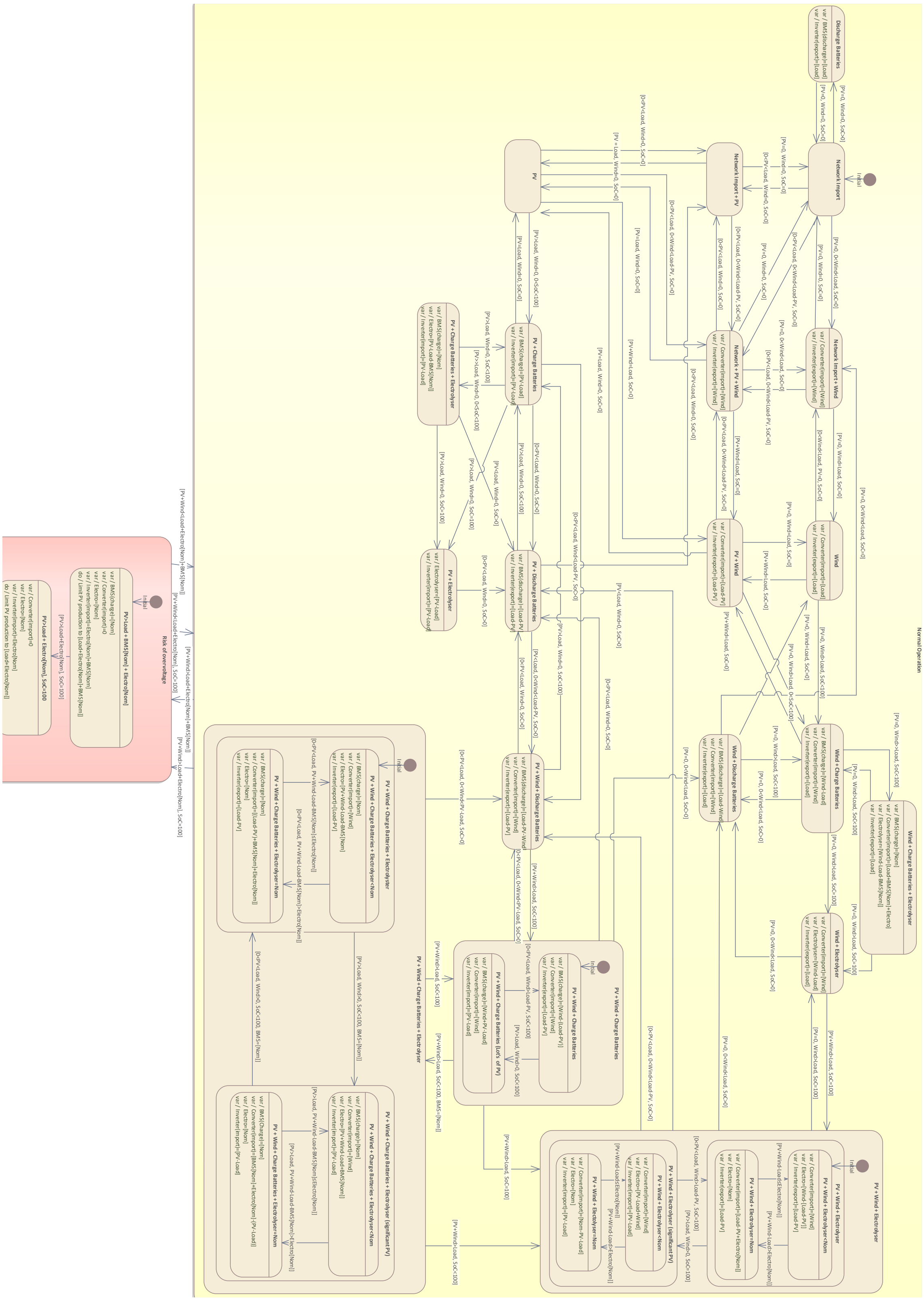

Figure 78 State Machine Diagram - System States.

