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Lubna Mariam
Technological University Dublin

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Modelling of an Intelligent Microgrid System in a Smart Grid Network

Lubna Mariam

B.Sc, M.Sc (EEE)

A thesis report for the degree of Doctor of Philosophy

Under the supervision of
Dr Malabika Basu and Prof Michael F Conlon

School of Electrical and Electronic Engineering
Dublin Institute of Technology
Republic of Ireland

August 2018

Dedicated to
- My parents and family members -

Abstract

To achieve the goal of decarbonising the electric grid by 2050 and empowering energy citizen, this research focuses on the development of Microgrid (μ Grid) systems in Irish environment. As part of the research work, an energy efficient and cost effective solution for μ Grid, termed Community- μ Grid (C- μ Grid) is proposed. Here the users can modify their micro-Generation (μ Gen) converters to facilitate a single inverter in a C- μ Grid structure. The new system could allow: (i) technological advantage of improved Power Quality (PQ); (ii) economic advantage of reduced cost of energy (COE) to achieve sustainability.

Analysis of scenarios of C- μ Grid (AC) systems is performed for a virtual community in Dublin, Ireland. It consists of (10 to 50) similar type of residential houses and assumes that each house has a wind-based μ Gen system. It is found that, compared to individual off-grid μ Gen systems, an off-grid C- μ Grid can reduce upto 35% of energy storage capacity. Thus it helps to reduce the COE from €0.22/kWh to 0.16/kWh. In grid connected mode, it can sell excess energy to the grid and thus COE further decreases to €0.11/kWh. Thus a **cost-effective** C- μ Grid is achieved.

The proposed system can advance its **energy management efficiency** through implementation of Demand Side Management (DSM) technique. For the test case, 50% of energy storage capacity could be avoided through DSM technique. It also helps to further decrease the COE by 25%.

The C- μ Grid system with storage is **optimised** by implementing the Economic Model Predictive Control (EMPC) approach operating at the pricing level. Emphasis is given to the operational constraints related to the battery lifetime, so that the maintenance and replacement cost would be reduced. This technique could help to improve the battery performance with optimised storage and also reduces the COE of the system by 25%.

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Date 12.08.2018

Candidate

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Abbreviations

AC	-	Alternating Current
CC	-	Charge Controller
CHP	-	Combined Heat and Power
C- μ Grid	-	Community Microgrid
C- μ GCC	-	Community Microgrid Central Controller
COE	-	Cost of Energy
DC	-	Direct Current
DG	-	Distributed Generation
DER	-	Distributed Energy Resource
DSM	-	Demand Side Management
DR	-	Demand Response
EE	-	Energy Efficiency
EEGI	-	European Electricity Grid Initiative
EMPC	-	Economic Model Predictive Control
EPS	-	Electric Power System
ESS	-	Energy Storage System
EU	-	European Union
GHG	-	Green House Gas
HFAC	-	High Frequency AC
ICT	-	Information and Communication Technology
IEEE	-	Institute of Electrical and Electronic Engineers
IoT	-	Internet of Things
IRR	-	Internal Rate of Return
μ Gen	-	Micro-generation
μ Grid	-	Microgrid

μ GCC	-	Microgrid Central Controller
MEMS	-	Microgrid Energy Management System
MPC	-	Model Predictive Control
PCC	-	Point of Common Coupling
PQ	-	Power Quality
PV	-	Photo Voltaic
RE	-	Renewable Energy
REFIT	-	Renewable Energy Fed-in-Tariff
RES	-	Renewable Energy Sources
RD & D	-	Research Development and Demonstration
RHC	-	Receding Horizon Control
SEAI	-	Sustainable Energy Authority of Ireland
S-Logic	-	Simple Logic
SOC	-	State of Charge
SGIRM	-	Smart Grid Interoperability Reference Model
SR	-	Spinning Reserve
TOU	-	Time of Use
UPS	-	Uninterruptible Power Supply
WT	-	Wind Turbine

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Chapter 1

Introduction

1.1 Background

According to the Sustainable Energy Authority of Ireland (SEAI) and the European Electricity Grid Initiative (EEGI), the electricity network of the future must be flexible, accessible, reliable and economic. In order to achieve this structure, research on μ Grid systems is getting more emphasis in the Irish / EU research task plan [1,2]. To achieve the goal of decarbonising the electric grid by 2050 and empowering energy citizen as set in energy policy, importance has been given to increase the penetration of Renewable Energy (RE) based Distributed Generation (DG) systems such as solar, wind, hydro, biomass and other micro-sources [2]. Therefore, strategies that will ensure the most efficient, reliable and economic operation and management of μ Grids are envisaged. μ Grids are expected to provide technical (reducing distribution power losses, peak load shaving, emergency supply), environmental that is to reduce Green House Gas (GHG) emission, economic, energy security and social benefits for end users, utilities and communities. In this regard, this project proposes to develop a working model of a smart μ Grid system suitable for the Irish distribution grid network with high penetration of Renewable Energy Sources (RES). The main questions of this research work are as follows:

1. What are the existing criteria for an energy efficient and cost-effective **μGrid** energy management system?
2. How should uncontrollable renewable energy sources be incorporated to optimise **μGrid** systems in the Irish environment?
3. How should smart **μGrid** systems be developed to cope with the future EU/Irish smart grid initiative?

The rest of this section describes briefly the related issues of this research including DG and μ Grids.

1.2 Distributed Generation (DG) and Microgrids (μ Grid)

DG is the term often used to describe small-scale electricity generation, but there is no consensus on how DG should be defined. Usually DG is classified according to its different types and operating technologies. A detailed description of the types, technologies, applications, advantages and disadvantages of every available resource and technology is given in [3]. μ Grid is an electricity distribution system containing controllable loads and distributed energy resources, (such as controlled/uncontrolled DGs and controlled storage devices) that can be operated in a controlled, coordinated way either while connected to the main power network or while islanded and all deployed across a limited geographic area [4]. The sustainability of DG/ μ Grid systems primarily depends on geographical location, types of resources and availability, technology and end user demand profile.

RESs such as solar and wind energy are the most promising DG sources and their penetration level in the grid is also on the rise. Ireland has also set their target to achieve 70% of its electricity from wind by 2050 [2]. From other sources, solar

energy is also gaining importance. Therefore, the scope in this project is limited to the study on solar and wind energy based μ Gen and μ Grid systems connected to the grid.

1.3 Energy Efficient μ Grid

Energy efficiency or efficient use of energy means using less energy to provide the same service. Traditionally, supply of generated power from large power plants to the end users is via the transmission and distribution networks which involves possible multiple conversions from AC to DC/DC to AC and vice versa. μ Grids have the ability to prevent these associated energy losses by generating power directly from sources close to the end users. In a μ Grid system, the operator/owner can efficiently manage their power and energy both by storing energy and tracking uses to minimise their own costs. Efficient performance of μ Grid can be achieved through: (i) advanced control algorithms and management system considering system uncertainty and predicted future conditions, (ii) deployment of DSM/Demand Response (DR) and (iii) optimise the storage in order to improve stability [5].

1.4 Energy Management in μ Grid

Energy management is achieved by balancing the supply and demand to minimise the cost of energy and thus to improve the energy efficiency of a system. Therefore, energy management in a μ Grid is to minimise the overall μ Grid operating costs to meet the predicted load demand of a certain period (typically one day) while satisfying complex operational constraints, such as the energy balance and controllable generators minimum operation time and minimum stop time [6]. One of the main challenges in energy management is to account for the random and uncontrollable nature of the RES. Therefore, a μ Ggrid is managed efficiently to achieve technical and economic sustainability by avoiding energy purchases during

peak periods, maximise the utilisation of energy from low-carbon/low-pollutant generation with higher energy efficiency and optimise the storage energy capacity. It also provides secure and reliable energy supply in off-grid conditions in the event of a serious blackout or power quality disturbances.

1.5 Optimisation

The optimisation of the μ Grid operation is extremely important in order to cost-efficiently manage its energy resources [4]. It includes market policy, robust formulation against RES uncertainty and prediction, modeling of storage with its operation and capacity optimisation, managing demand side policies for controllable loads (DSM) and power exchange with the utility grid. μ Grid central controller is responsible for the optimisation of its operation [7].

1.6 Research Objectives

With the increased penetration of small scale renewables in the electrical distribution network, maintaining or improving energy efficiency, integration with the grid to cope with the future smart grid, research and development of μ Grid systems are getting more importance. For this reason, the main objectives of the present research are to investigate:

- I. Development of energy efficient and cost-effective μ Grid energy management system for Irish environment.
- II. Possibility of implementing DSM technique
 - a. to improve the efficiency and reduce the COE of the system
 - b. to cope with the future smart grid network
- III. Optimisation of the μ Grid energy management system with uncontrollable sources such as solar and/or wind power system with storage.

1.7 Outline of the Thesis

This research report is divided into seven chapters.

Chapter One (Introduction)

The first chapter contains a brief introduction on DG and μ Grid, Energy efficiency, energy management, optimisation, research objectives and outline of the thesis.

Chapter Two (Microgrid: Architecture, Policy and Future Trends)

An extensive literature review has been carried out in the area of DG integrated μ Grid systems in terms of architecture, policy practiced around the world and its future trends. The review shows that all the existing test beds described have limited technical information but generally less economical information is available. In terms of techno-economic benefits, the systems should be optimised both technically and economically. Reducing the number of system components, reducing the installation and management costs, improving the system integrity, improving source and load efficiency, and introduction of source or demand side management can enhance the viability of any system. As there is no μ Grid policy and μ Grid system in operation yet in Ireland, existing and/or simulated μ Grid architectures and associated policies from various countries have been reviewed in this chapter.

Chapter Three (Sustainability of Micro-generation Systems)

Having in mind the findings from the review of μ Grids, this chapter starts with the analysis of μ Gen systems in Ireland. Previously published works show that Photo Voltaic (PV) based μ Gen systems are not yet feasible in Ireland. Wind Turbines (WT) as μ Gen system can be attractive for some locations. Therefore, a number of techno-economic improvements have been proposed and analysed here to achieve sustainability of μ Gen systems.

Chapter Four (Community μ Grid: A New and Energy Efficient Structure)

Review of μ Grid and analysis of μ Gen systems along with the energy policy for empowering the energy citizen helps to propose a new and energy efficient μ Grid structure, termed as Community- μ Grid system (C- μ Grid). In the proposed C- μ Grid system, each of the community users uses their own μ Generator and instead of having separate multiple converters, all the generators are connected through a central converter. The proposed system could allow greater penetration of RE in the electricity supply network, reduce the production COE to achieve sustainability and empower the energy citizen through active participation of prosumers in the energy trading mechanism. System integration, operation and a heuristic control method are discussed in this chapter. The effectiveness of the system is also analysed through the techno-economic viability study for off-grid and grid connected condition. A virtual location in Dublin, Ireland has been chosen for the overall study.

Chapter Five (Energy Efficient C- μ Grid through DSM)

The energy management efficiency of the system can also be improved through the implementation of DSM techniques. This chapter investigates the possibility of implementing DSM techniques in C- μ Grid to reduce the peak load demand as well as to maximise the utilisation of RESs. DSM could help (i) the community to reduce the storage requirement and (ii) the grid operator to improve their network efficiency. Finally, the required technological solutions to implement DSM and to synchronise C- μ Grid systems with future smart grid networks are suggested.

Chapter Six (Economic Optimisation)

The efficient performance of the proposed C- μ Grid system is achieved by the proper management of the energy control and exchange among the source, load, storage and the distribution network. In this chapter, the controlling capability of the

central controller of the C- μ Grid (C- μ GCC) with optimised storage is improved through an EMPC approach. With a central controller it is possible to satisfy the demand on the prosumer sides and, at the same time, optimising the various μ -Grid contrasting constraints. Emphasis here has been given to the operational constraints related to the battery lifetime, so that the maintenance and replacement costs would be reduced and the storage is optimised. A simulation study with a comparative analysis between heuristic and EMPC based C- μ Grid system reflects the possibility of efficient energy management with storage optimisation.

Chapter Seven (Conclusion and Future Work)

Conclusion and future work of this research work is presented in the final chapter.

Chapter 2

Microgrid: Architecture, Policy and Future Trends

2.1 Introduction

Most large power generation systems rely on conventional energy sources such as coal, natural gas and oil, each of which have a more or less negative impact on the environment. Furthermore, as long-distance, high-voltage transmission lines carry power to the customers from centralised generation sources, transmission losses are unavoidable. The increasing demand for clean, reliable and affordable electrical energy is changing the existing scenario for electricity generation. μ Grid systems have the potential to deliver an innovative, economic and environmental friendly solution. One of the major aims of μ Grid is to combine the benefits of non-conventional/renewable, low carbon generation technologies and high efficient Combined Heat and Power (CHP) systems. The choice of a DG technology mainly depends on the climate and topology of the region.

Microgrid embodies the concept of a single organised power subsystem comprising a number of DG systems, both renewable (such as photovoltaic, wind power, hydro and fuel-cell devices) and/or conventional generation (such as internal combustion engines, micro-turbines and diesel generators) and a cluster of loads [8].

The application of an individual DG system is also possible, which is termed μ Gen. This can cause a number of problems such as local voltage rise, the potential to exceed thermal limits of certain lines and transformers, islanding problems and high capital costs. μ Grid can be a better solution for those problems. Some of the benefits of μ Grid, including enhanced local reliability, reduced feeder loss, better local voltage support, increased efficiency, voltage sag correction or uninterruptible power supply function are also reviewed in [9]. In a μ Grid system, the DG systems must be equipped with proper Power Electronic Interfaces (PEIs) and control to ensure the flexibility to operate as a single aggregated system maintaining the PQ and energy output. μ Grid central controller takes the leading role for satisfactory automated operation and control of μ Grid while working in grid connected and islanded modes. Details of controller types and advancement in control technologies have been reviewed in [10]. From the grid point of view, the main advantage of the μ Grid is that it is treated as a controlled entity within the power system which can operate as a single load. From the customer point of view, this μ Grid can meet their electrical and heat requirement locally, can supply uninterruptible power, improve local reliability, improve PQ, reduce feeder losses and provide voltage support [4]. Furthermore μ Grid can reduce environmental pollution and global warming through utilizing low-carbon technologies.

Large scale penetration of distributed generation systems may also cause instability and thus it can introduce a negative impact on the distribution grid or μ Grid [11]. The aspects of stability in μ Grid are also revised in [12]. Therefore control and operational strategies for individual and integrated distributed generation systems are highly important and these also have been studied in [13]. On the other hand, to avoid the grid voltage fluctuation or black outs at any time instant, the electric grid should

be able to balance the power between the production and consumption. The power adjustment ensured by the excess capacity in stand-by mode, could be reduced if the peak consumption is shifted. Strategies for power management are being developed for a robust and reliable utility grid which can assist power balancing and avoid undesired injection and can perform peak shaving during peak hours [14]. To achieve this configuration, the Smart Grid has been created that employs intelligent monitoring, control communication and self-healing technologies. Smart grids have mainly the following features: bidirectional power flow, bidirectional communication and reduced mismatch between production and demand [15]. As the concept of μ Grid is for better penetration of RE in the existing grid that can help in energy management in a more controlled way, can help in peak shaving and can reduce energy cost, it (μ Grid) is considered as one of the possible approaches to develop a Smart Grid system [16]. This also depends on the design architecture of μ Grid systems. In that case, understanding and predicting the impact of geographical location, resource availability and load demand on μ Grid design is essential [17].