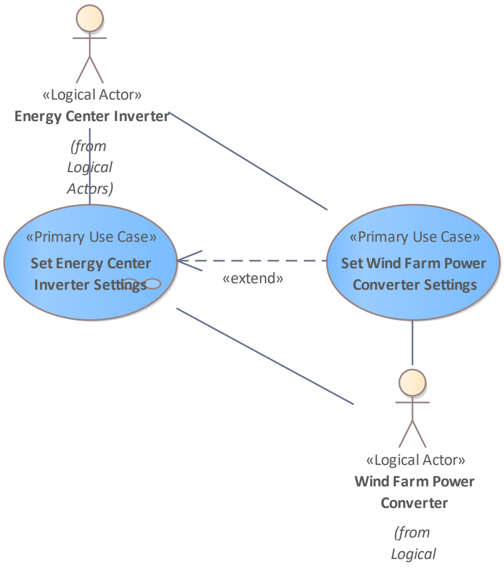

Figure 79 *PUC - Set Wind Farm Power Converter Settings.*

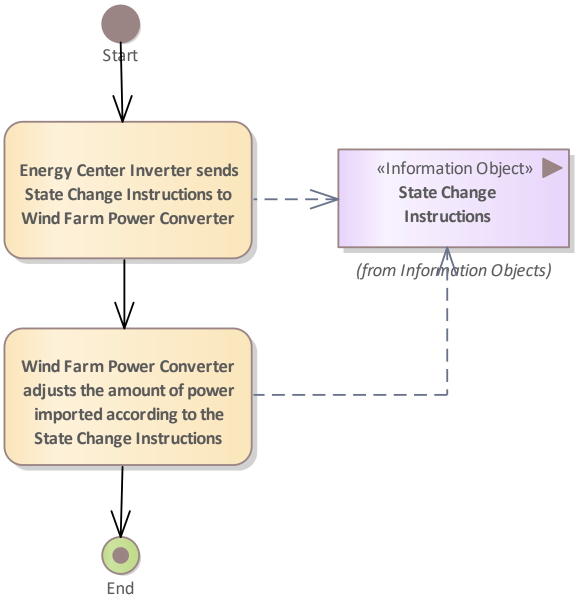

Figure 80 *Activity Diagram - Set Wind Farm Power Converter Settings.*