In recent years, emphasis has been placed on renewable energy based μ Grid systems because of their advantages over μ Gen systems in terms of stability, reliability and economics. Different types of architectures and control strategies have been practiced (in real scale, test-bed or simulation platforms) worldwide to achieve some specific goals. However, the commercial development of the μ Grid system has not yet progressed significantly. The most common barriers were identified and grouped into four categories: technical, regulatory, financial and stakeholder [18]. Another obstacle is that these are not included properly in the national energy policy. Along with these, the policies relating to the implementation of μ Grids differ from country to country. Most countries have not developed policies as yet and thus the

goals for introducing μ Grids as part of the existing electrical distribution network are not established. PQ issues related to DG connected grid network are also a matter of concern. Reviews have already been done in different literatures and published papers with a focus on a specified part of the μ Grid system. These include AC and DC technologies in μ Grid systems, hybrid structures, islanding techniques, details in control with hierarchy approach and progress in protection. These are referred in the relevant sections of this thesis.

Therefore, for integrating μ Grid into the existing grid or to the future Smart Grid Network, this chapter starts with the review of existing and simulated μ Grid architectures that have been developed and studied to date. This study helps to identify the (i) basic structure and architecture of μ Grid systems including types of DG sources, storage units, controller, PQ improvement and communication systems that have been used, (ii) operating policies and (iii) goals that have been achieved. Section 2.2 summarizes this study by formatting a table for existing μ Grid test-beds available in the literature together with their operating policies and goals. Based on the study, the basic μ Grid architecture is divided into four parts - distribution systems, DG sources, storage systems, control and communication systems, have been presented in section 2.3. A brief overview along with the advantages and disadvantages of different distribution systems, DG sources including their PQ issues, storage systems and communication technologies are presented and are discussed in this section. Some of the common policies (with the focus on grid protection) and goals (with the focus on viability) which are being implemented in some countries are described in Section 2.4 and these have been correlated to the test-bed as discussed in section 2.2. Section 2.5 discusses the findings from the existing μ Grid systems.

Concluding remarks and future trends of μ Grid systems are also highlighted in the final part of the chapter in Section 2.6.

2.2 Existing μ Grid Test-beds

Table 2.1 gives a comprehensive summary, available in the literature, of existing μ Grid systems across Europe, USA and Asia [19-58]. In the table examples 1 to 39 are AC μ Grids, 40 to 42 are DC μ Grids, 43 and 44 are real-time emulated studies and 45 is a High Frequency AC (HFAC) μ Grid system. It is to be noted that a review on μ Grid test-beds around the world is also presented in [59] where μ Grids are divided into three types: facility, remote and utility, based on their respective integration levels into the power utility grid, impact on main utility, their different responsibilities, application areas and relevant key technologies. In addition, this chapter emphasis is on the capacity, type of sources, inclusion of storage, types of operating loads, control and communication techniques. The operating policies used to achieve the goal of the system are also highlighted in the table. These may help other countries to decide their policy and goals. Finally references for each of the test-beds are also given in the table.

2.3 μ Grid Architecture

The basic architecture of a μ Grid system is presented in Fig 2.1(a), which shows that a μ Grid system generally consists of four parts: i) distribution system, ii) DG sources, iii) energy storage, iv) control and communication modules. Some of the details of each part of the system are discussed below.

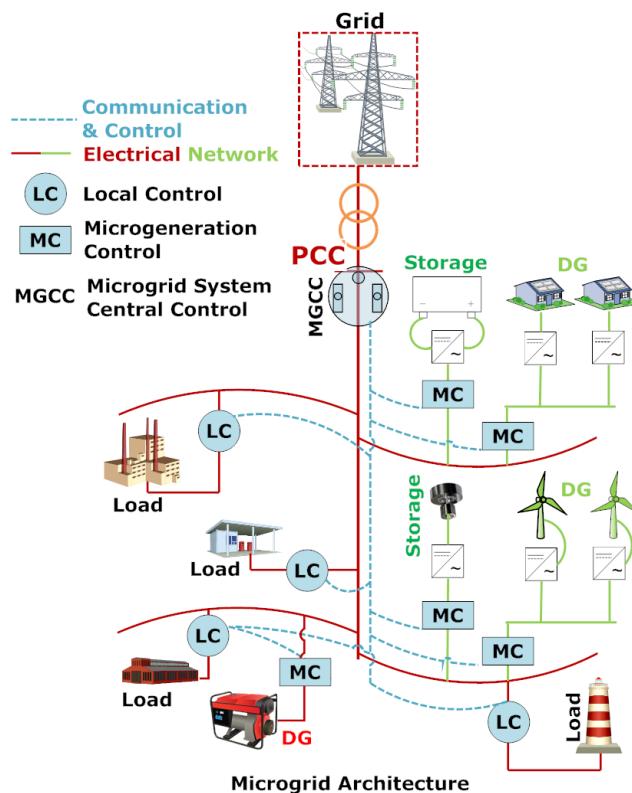
Table 2.1 Example of existing, simulated and emulated μ Grid systems

Serial No.	Location	DG Sources	Storage	Load	Control	PQ control	Communication	Remarks /Policy	Reference
1	Bronsbergen, Netherland	PV	Battery	Res	Central	√ (presented)	GSM	G1, G3, G5, G7, P1, P2	[16, 25]
2	DISPOWER German	CHP, PV	Battery	Res	Agent based	√	TCP/IP	G1, G3, G5, G7, P1, P2	[26 27]
3	KesselUniv, German	PV, Wind, Diesel	Battery	Res, Com	Central	x (not presented)	Ethernet	G1, G3, G5, G7	[26, 28]
4	Mannheim, German	PV	No storage	Res	Not known	x	Not known	G1, G3	[16, 29]
5	EDP, Portugal	CHP, Diesel	Not known	Com	Not known	x	Not known	G5, P1	[30]
6	Bornholm, Denmark	Diesel, Steam, Wind, Biogas	No storage	Static	Autonomous	√	Optical Fiber network	G1, G3, G5, P1,P2, P4	[31]
7	Samsø Island, Denmark	Wind, PV, Wood chip, Biomass, Geothermal	No storage	Res, Com	Not known	x	Not known	G2, G3, P5	[32]
8	Continuon, Netherland	PV	Battery	Res, Com	Central	Planning	Not known	G1, G3, G5, P1, P2	[33]
9	F.Y.R.O.M.-Kozuf	Waste water, Bio-gas	No storage	Com	Not known	x	Not known	G1, G3	[34]
10	Labein, Spain	PV, Wind, Diesel	Flywheel, Battery, SC	Com	Central	√	TCP/IP	G1, G3, G5, G7, P2	[35]
11	Kythnos Island, Greece	PV Diesel	Battery	Res	Central	x	Power line	G1, G5, G3	[36, 37]
12	NTUA, Greece	PV, Wind	Battery	Static	Multi- agent	x	XML	G1, G3, G5, G7, P1, P4	[28]
13	Manchester, UK	Sync generator Induc motor	Flywheel	Static	Central	√	Not known	G7, P1,P2	[28 , 38]
14	CAT, Walse, UK	Hydro, wind, PV, Biomass	Battery	Not known	Central	x	Not known	G1, G3, G7, P1, P5	[39]
15	Boston Bar, Canada	Hydro, Diesel	No storage	Res	Autonomous	x	Telephone line	G3, G4, P1	[40, 41]
16	Quebec, Canada	Steam Turbine	No storage	Res	Autonomous	x	x	G4, G3, P1	[41]

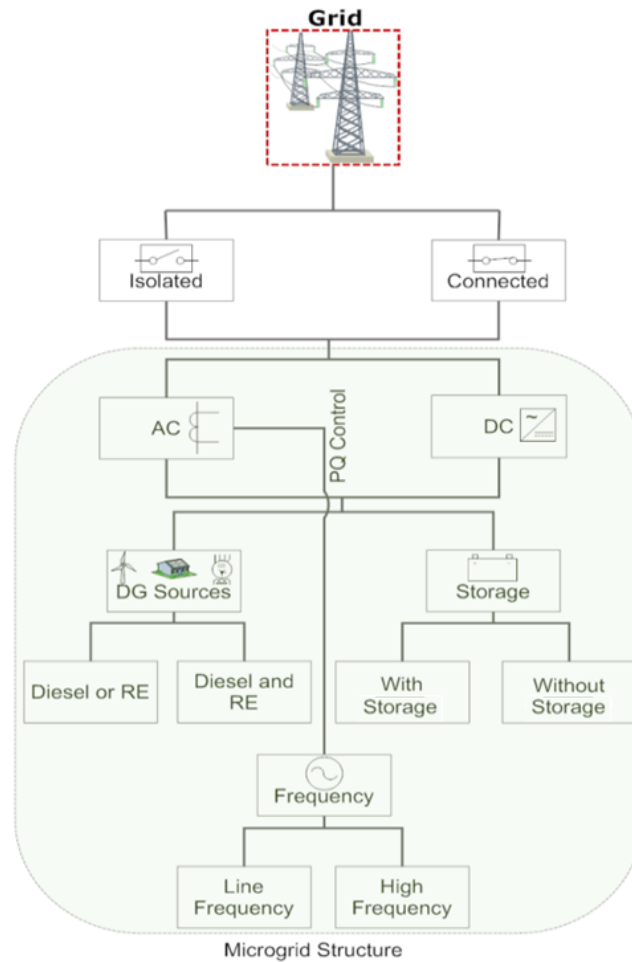
17	Ramea, Canada	Diesel, Wind	No storage	Not known	Autonomous	√	CSADA	G1, G3, G5, P2	[16]
18	Fortis-Alberta, Canada	Wind, Hydro	No storage	Not known	Not known	x	Not known	G1, G3, G7	[16]
19	GE Project Microgrids, US	PV, Generator, CHP	No storage	Com	Local, Supervisory	√	Not known	G1, G2	[42]
20	CERTS, Ohio, US	Natural Gas	Battery	Static	Autonomous	√	Ethernet	G5, G7, P2	[40, 43]
21	Wisconsin Madison, US	Diesel	No storage	Static	Autonomous	x	x	Not known	[44]
22	Global Research, US	Wind, Diesel, PV, Fuel cell	√	Res	Central	x	Local control network	G1, G2, G3, G5, G6, G7, P1, P4	[16]
23	Berkeley Lab, US	Natural oil, CHP	√	Com	Not known	x	Not known	G7, P5	[16]
24	Santa Rita Jail US	PV, Fuel cell, Wind, Diesel	Battery	Com	Not known	√	Not known	G1 – G7, P1 – P4	[45]
25	DUIT, US	PV, Microturbine, Genset	No storage	Com	x	x	x	G1, P1	[46]
26	NREL, Vermont, U.S.	Not known	Not known	Res	Not known	√	x	P1, P2	[16]
27	Aichi, Japan	Fuel cell, PV	Battery	Ind, Res	Central	x	Telecommunication	G3, G5, G7	[47, 48]
28	Kyoto, Japan	PV, Wind, Fuel cell, Gas	Battery	Res	Central	x	ISDN or ADSL	G1, G3, G4, G5, G7	[49]
29	Aomori, Hachinohe, Japan	Gas, PV, Wind, Wood	Battery	Com, Ind	Central	√	Private distribution line	G2, G3, G5, P1, P2, P3, P5	[16, 40, 49,]
30	Sendai project, Japan	PV, Fuel cell, Gas	Battery	Res, Com, Ind	Central	√	x	G1, G3, G7, P2	[49, 50]
31	Shimizu, Japan	Gas	Battery, Capacitor	Com	Not known	√	x	G7, P2	[16]
32	HFUT, China	PV, Wind, Hydro, Fuelcell, Diesel	Battery, Ultra-Capacitor	Static	Local, Central	√	x	G1, G3, G7, P3, P2	[51]
33	Laboratory-scale, China	PV, Wind	Battery	Static	Central	√	RS485 line	G3, G4, P1	[52]
34	Test μ Grid, IET, India	Fuel cell, Motor generator	Not known	Static	central	√	Not discussed	P2	[53]

35	Benchmark low voltage μ Grid, Greece	PV, CHP, Wind, Fuelcell	Battery, SC Flywheel	Res	Central/Autonomous	x	x	G3, P1	[54, 55]
36	2-DG μ Grid, Japan	Synchronous gen	No storage	Static	Autonomous	\sqrt	\sqrt	P2	[56]
37	Converter fed, Japan	Not known	Not known	Static, motor	Autonomous	\sqrt	Not known	P2	[57]
38	Tokyo, Japan	PV, Wind, Gas, Biogas	Battery	Com	Not known	\sqrt	Not known	G3, P2	[16]
39	NoBaDis, Mas Roig, Girona, Spain	PV, Wind, Diesel, CHP	Battery	Com, Res	Central	x	ZigBee	G1 – G7	[58]
40	DC linked μ Grid	PV, Fuelcell	Battery	Res	Autonomous	x	x	G3, G7	[59]
41	Japan	PV, Wind	Battery	Not known	Autonomous	x	x	G1, G2, G3	[60]
42	CESIRICERCA Italy	PV, Wind, CHP, Diesel	Battery, Flywheel	Static	Central	\sqrt	2.4 GHz radio channel	G2, G3, G5, G7, P2	[27, 61]
43	IREC's μ Grid, Spain	Wind, PV	Battery, SC, Flywheel	Com	Autonomous	x	Ethernet TCP/IP	G3, G4, G5, G7, P1, P3	[62]
44	CRIEPI, Japan	PV	No storage	Not known	Central	x	Fiber optic communication	G3, G7	[40, 63]
45	Texas, U.S.	Gas-turbine	No storage	Not known	Autonomous	\sqrt	x	G1, G5, P2	[64]

The classification of μ Grid systems is mainly based on the selection of the above components and the integration with the main electrical grid network. Fig 2.1(b) shows the basic structure of this classification. With regard to grid integration, grid system can be grid connected or isolated. μ Grids can be operated as AC or DC distribution networks. Based on DG sources, both AC and DC μ Grid can further be divided into three types - fully conventional, partially conventional/renewable and fully renewable. Both AC and DC systems can have energy storage devices incorporated. The AC μ Grid can further be classified as line frequency or HFAC μ Grid systems.



(a)



(b)

Fig 2.1 (a) Microgrid architecture (b) microgrid structure

2.3.1 Distribution Systems

In general, transmission and distribution systems and technologies are considered as AC and DC. Available technologies for μ Grid system are studied in [60] where the line frequency AC and DC technologies are considered for transmission and distribution systems. Research has also been carried out on HFAC system and thus there are three power electronics interfaces available by which the energy generated from the distributed sources can be connected to the distribution network. Therefore, the distribution network can also be classified as one of the following:

- DC line

- 60 / 50 Hz AC line (line frequency)
- HFAC

Table 2.2 shows some features of DC, AC and HFAC bus systems configured as μ Grids. A number of merits and demerits together with applications of these three systems are identified. In the case of merits, it is identified that the DC bus has higher reliability, lower losses, less PQ problems and no power converter is required. The AC bus has better reliability, easier connection to the utility grid and lower average cost; HFAC bus has fewer PQ problems, lower volume and weight.

2.3.2 DG Resources

DG technologies applicable for μ Grid may include a range of technologies: wind power systems, solar PV systems, hydropower systems, geothermal, biogas, ocean energy, single-phase and three-phase induction generators and synchronous generators driven by IC engines. From the review of existing μ Grid test-beds it is found that the most commonly used DG sources are PV, wind, micro-hydro and diesel. Biogas and ocean energy are also being used in some of the test-beds. A brief description of the most widely used DG sources is given in Table 2.3.

2.3.3 Storage Devices

One of the main requirements for successful operation of a μ Grid is inclusion of energy storage devices, which balances the power and energy demand with generation.