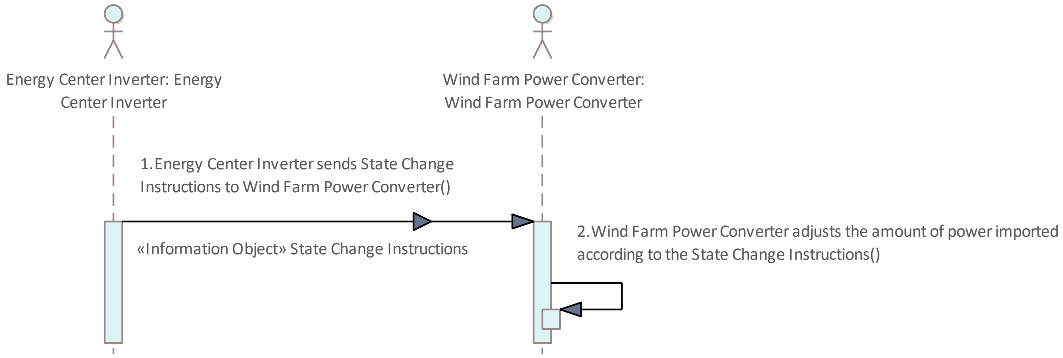

Figure 81 *Sequence Diagram - Set Wind Farm Power Converter Settings.*

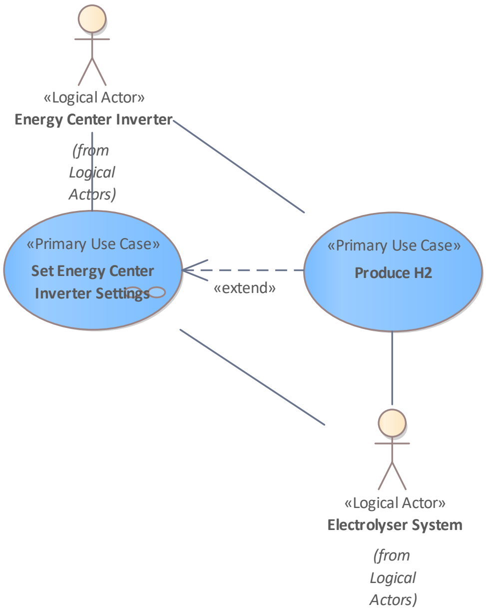

Figure 82 *PUC - Produce H2.*

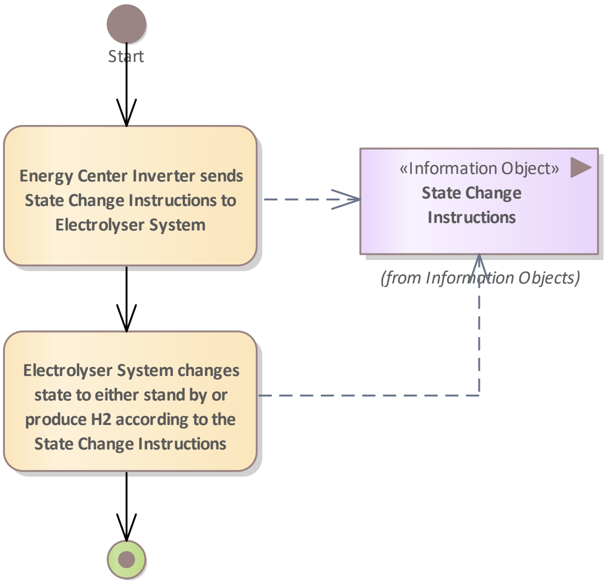

Figure 83 *Activity Diagram - Produce H2.*

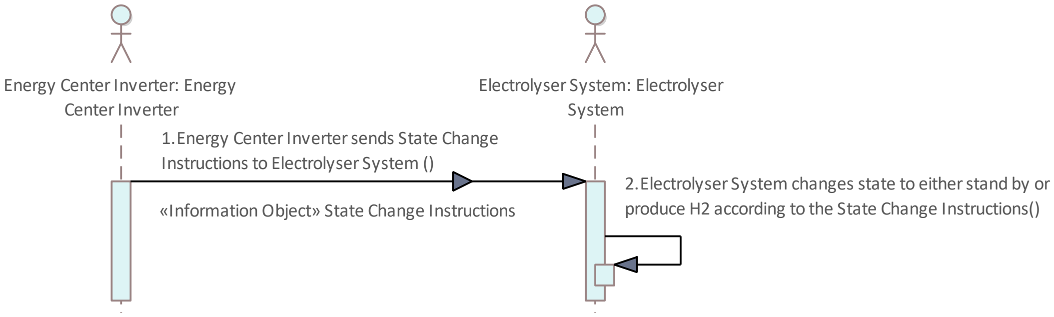

Figure 84 *Sequence Diagram - Produce H2.*

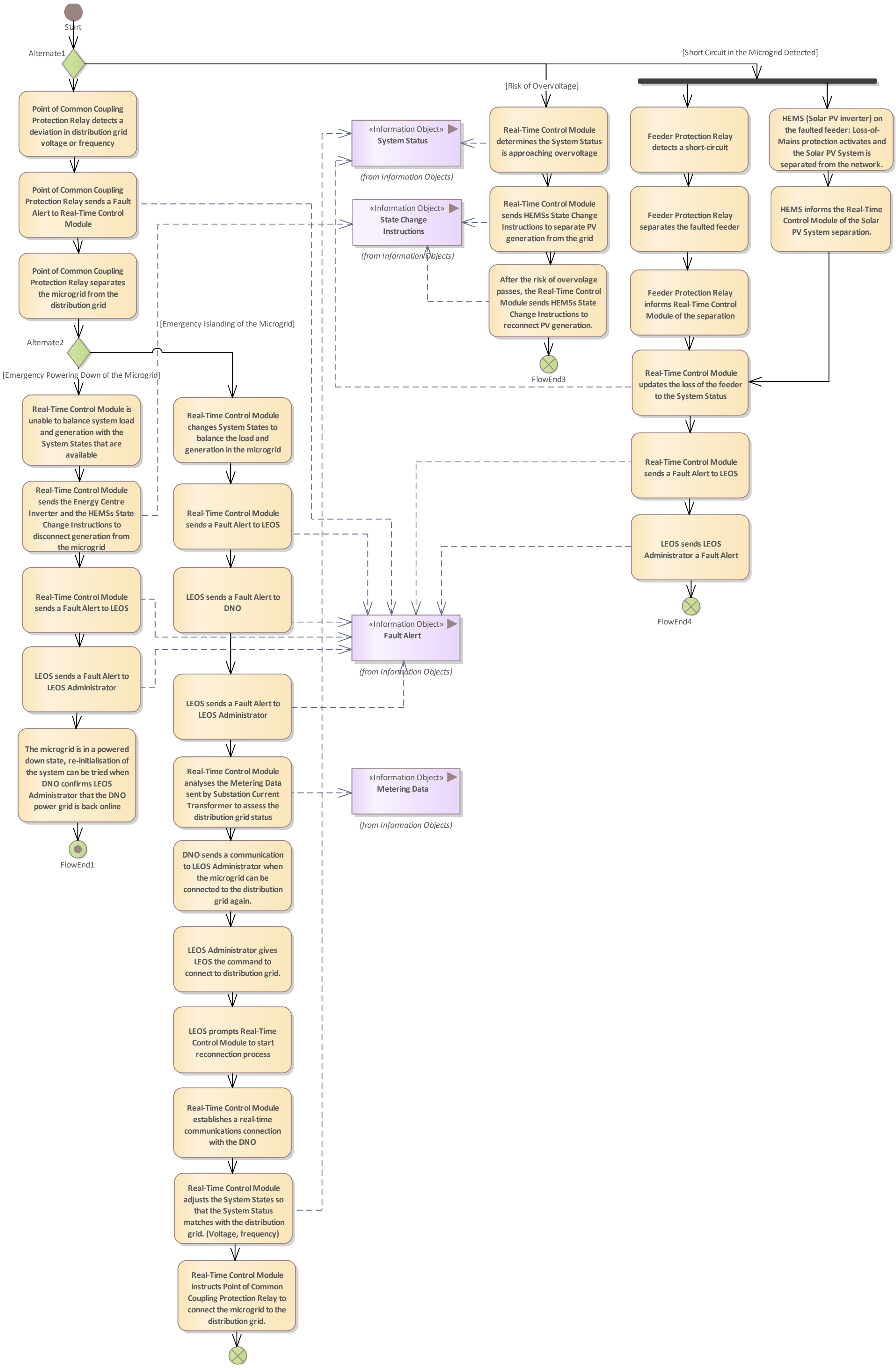