Table 2.2 Features of DC bus, 60/50 Hz AC bus and HFAC bus [65]

Interface Type	DC Bus	60/50 Hz AC Bus	HFAC Bus
Merits	good reliability; lower loss; longer grid length; lower cost; high power density due to elimination of magnetic transformer; less PQ issues are present; power conversion technology is not required; ac-grid connected inverters are needed for interfacing with grid.	good reliability; easier connection to the utility grid; possible galvanic isolation; easier adjustment of voltage levels; lower average cost.	Lower volume and weight; improvement of fluorescent lighting; direct connection of high frequency motors and compressors; smaller passive element; galvanic isolation with smaller high frequency transformers.
Demerits	High volume and weight due to presence of electrolytic capacitors in DC link; less compatibility of voltage levels; higher corrosion of electrodes; no galvanic isolation; few loads are operated in DC power systems. So implementation of DC μ Grid is very limited.	High volume and weight; stringent synchronisation requirement; current recirculation between sources; higher load effects; reduced grid length; galvanic isolation with bulky line frequency transformers; PQ problems are present; power conversion technology is needed.	Smaller grid length; higher cost; complexity of design and control; increase in voltage drop and power losses in the line.
Application	Renewable sources with DC output.	Renewable sources with variable AC output; direct connection through induction generators; requirement for galvanic isolation.	Any renewable sources; requirement of smaller volume and weight and higher power density.

Table 2.3 Typical characteristics of common DG sources [66, 67]

Characteristics	Solar	Wind	Micro Hydro	Diesel
Availability	Geographical location dependent	Geographical location dependent	Geographical location dependent	Any Time
Output Power	DC	AC	AC	AC
GHG Emission	None	None	None	High
Control	Uncontrollable	Uncontrollable	Uncontrollable	Controllable
Typical interface	Power electronic converter (DC-DC-AC)	Power electronic converter(AC-DC-AC)	Synchronous or Induction generator	None
Power flow control	MPPT &DC link voltage controls (+P, \pm Q)	MPPT, Pitch & Torque control (+P, \pm Q)	Controllable (+P, \pm Q)	Controllable (+P, \pm Q)

Depending upon the capacity, performance, purpose of use and future scope, details comparative studies among the different types of storage devices can be found in [63]. Some of the basic features of these storage devices are given in Table 2.4. From Table 2.1 it is observed that most commonly implemented storage devices in the μ Grid test-beds are various types of batteries, flywheels and ultra/super capacitors. Few of the test-beds did not include storage units. It was found that if the μ Grid is without storage, a controllable DG source should be included in the system such as a diesel generator. This can be observed in examples 5, 6, 15, 17, 20, 22, 24, 25, 32, 39 and 35. There are two exceptions where no storage device is included in the system and only uncontrollable DG sources are present in examples 4 and 18. In these cases grid integration is an important factor.

Table 2.4 Basic features of suitable storage devices in μ Grid system [63]

Basic Features	Battery	Flywheel	Supercapacitor
Continuous Power (W/kg)	50	200 - 500	500 - 500s
Typical Back up time	5	10	10
Losses at stand-by	Very low	Variable	High
Environmental impact	Medium-High	Low	Low
Maintenance	1 / year	1 / 5year	None
Charging efficiency (%)	75	90	85
Current energy price (€/kWh)	150 - 800	3000 - 4000	4000 - 4000
Service Life (year)	5	20	>10

2.3.4 Communication Systems

For power control and protection, communication systems are very important. The basic communication methods with their characteristics are given in Table 2.5. Details of the advantages and disadvantages of these systems together with the protocol have been discussed in [68]. From Table 2.5 it is observed that the

communication systems commonly applicable in the μ Grid systems are GSM, GPRS, 3G, WiMax, PLC and ZigBee. Among the systems mentioned, 3G and WiMax have fast data transfer rates and a long coverage range. However the limitation is that spectrum fees are costly. For long distance communication, WiMax and 3G are used and for short distance communication PLC and ZigBee systems are preferable. Table 2.1 shows that different μ Grid test-beds have implemented different types of communication systems.

Table 2.5 Different communication systems applicable in μ Grids [68]

Technology	Spectrum	Data Rate	Coverage Range	Applications	Limitations
GSM	900-1800 MHz	Up to 14.4 Kpbs	1-10 km	AMI Demand Response, HAN	Low data rates
GPRS	900-1800 MHz	Up to 170 Kpbs	1-10 km	AMI Demand Response, HAN	Low data rates
3G	1.92-1.98 GHz 2.11-2.17 GHz	384 kbps-2 Mbps	1-10 km	AMI Demand Response, HAN	Costly spectrum fees
WiMax	2.5, 3.5, 5.8 GHz	Upto 75 Mbps	10-50 km (LOS) 1-5 km (NLOS)	AMI Demand Response, HAN	Not Wide Spread
PLC	1-30 MHz	2-3 Mbps	1-3 km	AMI, Fraud Detection	Harsh, noisy environment
ZigBee	2.4 GHz-868-915 MHz	250 kbps	30-50 m	AMI, HAN	Low data rate, short range

2.4 Policy and Goals

Most developed countries are already engaged in Research, Development and Demonstration (RD&D) of different μ Grid structures from laboratory to field level. Table 2.1 shows that EU countries are advanced in RD&D of μ Grid systems. EU energy policy also focuses on creating a competitive single market, producing energy from renewable sources and reducing the use of imported fossil fuels. The EU target for 2020 is called 20-20-20 (Three Times Twenty) - (i) to improve energy efficiency by 20%, (ii) to reduce GHG emissions by 20% and (iii) to consume 20% of energy from renewable sources [1] The most important issue is the technical requirement for

connecting DGs to the distribution systems in order to maintain safety and power quality. It also includes the development of connection practices, protection schemes, ancillary services and metering. A number of policies have also been implemented to attract connection of Small Scale Embedded Generators (SSEGs) by providing financial incentives to small generators such as the exemption of transmission use of system charges and transmission loss charges, climate change levy exemption, and Renewable Obligation as in the UK [69].

The IEEE standard 1547-family has introduced a set of standards for interconnecting Distributed Energy Resources (DER) with EPS. These are [70]:

1. 1547.1 (2005): The rules governing connection of the DGs to the EPS
2. 1547.2 (2008): Application guide for IEEE standard 1547
3. 1547.3 (2007): Guide for monitoring and communication of DGs. It also facilitates interoperability of DGs in interconnected mode
4. 1547.4 (2011): Design operation of and integration of DER island systems. Part of 1547.4 standard is considered as one of the fundamental standards as it deals with vital planning and operation aspects of μ Grid, such as impacts of voltage, frequency, power quality, protection schemes and modification
5. 1547.6 (2011): Guide of interconnection with Distribution Secondary Networks types of area EPS with DG
6. 1547.7 (2013): This guide is a very significant step to standardize and universalize μ Grid and DG systems. It emphasizes on the methodology, testing steps and aspects to assess the impact of a DG on the system

IEEE 2030 standard provides alternative approaches for smart grid interoperability. This standard provides the reference model SGIRM (Smart Grid Interoperability Reference Model) and knowledge based addressing technology,

characteristics, functional performance and evaluation criteria. Moreover it describes the application of engineering principles for smart grid interoperability of the EPS with end-use applications and loads. The IEEE 2030 SGIRM defines three integrated architectural perspectives: 1) Power systems, 2) Communications technology and 3) Information technology.

A key element of μ grid operation is the μ grid Energy Management System (MEMS). It includes the control functions that define the μ grid as a system that can manage itself, operate autonomously or grid connected, and seamlessly connect to and disconnect from the main distribution grid for the exchange of power and the supply of ancillary services. In case of interoperability issues to integrated μ grid in smart grid network, the IEEE 2030.7 standard has to be followed. The scope of this standard is to address the functions above the component control level associated with the proper operation of the MEMS that are common to all μ grids, regardless of topology, configuration, or jurisdiction. Testing procedures are also addressed [71].

EN 50438 standard is for μ Gen systems which complies with specific Irish protection settings. According to the standard each μ Gen shall have interface protection which includes the following elements [72]:

1. Over Voltage
2. Under Voltage
3. Over Frequency
4. Under Frequency
5. Loss of Mains

Although sustainability of μ Grid depends on the geographical location, cost of energy production, technical viability and government policy in the energy market; some standards and policies towards the implementation of μ Grid in the future smart

grid are required. A number of the common and most important points for standards and policy development are discussed below.

2.4.1 Interconnection

Interconnection practices aim to ensure that DG systems will not disturb other users of the network during normal operation, and that safety will not be jeopardized in the case of abnormal conditions. To this end, interconnection procedure typically includes technical provisions as follows:

- Voltage regulation and power quality, including steady state voltage deviations, fast variations, flicker, harmonics, DC injection.
- Protection and anti-islanding schemes
- Earthing or grounding arrangements.

IEEE 1547 Standard for Interconnecting DERs with EPS describes the technical rules for interconnection. Fig 2.2 shows the recommended interconnections between the DG systems and EPS. Besides this, safety and protection issues related to μ Grid are also defined in IEEE Std 1547.4-2011. Policy that is required for interconnection to implement in EU, Japan and USA has been discussed in [94]. This interconnection issue has been defined as P1 in the common policy standard section below. Examples 1, 2, 5 in Table 2.1 have discussed this matter.

2.4.2 Power Quality and Reliability

Power quality in μ Grid systems has become an important issue as the penetration of DG sources, either connected to the grid or as part of a μ Grid. Solar, wind, micro-hydro and diesel are the leading DG sources. Power quality problems related to these DG sources have been identified in [73, 74] and are shown in Table 2.6. This table shows that, compared to PV and wind, small/micro hydro systems have fewer PQ

problems. The main advantages of these RESs are they have less pollution than other sources. Conventional diesel generation also has fewer PQ problems such as voltage sag/swell, over/under voltage and flicker. Table 2.1 shows that few μ Grid test-beds have implemented PQ devices in their systems. At the same time, for stability and reliability of the system, PQ control is one of the basic criteria to be considered and therefore more emphasis should be given to improving PQ problems in DG resources.

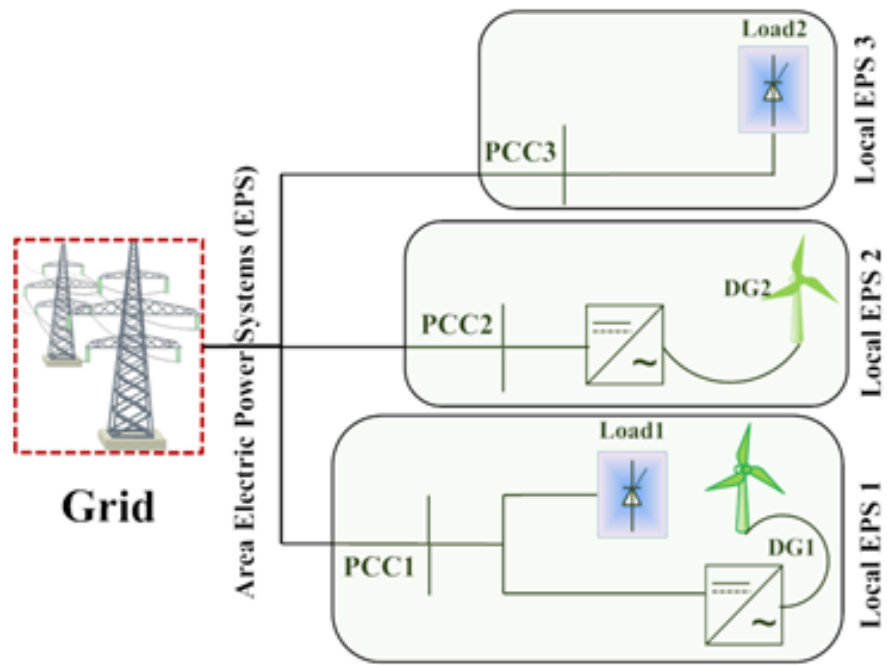


Fig 2.2 Recommended interconnection between the DG sources, load and EPS [74]

Table 2.6 PQ problems related to DG systems

PQ Problems	Wind energy	Solar energy	Micro/small hydro	Diesel
Voltage sag/Swell	•		•	•
Over/Under Voltage	•			•
Voltage Unbalance		•		
Voltage Transient	•			
Voltage Harmonics	•	•	•	
Flicker	•	•		•
Current Harmonics	•	•	•	
Interruption	•	•		

PQ issues and standards for electrical distribution network are mainly defined in IEC 61000-4-30 and EN 50160 [75]. Besides this, the active and reactive power

control, intentional islanding, load power quality, EPS power quality, voltage regulation, frequency regulation and ride through capability and policy standards for isolated and grid-connected μ Grid are described in IEEE Std 1547.4-2011. After an intentional islanding operation, DG island systems suffer adverse power quality problems such as voltage distortion. While DG is working in parallel with the area EPS, the DG equipment needs to meet the power quality standards according to IEEE Std. 1547-2003. This issue is defined as P2 in the common policy section and examples 1, 2, 6 in Table 2.1 have focused on this issue.

2.4.3 Economics

In a centralised system, the cost of energy production to energy distribution differs significantly. As an example, the electricity produced by large central generation is being sold in UK wholesale markets for around 0.02–0.04£/kWh, but by the time this electricity reaches the end consumers it is being sold at a retail price of 0.08– 0.10 £/kWh which is shown as a flowchart in Fig 2.3 [76]. This increase in value is driven by the added cost of transmission and distribution services to transport electricity from the point of production to consumption. At the same time, it increases the loss of energy which is also added as an extra cost for the consumer. Despite its critical effect on economics, this point is often overlooked in discussions of the relative efficiency and cost of small versus large scale generation. The practical limitations of the possible beneficial application of renewable sources are the high initial cost and the low power density. Therefore, economic viability study of μ Grid systems is very important. This issue is identified as P3 and only a few of the examples such as 29, 32 and 43 in Table 2.1 have discussed this point. More emphasis should be given to this matter.

The methodologies to evaluate and quantify the environmental economics-related benefits of μ Grid and μ Gen systems are found in [76, 77]. The policies to encourage integrating renewable energy based DG systems are set as:

- Exemption from transmission and loss charges
- Climate Change Levy exemption for renewable energy
- Renewable Obligation
- Cost reflective charging methodology for pricing of distribution network
- GHG emission reduction charge

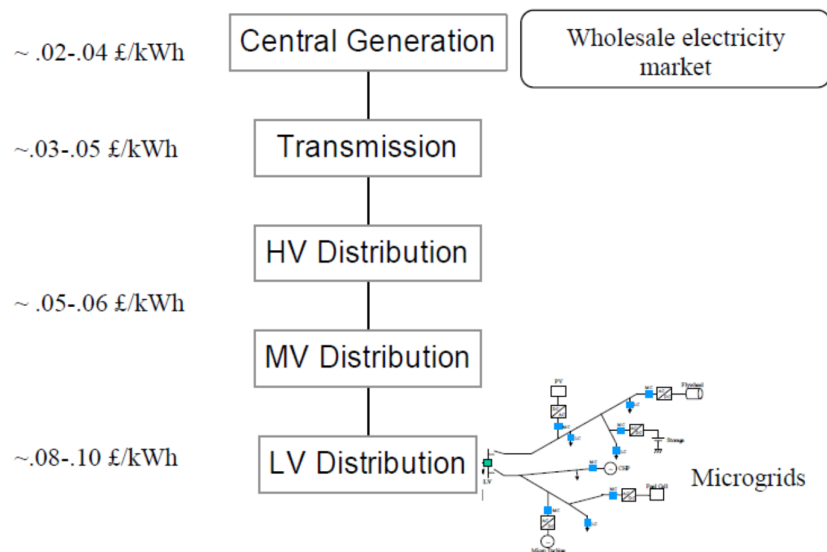


Fig 2.3 Price of electricity in UK energy market [76]

2.4.4 Participation in Energy Market

Techno-economic sustainability of a μ Grid depends on its participation policy in the energy market. Currently there are two basic types of policies applied to participants in the energy market [7]:

- (I) The Microgrid Central Controller (μ GCC) aims to serve the total demand of the μ Grid, using its local production, as much as possible, without exporting power to the upstream distribution grid. For the overall

distribution grid operation, such behaviour is beneficial, because at the time of peak demand, when energy price in the open market is high, the μ Grid relieves possible network congestion by partly or fully supplying its energy needs. From the consumers' point of view, μ GCC minimises the operational cost of the μ Grid, taking into account open market prices, demand, and DG bids. Thus the consumers of the μ Grid share the benefits of reduced operational costs.