***Figure 85** Activity Diagram - Initiate Emergency Procedures*

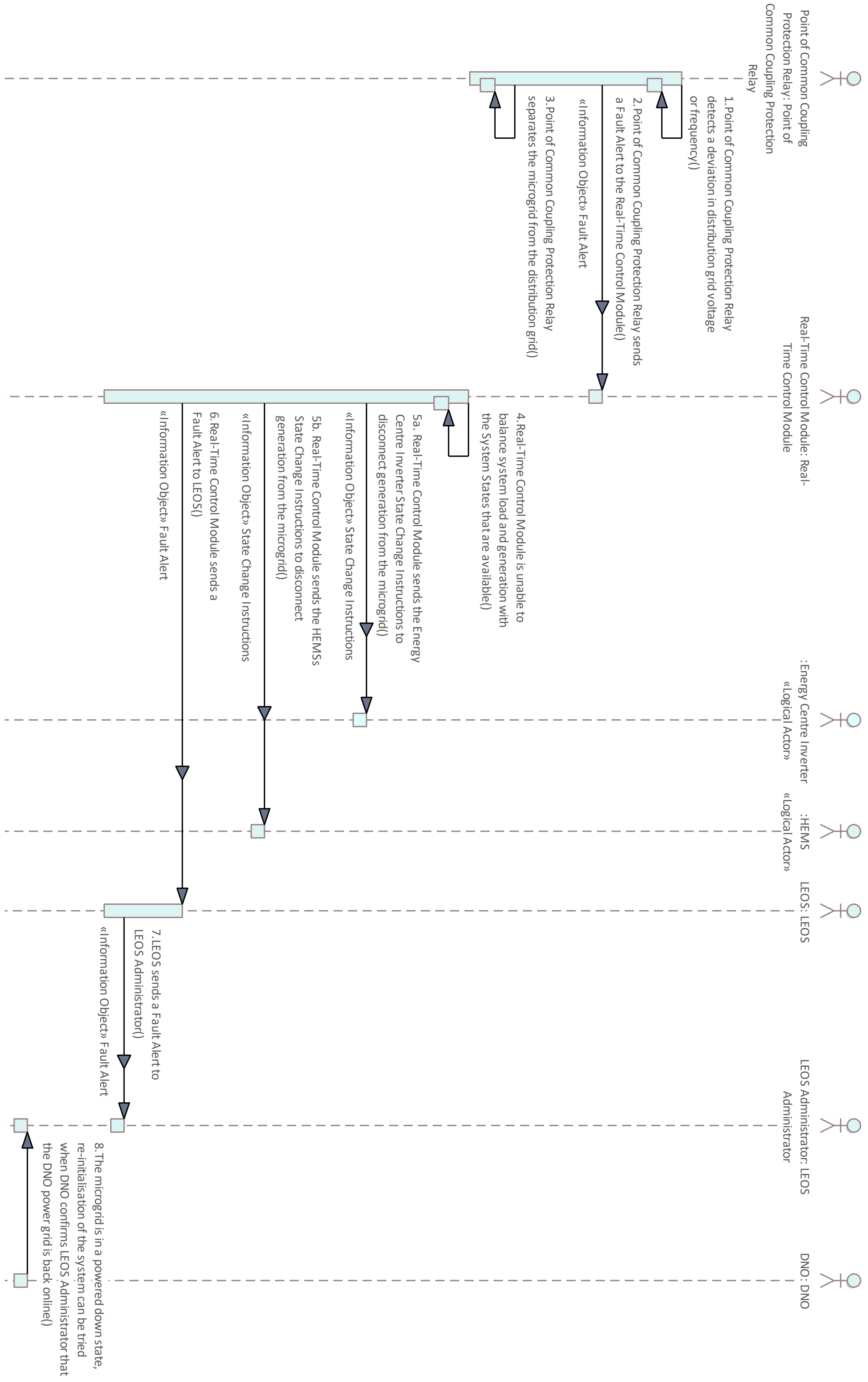

Figure 86 *Sequence Diagram - Initiate Emergency Procedures - Path 1. Emergency Powering Down of the Microgrid.*

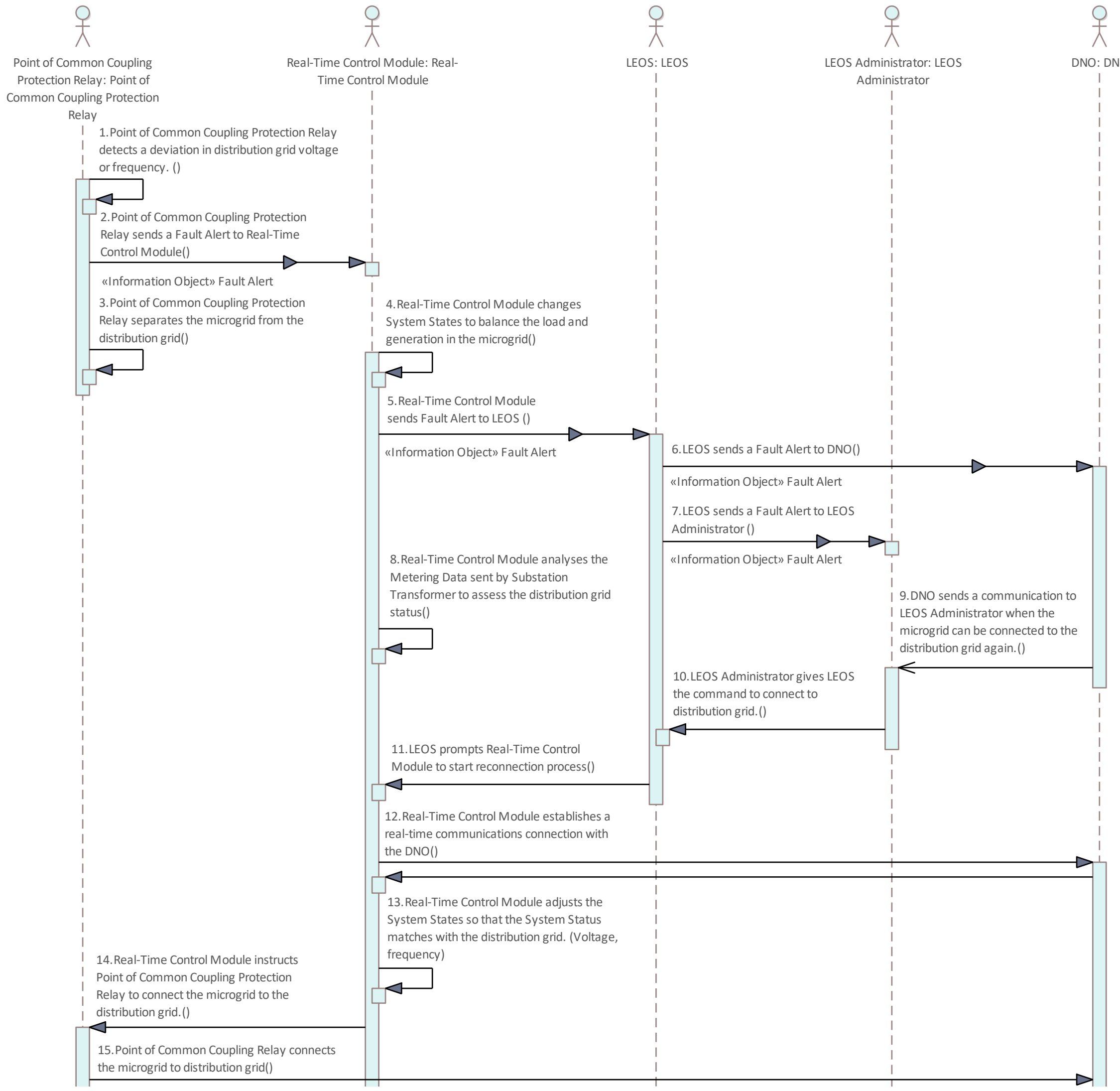

Figure 87 *Sequence Diagram - Initiate Emergency Procedures - Path 2. Emergency Isolation of the Microgrid.*

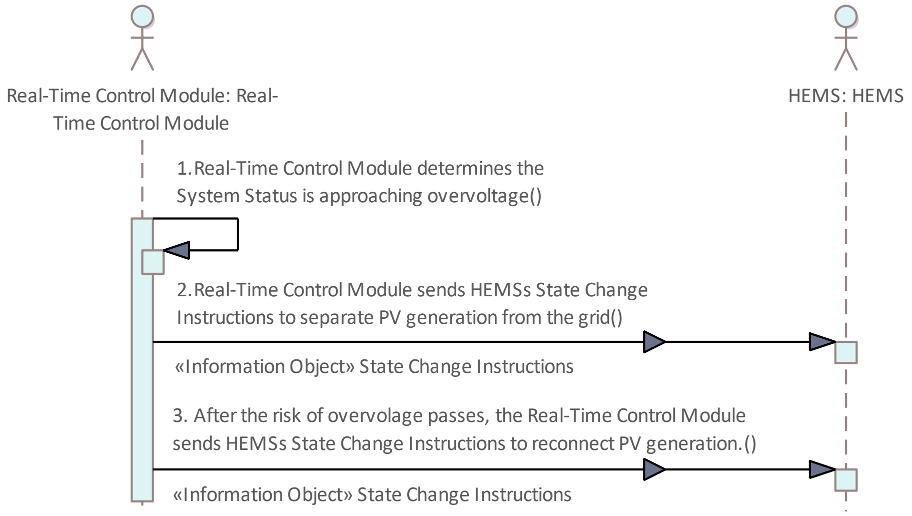

Figure 88 *Sequence Diagram – Initiate Emergency Procedures – Path 3. Risk of Overvoltage.*