- (II) In this case, μ Grid participates in the open market, buying and selling active and reactive power to the grid, probably via an aggregator or similar energy service provider. According to this policy, the μ GCC tries to maximise the corresponding revenues of the aggregator, by exchanging power with the grid. The consumers are charged for their active and reactive power consumption at the open market prices. The μ Grid behaves as a single generator capable of relieving possible network congestions not only in the μ Grid itself, but also by transferring energy to nearby feeders of the distribution network. This point is defined as P4 and examples 6, 12 and 22 in Table 2.1 have highlighted this matter.

Based on the study of these existing test-beds and the relevant policies, some common goals and policy indicators are given below. Common goals for introducing μ Grid systems are:

- G1. More penetration of renewable sources to the existing grid leading to a smart grid
- G2. Reducing the main grid transmission and distribution cost
- G3. Reducing GHG emission and leading to environmental benefit
- G4. Improving the energy security and stability
- G5. Smart communication/control for both load management and generation systems

G6. Maximizing operational efficiency

G7. μ Grid dispatch ability/storage integration

Some of the common standards and policies should be considered in general are:

P1) Interconnection

- a) Protection and anti-islanding schemes
- b) Earthing or grounding arrangements
- c) Re-connection to the power system

P2) Power quality and reliability

P3) Economics

P4) Participation in energy market

P5) Less CO₂ emission/ low carbon/ zero carbon policy

2.5 Findings

From the review of μ Grid architectures, it was found that most of the test-beds are line frequency, AC μ Grid. As the main grid and most of the loads are AC, AC μ Grid is easy to integrate with the grid. Maintaining the PQ is one of the critical tasks in AC systems. HFAC μ Grid is a new concept and is a possible way for integrating RESs to the μ Grid. One of the main advantages is that, PQ problems are reduced in this system. The main problems of the HFAC μ Grid system is the complexity of the control devices, large voltage drop and higher long distance power loss. These issues limit its practical implementation, but this technology remains a topic for farther research. On the other hand, the main advantages to DC systems are few PQ problems and therefore fewer additional control or components are required. The application of DC μ Grid is very limited due to the unavailability of DC loads. But in recent years research emphasis has been given on DC μ Grid systems. These papers present different research aspects on DC μ Grid system [78-80]. Recently hybrid μ Grid system

(combined AC and DC) is also a point of interest to the μ Grid researchers. Different aspects of AC DC hybrid μ Grid systems have been discussed in [81, 82].

Most commonly used DG sources in μ Grid systems are solar PV, wind, micro-hydro and diesel. Considering the environmental benefits and reducing GHG emission, RESs are popular as DG units in Europe. America prefers wind and diesel, whilst Asia is mostly utilizing natural gas.

PQ is a potential issue in μ Grid systems. As the renewable DG sources are highly dependent on the environment; variability of the resource introduces some PQ problems. Power electronics converters, to interface the DG sources to the grid, introduce additional harmonics to the grid also. Review of the test-beds show that very few μ Grid test-beds have implemented PQ devices. Recent research on μ Grid control and PQ improvement [83, 84] also show that control of the DG inverters and μ Grid central controller becomes more complex to improve PQ and reliability. In this aspect, integration of custom power devices such as Active Power Filter and Unified Power Quality Conditioner in grid connected/autonomous μ Grid system is getting more importance to reduce the control complexity and improve the power quality [85, 86]. Therefore, further research and implementation of more test-beds with custom power devices are required to improve PQ and reliability. Thus it can improve the performance of μ Grid systems.

Storage systems are one of the important options that a μ Grid should have for its efficient and stable operation. Most of the existing test-beds have battery storage. Some have capacitor banks and flywheels as storage devices. Some of the μ Grids have a combination of two or three storage units and some do not have any storage units at all. From the review it was found that in most cases (except two), if there is no storage device, at least one controllable DG source such as diesel or natural gas is

present in the system. If the system does not have any storage devices and only RESs are present, then grid integration is a very important factor for that μ Grid system.

Policies for μ Grid systems are not yet well defined. From Table 2.1, it has been identified that in terms of existing prominent μ Grids, EU countries are in the leading position. In most μ Grid systems some of the common goals and policies are found such as more penetration of RE sources (as a hybrid system) to the existing grid, reduced main grid transmission and distribution cost, reducing GHG emission, smart communication/control, improved energy security and reliability. Very few systems deal with the interconnection (anti-islanding schemes, earthing, and reconnection), power quality and reliability, economics, participation in energy market and low/zero carbon policy for their policy development. USA also focuses on these agendas including maximum operational efficiency and μ Grid dispatch ability. μ Grids in Asia has not yet penetrated to any significant extent in energy markets.

2.6 Conclusion & Future Trends

DC μ Grid is not yet popular in the European region although they have advantages with fewer PQ problems. More emphasis should be given to their development. The main barrier to expand this technology is the low number of DC loads. As technology has advanced, more DC compatible loads will be introduced. Most of the existing AC μ Grid test beds have included batteries as storage devices although they are expensive and further technological improvement can help to make them become economically viable.

More penetration of RES is expected in μ Grid systems as they are almost pollution-free and thus environment friendly. In that case, further efforts should be made to solve the PQ problems associated with RE sources.

A combination of different RE systems together with storage has the significant potential as such a system helps to store clean energy whenever available. As most of the μ Grids are close to the grid and integration is possible, it would be beneficial to have some experimentation and performance analysis on μ Grids with fully renewable sources.

The advancement in storage and battery systems is promising in terms of cost and technology. Although their initial system cost and Operation and Maintenance cost (O&M) may be higher, the requirement of demand side management and maximizing the use of available RESs, μ Grid with storage devices could be viable options in the near future.

All the existing test beds described have limited technical information but generally no commercial information is available. In terms of techno-economic benefits, the systems should be optimized both technically and economically. Reducing the number of system components, reducing the installation and management costs, improving the system integrity, improving source and load efficiency, and introduction of source or demand side management can enhance the viability of any system. Reducing conventional sources is required to achieve environmental benefits. Therefore, moving towards the operation of AC or DC and a hybrid μ Grid consisting of fully renewable sources with reduced storage and integration with grid may be the better candidate for future μ Grid implementations.

Communication systems are all pervasive and the energy required for such communication system is reducing by implementing energy efficient and low cost wireless sensor networks. Load management and control of μ Grid system now becomes more efficient. These issues indicate that present μ Grid research and development are concerned with the gradual move towards the smart grid concept.

Chapter 3

Sustainability of Micro-generation Systems

3.1 Introduction

The literature review shows that Ireland does not have μ Grid policy and under the present REFIT (Renewable Energy Fed-in-Tariff) policy, PV/Wind energy based micro-generation (μ Gen) system is not sustainable in Irish environment [87-88]. On the other hand, empowering the energy citizen is one of the important agenda items in the green paper of energy policy in this country [89]. The Irish government has also identified μ Gen systems as an option for alternative energy supply in a report for Building Regulations 2011 [90]. This regulation stated that for new installations, a reasonable portion of energy consumed by the dweller should be provided by RES. Therefore, research has been started with μ Gen system. The aim of the present work is to determine a few possible ways to reduce the energy production cost of PV/Wind energy based μ Gen system as a sustainable/viable solution for Ireland. Some techno-economic analysis have been done here a) to increase the energy production and b) to reduce the produced cost of energy. Increasing the energy production is related to the implemented technology and optimum placement of the system based on geographical and environmental conditions. Reduction of the cost of energy depends on the energy

utilisation factor and this also depends on the behavior of occupants, operating time of appliances, system integration with/without storage. From the geographical and environmental point of view, this research considers the time series data from a location in Dublin, the capital of the Republic of Ireland. The load profile is considered for the occupants consisting of 2 adults and 2 children (one of the highest energy consumed occupant types in the residential sector).

3.2 PV Based Micro-generation System

Ireland is located in a low irradiation region. Findings of previous articles show that, most analysis has been carried out for 53° tilted fixed axis PV system. Based on the current market price and REFIT policy, this system is not viable. System cost also has been taken from the existing test-bed in Dublin Institute of Technology which was installed in 2009 [87]. Component cost and analysis based on that existing system also shows that the PV based μ Gen system is not a sustainable solution for Ireland. Present market trends in the reduction of PV system cost and increase in Irish grid electricity costs lead to the need to re-analyze the sustainability of μ Gen systems.

Therefore the following techno-economic issues have been considered and analysed in detail to improve the technical performance as well as to increase the energy production of the system. This could help to reduce the cost of produced energy (COE) below the purchased grid electricity cost or the REFIT cost to make it sustainable. The considered issues are:

✓ Technical issues:

Ta) Optimum placement (tilted angle) of PV panel for a fixed axis system

Tb) Auto tracking system: One axis

Tc) Auto tracking system: Two axis

Td) Manual tracking system: Monthly optimum tilt angle

✓ Economic issues:

Fa) Reduction of interest rate – Generally the interest rate is 4.99% in Irish banks.

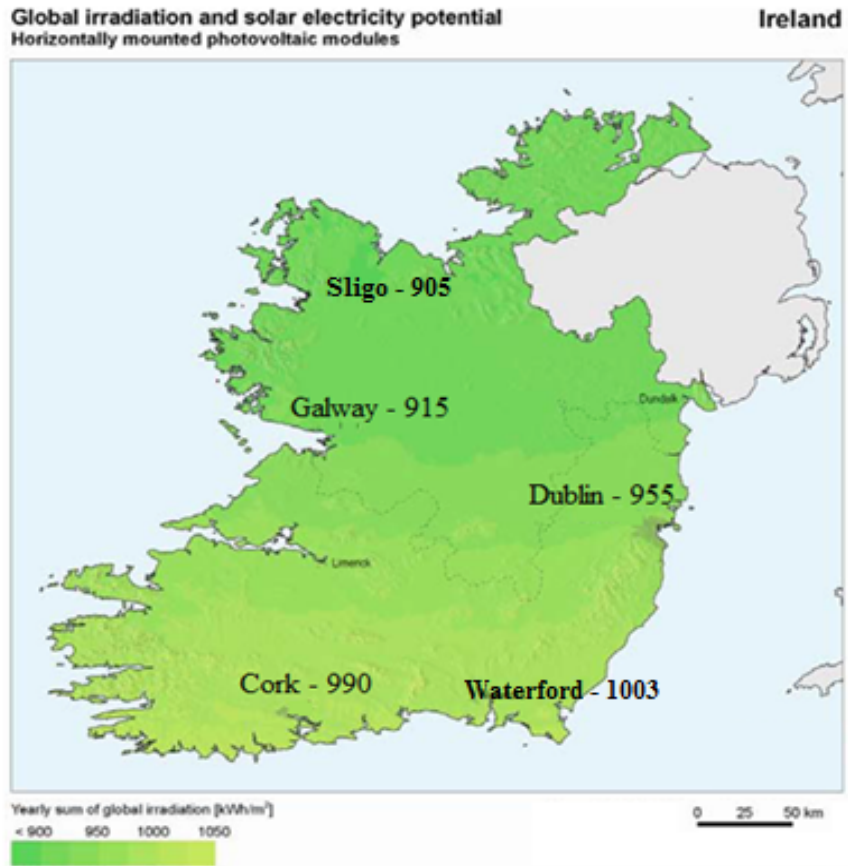
Fb) VAT waiver for the component cost – VAT over the component cost is assumed to be reduced by 20% so the systems can become economically viable.

A methodology has also been discussed to show step-by-step how the techno-economic issues help to improve the technical performance of the system and thus reduce the production cost of energy to achieve sustainability. This methodology can be followed by any region to decide the factors to make their PV based μ Gen system sustainable.

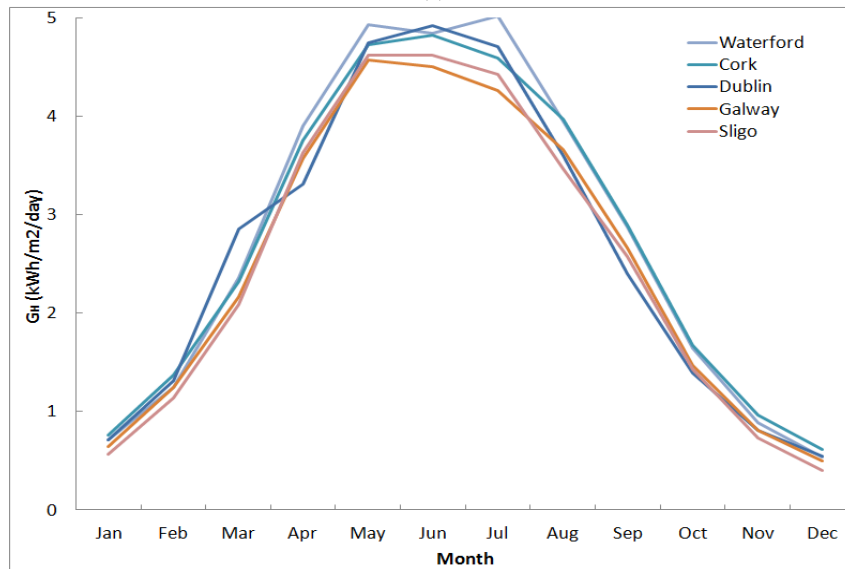
3.2.1 Supply (solar) and Demand (load) Energy Profile

Fig 3.1(a) shows the annual average solar radiation map (kWh/m^2) with some numerical values (average of last 10 years) for some of the locations in Ireland. These dataset are collected from the GIS dataset [91] and Met Éireann [92]. The map shows that the northern and western parts of Ireland (Sligo, Galway) have lower solar radiation. As we move towards the southern region of the country (Cork, Waterford) the solar radiation increases by approximately 10%. Dublin is located in the middle and the radiation is 955kWh/m^2 . Therefore, Dublin is considered for detailed analysis.

Fig 3.1(b) shows the monthly average solar radiation for a number of places in Ireland. This graph shows that Sligo and Galway experiences less solar radiation in the range of $4.5\text{ kWh/m}^2/\text{day}$ in the summer months (May-Aug). Dublin, Cork and Waterford shows slightly better performance in these months, and solar radiation is in the range of $5\text{kWh/m}^2/\text{day}$.