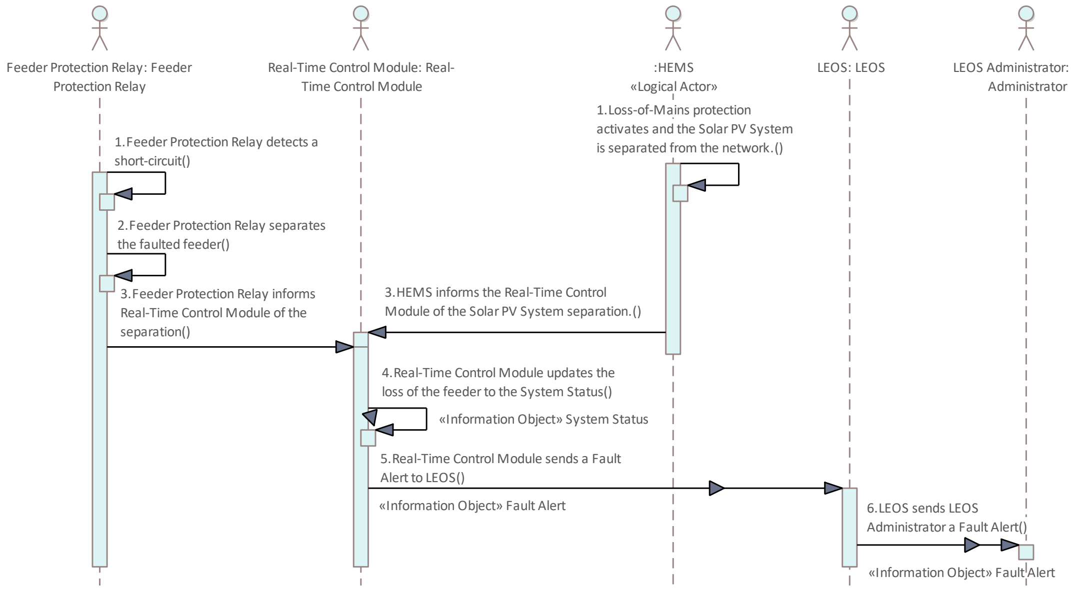

Figure 89 *Sequence Diagram - Initiate Emergency Procedures - Path 4. Short Circuit in the Microgrid.*

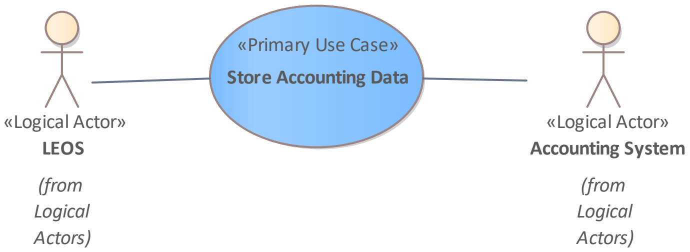

Figure 90 *PUC - Store Accounting Data.*

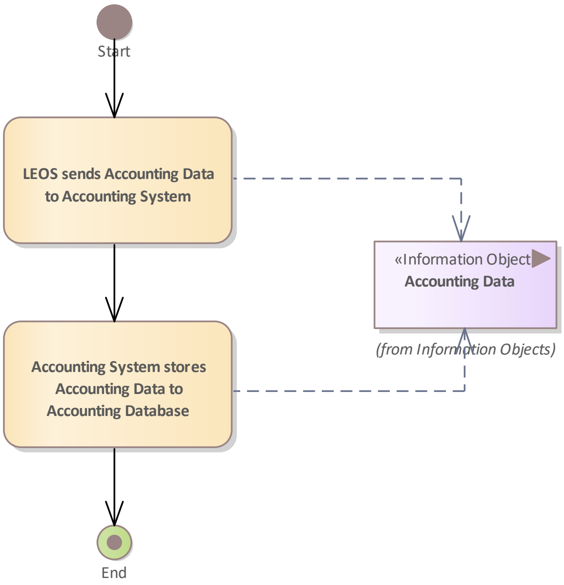

Figure 91 *Activity Diagram - Store Accounting Data.*

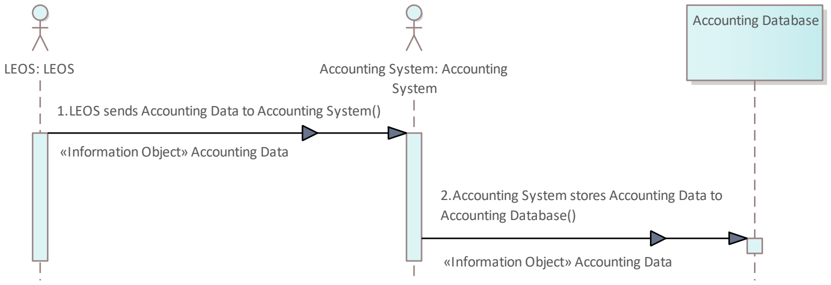

Figure 92 *Sequence Diagram - Store Accounting Data.*