(a)

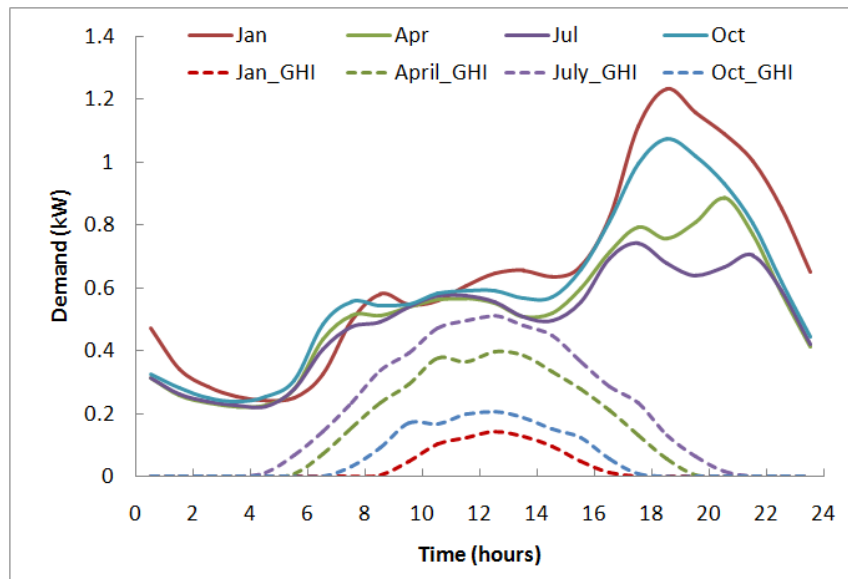


(b)

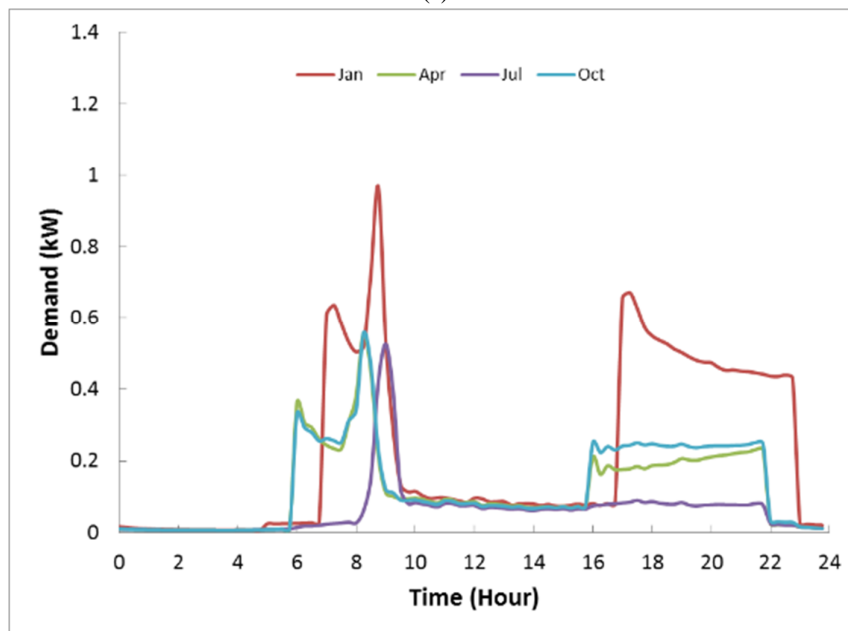
Fig 3.1(a) Solar radiation map of Ireland [91] (b) Monthly average solar radiation of Ireland

Fig 3.2(a) shows per capita energy consumption pattern (kW/h) per house for four months in Ireland with solar radiation availability in those months. This figure

shows that, load consumption is relatively high (>1.2 kW/h) in winter months (Oct – Jan) at night time (17:00 - 22:00) whereas solar radiation is available in the day time (8:00 - 17:00). For most of the time, the available radiation (<0.2 kWh/m²) at that time is not sufficient to produce electricity.



(a)



(b)

Fig 3.2 (a) Per capita energy consumption (kW/h) and solar radiation (kWh/m²) pattern in Dublin, Ireland (b) load pattern of a typical residential house (considered in the analysis)

On the other hand, in summer months, peak load demand (<1.0 kW/h) occurs at times between (17:00 - 22:00). Solar radiation for those months is relatively high in the range of 0.5kWh/m² and also suitable for electricity production and storage. Fig 3.2(b) shows the load pattern of a typical residential house that has been considered for rest of the analysis.

3.2.2 Methodology

Fig 3.3 shows a pictorial representation of the methodology for the techno-economic analysis of a PV based μ Gen system. The outcome of this method can determine the conditions to achieve sustainability of the system. This methodology is also applicable for other RE systems. The method will compare outcomes of the two systems; one is defined as the base case or the currently practiced system and the other one is the proposed case. In this analysis, the base case is the grid electricity and fed-in-tariff cost and the improved μ Gen system cost is the proposed case. For both cases, the required information or the input of the methodology is divided into three parts:

- i) *Load and Resource input/information*
- ii) *Technical input*
- iii) *Economic input*

The outcome of the methodology will determine the conditions for sustainability through the following process:

- iv) *Production COE*
- v) *Compare with base case*
- vi) *Technical or/and economic improvement*

An example, as a case study, is discussed below to show the step-by-step procedure and the outcomes to achieve sustainability of a PV based μ Gen system. The reasons for relating the analysis to Dublin are as follows:

- Geographically, Dublin is at the mid-latitude of the island
- It has moderate solar radiation availability
- It is the highest populated county
- A number of PV μ Gen systems exist in Dublin and the city council has planned to install more

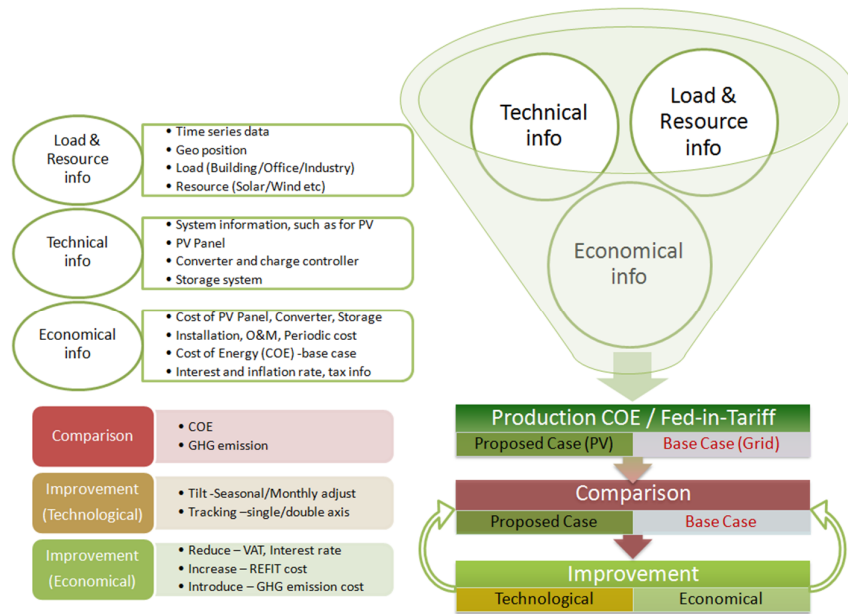


Fig 3.3 Methodology for techno-economic analysis of PV based μ Gen system

3.2.2.1 Load and Resource Information

Real measured data of average annual households are taken from ISSDA (Irish Social Science Data Archive) [93] for the Dublin location. Monthly averaged solar radiation values are taken from Met Éireann, the Irish national meteorological service. Artificial but realistic hourly solar radiation data then has been generated with the help of HOMER software [94]. The clearness index (K_T), which is a dimensionless

number between 0 and 1, indicates the fraction of the solar radiation striking the top of the atmosphere is also calculated. Fig 3.4 (a) shows the monthly average global horizontal radiation ($H_{G,ave}$ kWh/m²/day) and the clearness index. Fig 3.4 (b) shows the monthly minimum and maximum values of $H_{G,ave}$. Experimentally, it is found that around 0.08kW/m² solar radiation is required to produce electricity [95]. In this regard the graph shows that average winter months in Dublin are correlatively less productive than the summer months. Therefore it would be better to determine the orientation of the PV module to collect the maximum possible solar radiation during the summer months. Table 3.1 shows some of the calculated values based on the load and resource data for a typical location in Dublin.

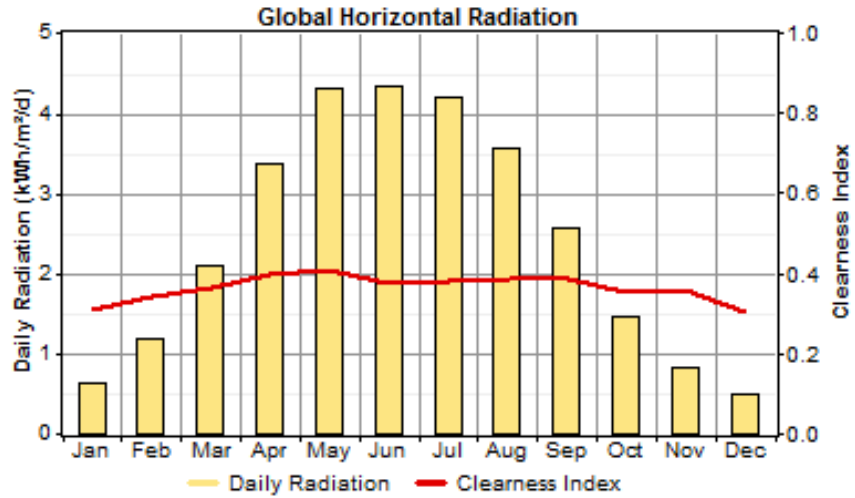
Table 3.1 Load and resource information for μ Gen system

Geo location & position	Dublin, Ireland (53.4 ^o N and 6.2 ^o W)	
Load type	Residential	
Load profile	Time series measured data.	
	Peak Load (kW)	1.8
	Average Energy demand (kWh/day)	14
Resource profile	Solar Radiation (Annual Average - kWh/m ² /day)	2.43
	Clearness Index (Annual Average)	0.38

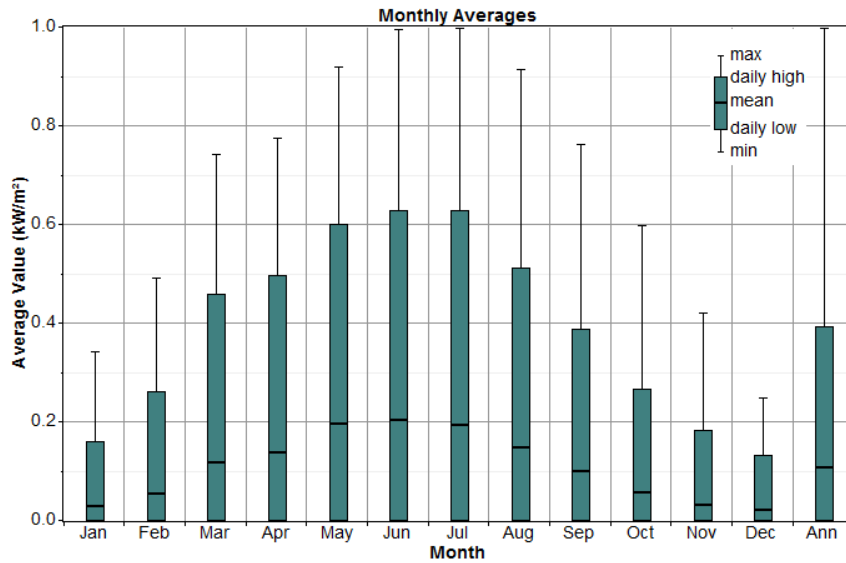
3.2.2.2 Technical Information

Fig 3.5 shows a simple grid-connected and PV based μ Gen system. According to the typical limit in Ireland, a maximum 6kW μ Gen system is to be connected to the grid. The calculation method of power output from a micro solar PV system (P_{inv}) is given in [96]. Based on the inverter efficiency curve; an average power loss (k) in the inverter is considered here which is 10%. Thus, the final power output (P_{inv}) from a domestic solar PV system is calculated as:

$$P_{inv} = P_{pv}(1 - k) \quad (3.1)$$



(a)



(b)

Fig 3.4 (a) Monthly average value of solar radiation with clearness index and (b) Monthly minimum and maximum radiation of Dublin

3.2.2.3 Economic Information

For most of the components such as the PV module, inverter, rest of the Balance of System (BOS) and installation cost has been taken from present market price. This will allow a better understanding of the methodology and analysis to calculate the cost of energy and to achieve sustainability. It would also help the consumers to determine their threshold point or upper limit to achieve the system's sustainability.

a) PV panel cost

PV panel cost has been decreasing dramatically over recent years. Table 3.2 shows a price list of some of the most commonly used PV panels in Ireland and UK [97]. Depending on the manufacturer, type of solar cell, module size and efficiency, the per unit watt-peak module cost varies. In this methodology and analysis process, the panel cost has been generalised as (€Wp). Based on the panel cost presently available in the market, the generalised cost has been considered between 1&4 € Wp .

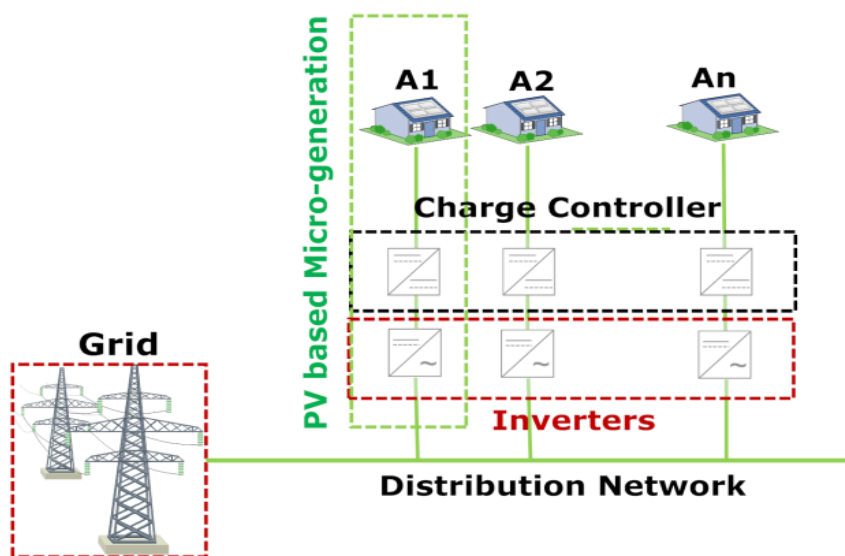


Fig 3.5 PV based μ Gen system

Table 3.2 Presently available PV panel cost [97]

Manufacturer	Module Size (Wp)	Efficiency (%)	Cost (€Wp)
Kyocera	215	16	2.82
Sharp	220	17	3.16
Nanosolar	230	17.1	0.78

b) Converter cost

Table 3.3 shows the price list of commonly used converters in Europe. Based on this information, a cost-capacity curve graph, as shown in Fig 3.6, has been generated to calculate the converter cost for any other size. It is found that the cost for converter varies from 0.8 to 0.3 (€Wp) for small to large size in capacity.

Table 3.3 Converter cost [98]

Model (Sunny Boy)	Peak Capacity (Wp)	Cost (€)	Lifespan (years)
SB-1700	1700	1300	15
SB-2500	2500	1660	15
SB-3000	3000	1900	15
SMC-6000	6000	2630	15

The converter and battery (if present) for any renewable based power system are the most costly components. The unit price also varies depending on the manufacturer and technology that are used. In this calculation, these two components have been considered separately. BOS consists of the rest of the components for the system such as charge controller, wiring, switches, frame etc. The cost for BOS and labour cost for installation are considered as 0.3€/Wp and 0.2 €/kWp respectively. Based on these data, Table 3.4 shows the generalised initial cost for the grid connected PV based μ Gen system.

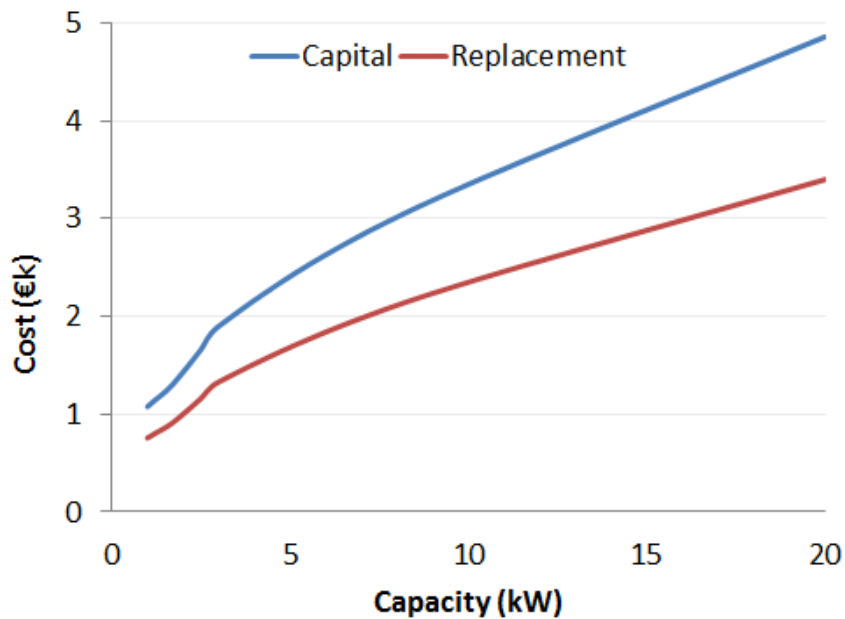


Fig 3.6 Cost vs capacity curve for grid-tie converter

Table 3.4 Generalised initial grid-tie PV based μ Gen system cost (€/Wp)

PV Panel cost	BOS	Installation cost	Converter cost
4	0.3	0.2	Varies with capacity (0.8 to 0.3)
3	0.3	0.2	
2	0.3	0.2	
1	0.3	0.2	

c) Interest and inflation rate

A green loan having a loan rate of 4.99% is considered here as it is obtained from a commercial bank. All calculations are based on this loan rate unless it is stated differently. An inflation rate of 2.16% is considered. This was the average annual inflation rate for Ireland in year 1996 and 2015 [99].

d) Grid electricity cost

The grid electricity cost for day and night time has been taken from the ESB, Ireland. The prices are as follows:

- Day time (including vat): 20.78 + 2.54 (Public service obligation levy)
= 23.32€cent/kWh
- Night time (including vat): 10.27 + 5.0 (standing charge/night hr)
= 15.27€cent/kWh

e) REFIT policy

Under the grid-connected μ Gen REFIT policy, the μ Gen electricity producer receives 0.10€ for per unit electricity feed into grid which is opt out from 2015 [100].

3.3 Techno-economic Improvement

Based on the primary information, the Levelised Cost of Energy (LCOE) has been calculated for grid-connected μ Gen system which is given as:

$$LCOE = \frac{\Sigma(C_{ann,Cap} + C_{ann,Repl} + C_{ann,OM}) + C_{ann,Ext}}{E_{ann,L} + E_{ann,Gs}} \quad (3.2)$$

where,

$C_{ann,Cap}$ = Annualised capital cost of each component

$C_{ann,Repl}$ = Annualised replacement cost of each component

$C_{ann,OM}$ = Annualised operation and maintenance cost of each component

$C_{ann,Ext}$ = Annualised other external cost of the project

$E_{ann,L}$ = Annualised energy served to the load

$E_{ann,Gs}$ = Annualised energy sold to the grid

Either capital/replacement, the annualised cost of any component can be calculated as:

$$C_{ann} = C_{init} \cdot \frac{i_r(1+i_r)^N}{(1+i_r)^N - 1}$$

Where,

C_{init} = Initial cost

$$i_r = \frac{i - f}{1 - f}$$

i_r = Real interest rate

N = Number of years

f = Inflation rate

The economical sustainability of the system depends on the calculated LCOE which should be lower than the purchased grid electricity cost. Comparative analysis shows that for certain conditions, fixed angle tilted system can be viable. Sustainability can be even upgraded by technical and economic improvement of the system.

3.3.1 Technical Improvement

The position of the sun changes continuously over time, therefore fixed angle tilted PV systems cannot receive optimum solar radiation. As a technical improvement, this is one of the reasons for introducing sun tracking technology in the system. The racks that allow the collectors to track along the movement of the sun are quite costly. If the obtained solar radiation increase by the tracking system is not significant enough, the system COE can increase. The obtained solar radiation for tracking system can be derived as [96]:

$$I_{G-track} = I_B \cos \delta + CI_B \left[\frac{1+\cos(90^\circ-\beta+\delta)}{2} \right] + \rho(I_{BH} + I_{DH}) \left[\frac{1+\cos(90^\circ-\beta+\delta)}{2} \right] \quad (3.3)$$

I_{BC} = Beam radiation

I_{DC} = Diffuse radiation

I_{RC} = Reflected radiation

I_{DH} = Horizontal Diffuse radiation

I_{BH} = Horizontal beam radiation

C = Sky diffuse radiation

I_B = Direct beam radiation

β = Tilt angle

δ = Declination

Sun-tracking systems can be classified into two categories: (a) one axis tracking and (b) two axis tracking. In one axis tracking system, the system tracks the sun either in azimuth or in altitude angle, which is defined as declination angle, δ . It is mostly done with a mount having manually adjustable tilt angle along north-south axis and a tracking system that rotates the collector array from east to west. In two axis tracking system, the system tracks the sun in both azimuth and altitude angles so that the collectors are always pointing directly to the sun. In that case, δ becomes 0.

For technical improvement of PV μ Gen system, three conditions have been considered here

Ta) Fixed system, tilt at 53° and 38° angle

Tb) One axis tracking with tilt at 53° angle

Tc) Two axis tracking system

To adopt tracking systems, the overall μ Gen system cost could be increased. Excluding the PV panel and converter cost, $1.0\text{€}/\text{Wp}$ and $1.2\text{€}/\text{Wp}$ have been added for 1 axis and 2 axis tracking systems respectively [101].

3.3.2 Economic Improvement

To reduce the energy production cost, proper financial information is very important. PV panel cost has been drastically decreasing in recent years and therefore cost benefit analysis should be updated. In this calculation, for financial improvement two conditions have been considered:

Fa) VAT waiver from the component cost by 20%

Fb) Reduction of interest/discount rate, so that the real interest rate becomes 0%

Based on the financial information for fixed and tracking system including VAT waiver, the generalised cost (€/Wp) of a grid-connected PV based μ Gen system has been calculated. Considering the cost for converter, BOS and installation as 0.6, 0.3 and 0.2 (€/Wp) respectively, Table 3.5 shows the generalised cost of the system with techno-economic improvement.

Table 3.5 Generalised PV μ Gen system cost (€/Wp) without/with VAT (20%) in component cost

Cost of PV Panel €/Wp	Cost Without VAT waive			Cost With VAT waive		
	Fixed system €/Wp	1 axis tracking system €/Wp	2 axis tracking system €/Wp	Fixed system €/Wp	1 axis tracking system €/Wp	2 axis tracking system €/Wp
4	5.1	5.6	5.8	4.2	4.6	4.8
3	4.1	4.6	4.8	3.4	3.8	4.0
2	3.1	3.6	3.8	2.6	3.0	3.2
1	2.1	2.6	2.8	1.8	2.2	2.4

3.4 Simulation Results and Analysis

3.4.1 Energy Gain

Fig 3.7 shows the ratio of solar radiation on tilted and horizontal (G_{β}/G_H) along with the tracking surface. It indicates how solar radiation in Dublin can be improved significantly from the fixed axis to one or two axis tracking system. From the figure, it is observed that the maximum G_{β}/G_H for 38° tilt angle is found to be 17% more than that of horizontal surface. At 53° tilt, this ratio is 15% which is commonly practiced in

Dublin. Further improvement can also be possible by introducing tracking systems. With 1-axis tracking at 38° tilt, the ratio increases to a maximum 45% whereas for 2-axis tracking it is 49%.

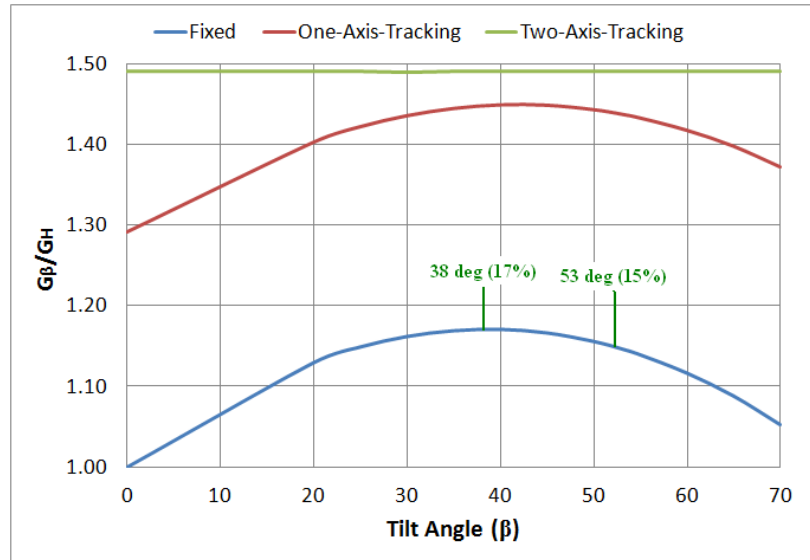


Fig 3.7 Ratio of solar radiation on tilted (G_{β}) and horizontal (G_H) surface in Dublin, Ireland

Table 3.6 shows the monthly average solar radiation values for this selected position and tracking systems, as shown in Fig 3.7. As a part of manual tracking system, monthly optimum (maximum radiation obtained at each month at a specific tilt angle) values have also been calculated. It is observed that in the case of a fixed system, tilt at 53° can give better performance in winter months whereas 38° tilt angle could be suitable for summer months (shown by the green colour in Table 3.6). Annual average radiation values for 38° and 53° tilt angle are 3.06 and 3.00 kWh/m² respectively. Therefore, from the analysis, it can be stated that PV panel at 38° tilt angle can produce more electricity for this location. Monthly optimum values indicate an improved performance of manual tracking system by fixing the optimum angle for each month. It could increase the available radiation from 5% to 7% compared to the fixed system. But this system requires an extra installation cost for manual tracking

with manpower for angle adjustment each month. It would increase the overall system cost and thus may not be viable.

Table 3.6 Global Radiation (G), in kWh/m²/day, in Dublin, Ireland

Month	Fixed system				Tracking system		
	Tilt Angle, β (degree)				One axis		Two Axis
	0 ⁰	38 ⁰	53 ⁰	MO*	38 ⁰	53 ⁰	
Jan	0.71	1.49	1.67	1.74	1.71	1.87	1.94
Feb	1.31	2.14	2.28	2.31	2.54	2.66	2.67
Mar	2.86	3.98	4.07	4.07	5.10	5.17	5.16
Apr	3.31	3.65	3.50	3.66	4.47	4.37	4.47
May	4.75	4.77	4.43	4.93	6.28	6.06	6.42
Jun	4.92	4.71	4.30	4.97	6.04	5.78	6.27
Jul	4.70	4.59	4.22	4.80	5.90	5.66	6.07
Aug	3.61	3.80	3.59	3.85	4.62	4.48	4.65
Sep	2.40	2.84	2.79	2.84	3.30	3.27	3.28
Oct	1.39	1.98	2.05	2.05	2.27	2.33	2.32
Nov	0.81	1.61	1.67	1.72	1.84	1.86	1.90
Dec	0.54	1.10	1.38	1.46	1.26	1.55	1.62
Ave	2.62	3.06	3.00	3.20	3.79	3.76	3.90
Annual (kWh/m ²)	955	1118	1095	1168	1382	1373	1423
G_{β} / G_H	1.0	1.17	1.15	1.22	1.45	1.44	1.49

*MO= Monthly Optimum

Table 3.6 shows that in the case of 38⁰ tilt angle, both the fixed and 1 axis tracking system shows better performance in summer months, whereas winter months have more solar radiation for 53⁰ tilt angle (shown by green colour in Table 3.6). On the other hand two axis tracking system shows better performance over the year than the fixed and one axis tracking systems. Therefore, from the analysis it can be summarised that in case of Dublin, sun tracking PV system can achieve 44% – 49% more solar energy annually compared to fixed axis system.

3.4.2 Export/import Electricity

Based on the μ Gen policy in Ireland, a maximum 6kW system can be connected to the grid. Therefore, this analysis considers three case studies for PV based μ Gen system: 1kW, 3kW and 6kW. Export/import electricity analysis is discussed here for the maximum capacity (6 kW) of μ Gen system. Table 3.7 shows the day and night

load demand of a residential house and the export/import electricity from a 6kW μ Gen system tilted at 53°. It is found that during the months of May, June and July, PV system produces more energy than the load demand, as shown in the green cells.

Table 3.7 Export/import energy for a single house of 6 kW PV based μ Gen system (at fixed angle 53°)

Months	Load demand (kWh/month)		Energy import (kWh/month)		Energy exported (kWh/month)	
	Day	Night	Day	Night	Day	Night
Jan	372	112	287	112	180	0
Feb	319	91	205	91	219	0
Mar	349	100	180	88	453	6
Apr	323	97	178	62	286	25
May	324	98	162	50	390	42
Jun	296	93	136	48	346	39
Jul	302	94	139	51	349	36
Aug	309	96	159	61	298	25
Sep	300	93	178	66	238	17
Oct	301	95	180	89	162	2
Nov	302	92	215	92	170	0
Dec	337	105	259	105	119	0
Annual	3,833	1,167	2,279	916	3,212	193

Table 3.8 shows the net purchase energy over the year of a residential house with a 6kW PV based μ Gen system. The prosumer can sell the excess energy produced by the system and thus can reduce purchased energy from the grid. Analysis shows that for the fixed tilt at 53°, the system can sell more energy to the grid during the winter months. On the other hand, a tilt at 38° shows better results for the summer months. Annual energy sold to the grid is also high if the system is placed at 38° tilt angle.

Similar results are obtained for the auto tracking systems, as shown in Table 3.9. Here it shows that a two-axis tracking gives the better output round the year and can sell more energy than the other systems, as shown by the red cells.

Another finding is that, because of the hourly difference between the load demand and solar radiation availability, the user has to purchase grid electricity every single day. There could be a possibility to store the additional sold energy in a storage

system and use it during the peak demand or solar radiation shortage periods. But the storage could then increase the cost of the system and thus also increase the COE.

Table 3.8 Energy purchased and sold for 6 kW PV based μ Gen system (at fixed 53° and 38°)

Month	Energy Purchased (kWh)		Energy Sold (kWh)		Net Purchases (kWh)	
	53°	38°	53°	38°	53°	38°
Jan	399	398	180	153	219	245
Feb	295	294	219	194	76	100
Mar	268	267	460	434	-191	-167
Apr	239	235	311	325	-72	-90
May	212	208	432	473	-221	-266
Jun	184	179	385	432	-201	-253
Jul	191	185	386	430	-195	-245
Aug	221	214	322	343	-102	-99
Sep	244	241	254	252	-10	-11
Oct	270	267	164	152	105	115
Nov	307	306	170	146	137	160
Dec	364	363	119	100	245	163
Annual	3,195	3,157	3,405	3,435	-210	-277

Table 3.9 Energy purchased and sold for 6 kW PV based μ gen system (1-axis at 53° angle and 2 axis tracking system)

Month	Energy Purchased (kWh)		Energy Sold (kWh)		Net Purchases (kWh)	
	1-axis track	2 axis track	1-axis track	2 axis track	1-axis track	2 axis track
Jan	399	402	189	201	210	201
Feb	294	297	248	259	47	38
Mar	259	261	401	617	-342	-356
Apr	220	222	452	460	-232	-238
May	187	189	692	712	-505	-523
Jun	155	156	635	657	-480	-501
Jul	167	169	620	641	-453	-471
Aug	200	202	487	498	-286	-296
Sep	236	239	335	339	-99	-101
Oct	268	272	199	204	68	67
Nov	307	311	183	193	124	118
Dec	364	367	122	130	242	237
Annual	3,057	3086	4,762	4,910	-1,704	-1,824

3.4.3 Cost Benefit Analysis

Cost benefit analysis has been performed for the considered 3 cases with all conditions for fixed and auto tracking systems. Table 3.10 shows the economic information of the μ Gen system for a fixed angle where a PV panel cost is considered as 4€/Wp. Based on the energy production from 1 to 6 kW system, the COE is better

in the case for tilt angle of 38°. Renewable fraction that is used by the consumer is also higher for the 38° tilted system.

Table 3.10 Economic information for PV system (fixed angle); PV panel cost 4€/Wp

System Size	Initial Cost	Total NPC	COE €/kWh		Renewable Fraction%	
			53°	38°	53°	38°
kW	€	€				
1	4600	6600	0.48	0.47	0.17	0.17
3	13800	17230	0.42	0.41	0.42	0.43
6	27600	32380	0.39	0.38	0.62	0.63

Table 3.11 shows the COE for both the fixed angle tilted systems where PV panel cost varies from (4 to 1)€/Wp. It is found that in the present market all three systems would become sustainable only when the PV cost becomes 1€/Wp. The 6kW system will be sustainable even in the case of 2€/Wp, as shown by the green cells.

Table 3.11 COE in (€/kWh) for fixed PV systems at 38° and 53° angle

System size	4€/Wp		3€/Wp		2€/Wp		1€/Wp		Grid
	COE €/kWh								
kW	53°	38°	53°	38°	53°	38°	53°	38°	
1	0.48	0.47	0.40	0.39	0.32	0.31	0.23	0.23	0.23
3	0.42	0.41	0.34	0.33	0.26	0.25	0.18	0.17	0.23
6	0.39	0.38	0.31	0.31	0.23	0.23	0.15	0.15	0.23

3.4.4 Techno-economic Improvement

Tables 3.12 and 3.13 show the economic information and the COE for auto tracking systems. It also shows that the use of renewable energy by the consumer is increasing compared to the fixed angle system. Due to the increase of energy production, the COE also decreases. In both cases, the 6kW system can be sustainable even if the PV cost becomes 3€/Wp.

Table 3.12 COE in (€/kWh) for 1 axis tracking system

System (kW)	4€/Wp	3€/Wp	2€/Wp	1€/Wp	Grid	Renewable Fraction%
	PV Panel cost, COE (€/kWh)					
1	0.32	0.28	0.24	0.19	0.23	0.22
3	0.28	0.23	0.19	0.15	0.23	0.47
6	0.26	0.22	0.17	0.13	0.23	0.67

Table 3.13 COE in (€/kWh) for 2 axis tracking system

System size (kW)	PV Panel cost					Renewable Fraction%
	4€/Wp	3€/Wp	2€/Wp	1€/Wp	Grid	
	COE (€/kWh)					
1	0.33	0.29	0.24	0.19	0.23	0.22
3	0.29	0.24	0.20	0.15	0.23	0.50
6	0.27	0.23	0.18	0.13	0.23	0.69

Fig 3.8 shows the comparative analysis of COE for a 6kW PV based μ Gen system for different PV panel cost (1-4 €/Wp). It is observed that for a fixed axis system COE is higher than the other two systems when the PV panel cost is (2-4 €/Wp). On the other hand COE in 1-axis tracking system is lower than the 2-axis tracking system. The reasons might be that, (i) in a 2-axis tracking system, obtained solar radiation does not improve significantly in Irish climatic conditions and (ii) the cost difference between 1-axis and 2-axis tracking system is high compared to the system performance. Therefore, 2-axis system may not be cost effective in Irish environment.

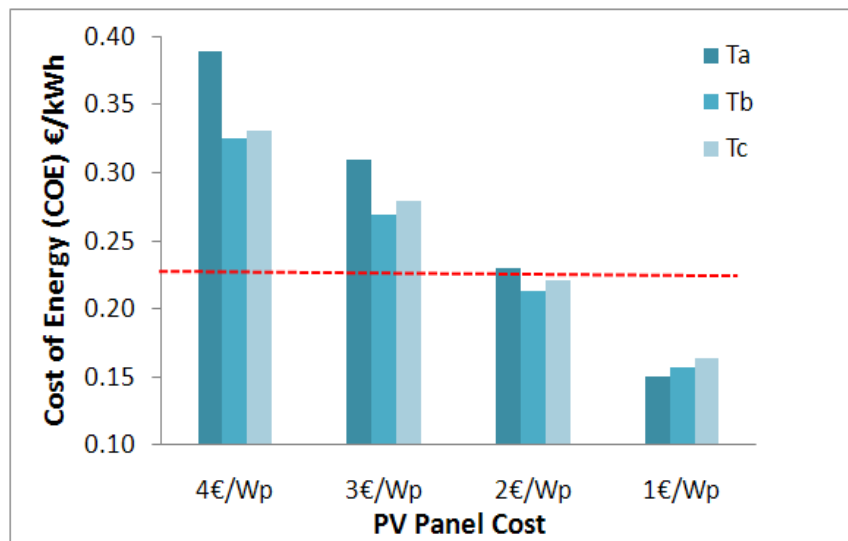


Fig 3.8 Comparative study of COE for 6kW PV μ Gen system; Ta - fixed axis, Tb - 1 axis tracking, Tc - 2 axis tracking system and grid electricity cost - red dotted line

When the panel cost decreases to 2€/Wp then COE in a fixed axis system becomes closer to the grid electricity cost. Tracking systems become sustainable in these conditions. When the panel cost is lower than 2€/Wp then it is expected that fixed and tracking both systems can become viable.

When the panel cost becomes 1€/Wp, fixed axis systems can be better than the tracking systems. It happens because the additional system price in the tracking system is comparatively higher than the panel cost. It indicates that the tracking system cost must also be decreased in time to make it viable.

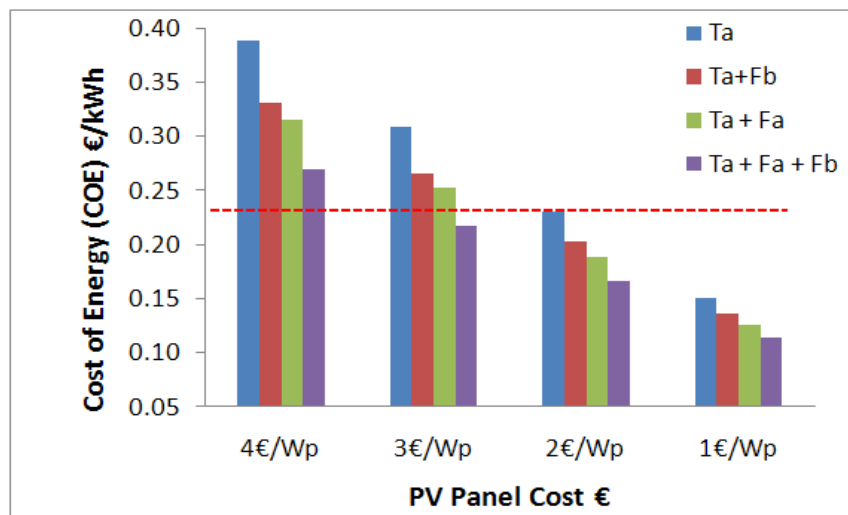
Fig 3.9 shows the comparison for the combined effect of technical and financial improvement on COE of a 6kW system. Analysis shows that for a fixed axis system (Ta) COE becomes the same as the grid price when the PV panel cost is equal to 2€/Wp. Sustainability of this system can be improved by introducing economic incentives: (i) removing VAT of 20% from the component cost (Fa) and (ii) applying a real interest rate of 0% (Fb). The COE can decrease upto 26% (0.17€/kWh) compared to the base case when PV panel cost is equal to 2€/Wp. When both the improvements are applied at the same time (Ta+Fa+Fb), the system can be feasible even when the PV panel cost is equal to 3€/Wp.

For 1 axis tracking system with 53° tilt angle, analysis shows that the system can become sustainable for a PV panel cost of 3€/Wp if either one or combined effects of economic incentives are applied. When the PV cost goes to 4€/Wp, the range of sustainability is further improved by introducing combined techno-economic changes (Tb+Fa+Fb).

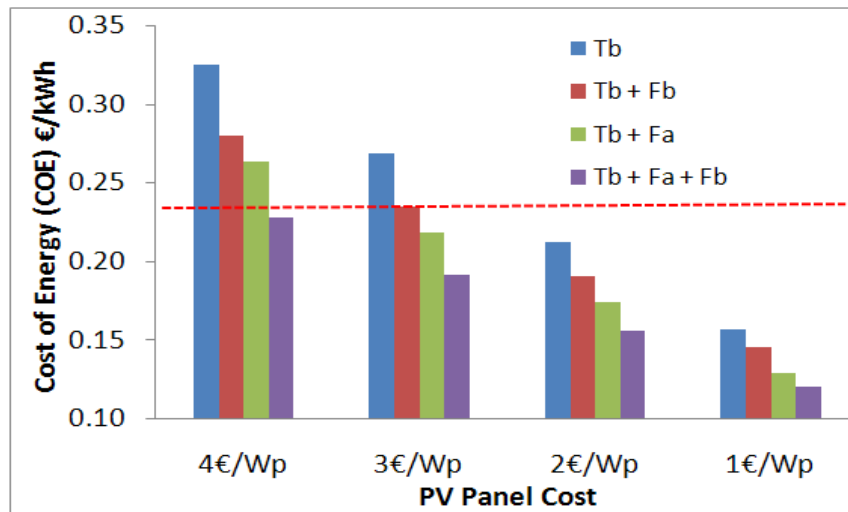
Similar analysis was carried out for a 2 axis tracking system. In this case, reducing VAT only system (Tc+Fb) will not be feasible when the PV panel cost is 3€/Wp. On the other hand if the real interest rate is reduced (Tc+Fa), the COE

becomes lower than the grid electricity price when the PV panel cost is 3€/Wp. If both the conditions are applied together, the system can become feasible even when the PV panel cost is 4€/Wp.

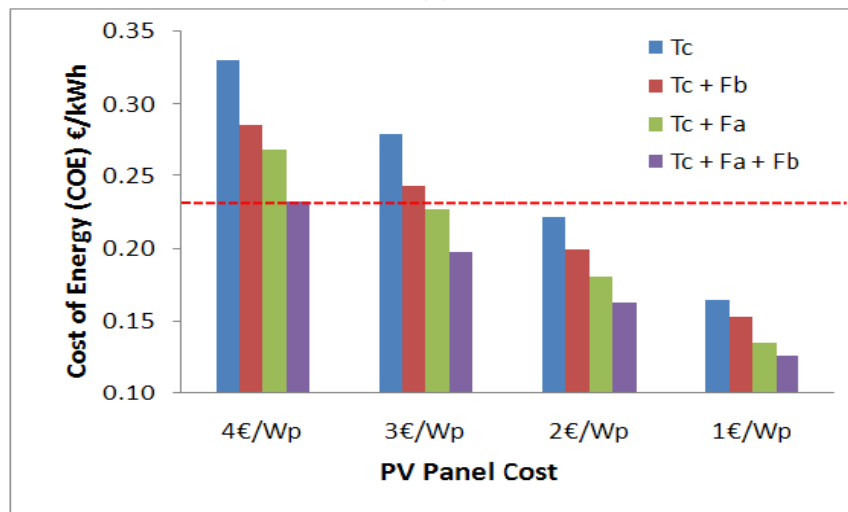
Comparing the graphs in Fig 3.9 (b, c) for 1 axis and the 2 axis tracking systems, it is observed that the 1 axis tracking system can become feasible with conditions Fa and Fb separately when the PV panel cost is ≤ 3 €/Wp. On the other hand the 2 axis tracking system can become feasible under condition Fa only when PV panel cost is ≤ 3 €/Wp. When both the conditions are considered, COE of a 1 axis tracking system is lower than the base case. Whereas COE in a 2 axis tracking system is the same as the base line when PV panel cost is ≤ 4 €/Wp. Therefore, from the analysis it can be summarised that, 2 axis tracking systems may not be cost effective as 1 axis tracking system in Irish condition.



(a)



(b)



(c)

Fig 3.9 Comparative study of COE for 6kW PV μ Gen system; Fa – Real interest rate 0%, Fb - Reduced VAT by 20% on component cost; (a) Ta - Fixed axis, (b) Tb - 1 axis, (c) Tc - 2 axis tracking

3.5 Wind based Micro-generation Systems

Amongst the μ Gen systems, micro-wind is the most popular system but still is at an early stage of development. According to [102], there are 357 micro wind turbines which have already been registered and connected to the networks with a total capacity of 3MW. The micro-generation certification scheme is the independent scheme to certify the micro-generation products for UK and Ireland according to the standards. Amongst these registered micro wind turbines Proven 11, Skystream 3.7, Swift 1.5, Silican 3.4, Silican 4.1 are the most popular in UK and Ireland. Therefore a

comparative study of techno-economic analysis has been performed in this chapter for two of the most popular micro wind turbines, 6kW Proven 11 and 1.8kW Skystream 3.7 which are the highest and lowest capacity wind turbines used in Irish μ Gen system.

3.5.1 Proven 11 Wind Turbine

The Proven turbine is robust and low maintenance electricity generator. The Proven blade system is flexible, enables the turbine to generate power in strong or light winds. As the wind speed increases, the proven blades twist to reduce their aerodynamic efficiency. Thus allows the Proven 11 turbine to keep high output even in high wind condition. The turbine is designed in a manner to ensure minimum noise and low maintenance. Its power output is optimised whilst monitoring the generator load and keeps blades rotating at a low speed. Fig 3.10 shows the power output of the turbine at a given speed according to the manufacturers.

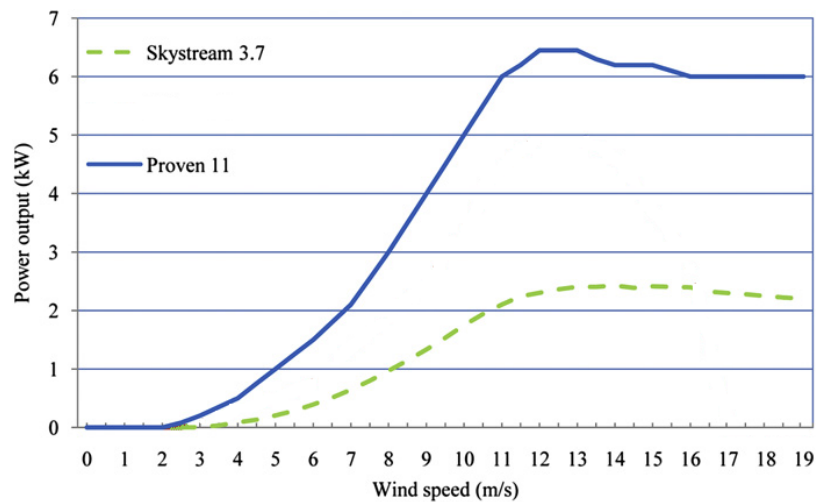


Fig 3.10 Power output curves

3.5.2 Skystream 3.7

The Skystream 3.7 is a 1.8 kW rated turbine which has a blade diameter of 3.72 m. It has a capture area 10.87 m^2 . Fig 3.10 also shows the power output curve of the wind turbine according to the manufacturers.

The actual performance shows that both turbines work with an efficiency of around 25% at a typical wind speed of 5 m/s.

3.5.3 Techno-economic Analysis

For techno-economic analysis, the same load profile of a residential house has been considered as shown in the Fig 3.2. Analysis has been performed for both the micro-wind turbine separately. The hub height and project lifetime of the turbines are considered as 20m and 20 years respectively. These μ Gen systems are grid connected and no storage has been considered in the analysis.

Fig 3.11(a, b) shows the share of monthly average electric production from the wind based μ Gen system and the imported grid electricity for a single house. Fig 3.11(a) shows that the Proven11 (6kW capacity) wind turbine is producing highest average power of 2.2 kW in winter months and lowest average power 1.4 kW power in summer months. The highest amount of purchased electricity from the grid in summer is 0.23 kW and the lowest in winter, 0.10 kW. On the other hand Skystream3.7 (1.8 kW capacity) wind turbine is producing an average power of 0.80 kW in winter months and 0.40 kW in summer months as shown in Fig 3.11(b). The consumer is purchasing ~ 0.30 kW in summer months and ~ 0.20 kW in winter months.

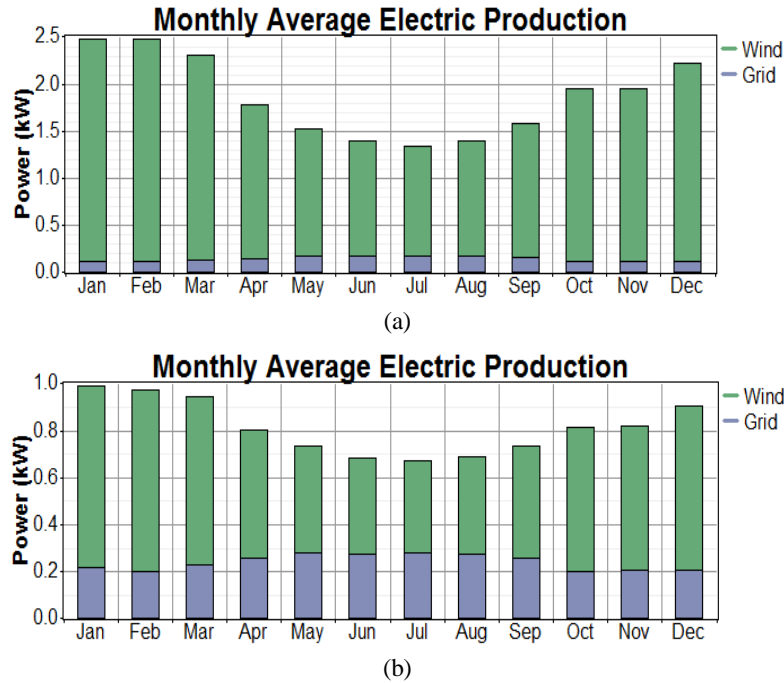


Fig 3.11 Monthly average production; (a) Proven 11; (b) Skystream3.7 wind turbine for single house

Capacity factor is one of the important parameters to analyse the performance of the wind turbines. It is defined as the ratio of turbines actual output over a period of time to the potential output if it is operated with full capacity continuously over the same period of time. Capacity factor can be calculated as:

$$\text{Capacity factor, } C_p = \frac{\text{Total generation}}{365 \text{ days} \times 24 \frac{\text{hr}}{\text{day}} \times \text{total capacity of the generator}} \quad (3.7)$$

For both of the turbines, C_p is found as 23.8%. From this point of view both the turbines have the same performance.

To understand the technical performances in terms of (energy export/import) load demand, generated wind power, import from grid (grid purchases) and export to grid (grid sales), both of the systems have been analysed. Fig 3.12 shows the performance for both the systems for four months over the year (January, April, July and October). Fig 3.12 (a, b, c, d) represents a Proven11 turbine from where it is found that the load profile over the day almost follows the wind power profile, although the average wind

power availability during this time period is much higher than the load demand, the user still purchases energy from grid. It happens due to the mis-match of the profile for some typical days over the month. Also the wind power is higher in the winter months (October, January). Another finding is that, wind production is very high in the mid-day when load demand is low. Therefore, most of wind power is transferred to the grid. At peak load hours, the consumer does not have to buy much electricity from the grid.

On the other hand Fig 3.12 (e, f, g, h) shows the performance of the Skystream3.7 for those months. It is observed that the load profile is always higher than the wind profile in peak hours especially in months of April and July. The average wind profile is not always higher than the load profile in the summer months (April, July). The system is selling less electricity to the grid, but buying a significant quantity of electricity from the grid. Consumers have to buy electricity for most of the peak hours. Thus due to the mismatch between load and supply profile and the low REFIT cost, this turbine cannot save much money and might not be economically feasible.

Besides the technical analysis, the economic analysis shows that the net grid purchase of energy for the Proven11 system is negative, as shown in Table 3.14. The table shows that a 6kW micro wind based μ Gen system in Irish conditions can produce energy greater than the load demand of one household and supply the extra electricity to the grid. On the other hand, Skystream 3.7 is selling much less electricity to the grid.

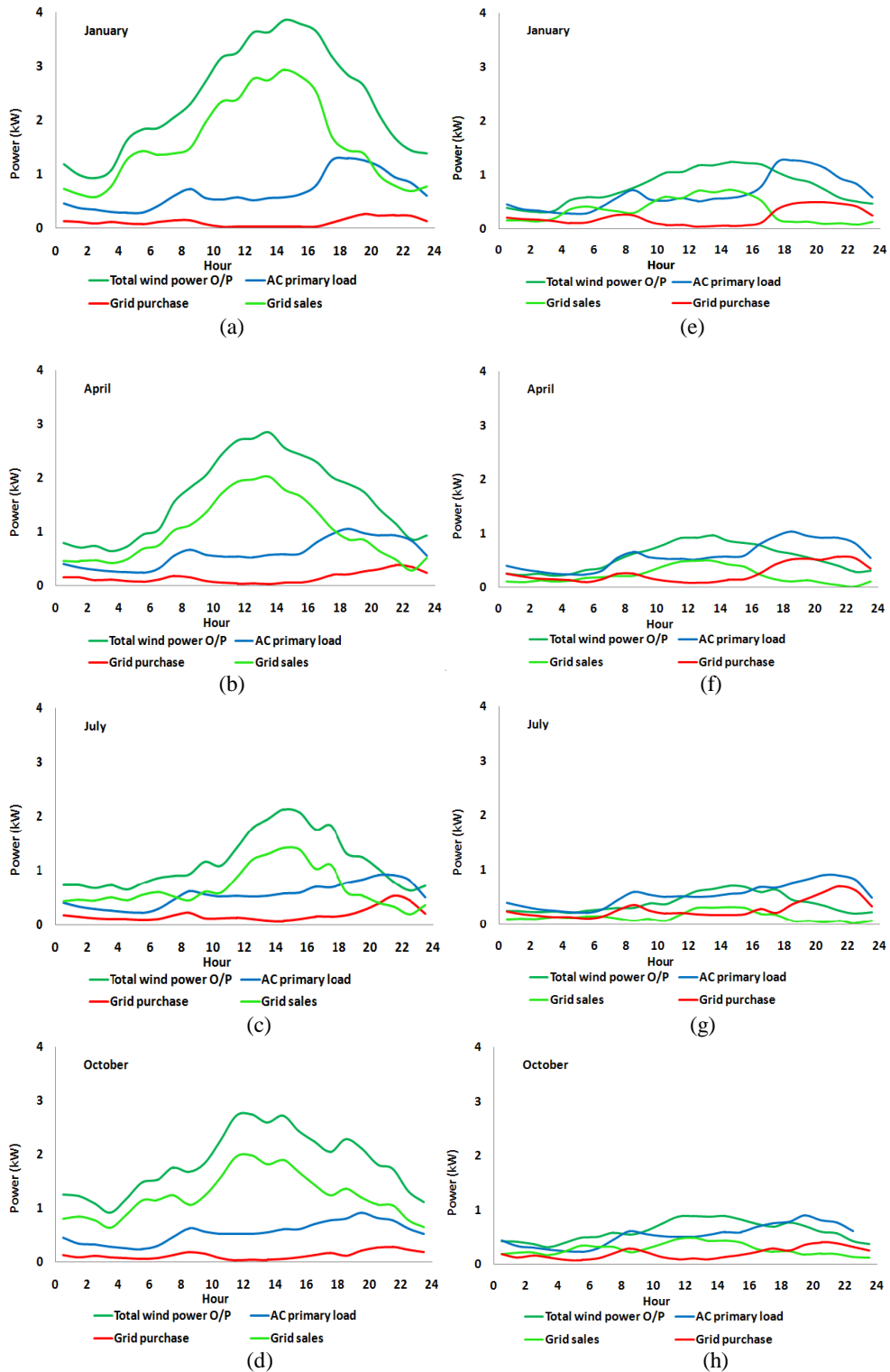


Fig 3.12 Technical performance of (a, b, c, d) 6 kW Proven 11 and (e, f, g, h) 1.8 kW Skystream 3.7 wind system in typical days in winter, spring, summer and autumn months

Table 3.14 Bought/sold electricity from/to the grid

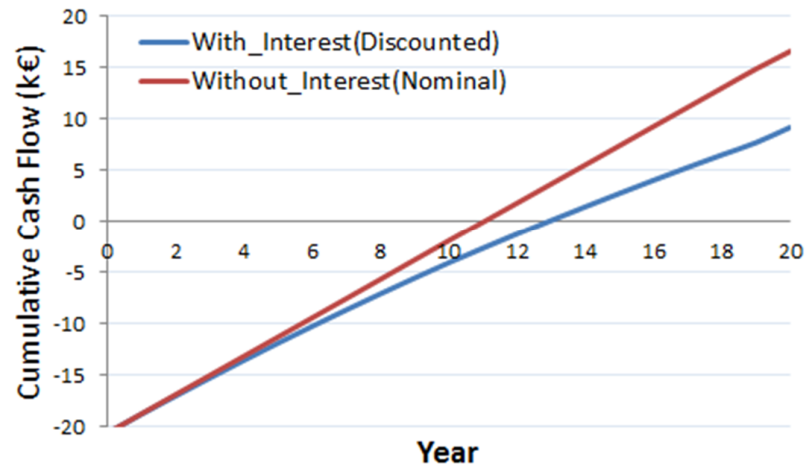
Month	Proven11				Skystream3.7			
	Energy Purchased	Energy Sold	Net Purchases	Energy Charge	Energy Purchased	Energy Sold	Net Purchases	Energy Charge
	(kWh)	(kWh)	(kWh)	(€)	(kWh)	(kWh)	(kWh)	(€)
Jan	81	1,182	-1,101	-110	159	252	-92	-9
Feb	76	1,091	-1,015	-102	134	244	-110	-11
Mar	96	1,099	-1,004	-100	168	250	-82	-8
Apr	102	737	-634	-63	185	156	29	6
May	124	610	-486	-49	208	125	84	19
Jun	118	523	-404	-40	195	102	93	20
Jul	128	510	-382	-38	209	102	107	23
Aug	125	541	-416	-42	204	106	99	21
Sep	110	640	-530	-53	183	133	50	11
Oct	86	918	-832	-83	149	207	-58	-6
Nov	84	879	-795	-80	149	195	-45	-5
Dec	81	1,048	-967	-97	154	228	-74	-7
Annual	1,211	9,777	-8,566	-857	2,097	2,099	-2	53

The economic information of the μ Gen systems are shown in Table 3.15. The production COE from Proven11 is 0.11€/kWh and 0.09€/kWh for 2.5% and 0% interest rate respectively. The COE from Skystream3.7 is 0.14€/kWh and 0.11€/kWh for 2.5% and 0% interest rate respectively. The table shows that Proven11 turbine can pay back the cost of the system for 2.25% interest rate in 11.9 years and its Internal Rate of Return (IRR) is 7.33%.

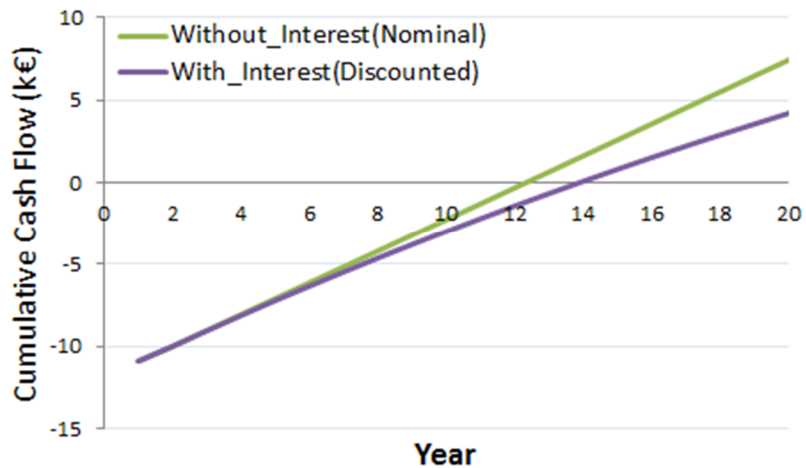
Table 3.15 Micro-generation systems Proven 11 and Skystream 3.7 wind turbine

Wind Turbine	Total system cost (€)	Total NPC (€)		Cost of energy (COE) €/kWh		Payback period (yr)		Internal rate of return (IRR) (%)
		Interest rate		Interest rate		Interest rate		
		2.25%	0%	2.25%	0%	2.25%	0%	
Proven 11 (6kW)	20630	9386	6538	0.11	0.09	11.9	10.3	7.33
Skystream 3.7 (1.8kW)	10900	11646	9545	0.14	0.11	13.9	12	5.86

Fig 3.13(a, b) shows the graphs of payback period for nominal and discounted real interest rates, which is considered as 0% and 2.5% respectively for the analysis. For the Proven turbine, nominal and discounted payback periods are found to be 10.3 and 11.9 years whereas for Skystream it is 12 and 13.9 years respectively.



(a)



(b)

Fig 3.13 Payback period of (a) Proven 11 and (b) Skystream 3.7 micro-wind turbine

3.6 Conclusion

This chapter deals with the techno-economic analysis of grid connected PV and Wind based μ Gen systems in the Irish environment. The goal of this task is to achieve the sustainability of this system through some technical and economic improvement of the existing systems. Therefore, a step-by-step methodology has been developed

and the analysis are discussed accordingly. The advantage of this methodology is that it can be applied to other types of μ Gen system to analyze their sustainability.

For Irish conditions, it is found that for a fixed axis system the PV based μ Gen can be placed at 38° tilt angle also. As the summer months have more solar radiation, grid connected PV based μ Gen with 38° tilt would be a better choice. Because of the difference in the additional cost, COE for a 1-axis tracking is lower than that of 2 axis tracking system. Based on the present market price and grid electricity cost, both the fixed and tracking systems can become sustainable when the PV panel cost becomes lower than or equal to 2€/Wp. If the tracking system cost does not decrease in time, a fixed axis system can show better performance when PV panel cost is reduced to 1€/Wp. The combined effect of technical and economic improvement could extend the range where an investment is viable.

The results show that large capacity systems such as 6kW Proven11 could benefit most from exported grid electricity price. Because of the significant quantity of electricity exported to the grid and less electricity is bought from the grid, the net income would make the system have a reduced financial loss. Therefore, small capacity wind based μ Gen systems may not be feasible for grid sale arrangements.

Integration of storage in the μ Gen system could be beneficial for the consumers in the way that they could store energy in the low demand period and then use it in the peak demand period. It could increase the stability of the system, but at the same time it can also increase the cost of the system. This issue is a matter of compromise with the economic sustainability of the system.

Chapter 4

Community μ Grid: A New and Energy Efficient Structure

4.1 Introduction

Studies in previous chapters show that μ Gen systems could be viable if some techno-economic improvements are made. The literature review also shows that μ Grid systems have several advantages over μ Gen systems [103]. Moreover, the concept of μ Grid has been identified as an easy way to integrate micro-generators to the LV networks. Along with this, the potential revenue streams that can offset investments and business-as-usual cost are also reviewed in [104]. It identifies that μ Grid can take part in demand response and local energy market programs to increase value streams. Therefore, a new structure/integration method for RE-based μ Gen systems in the distribution network, termed as Community- μ Grid (C- μ Grid), has been proposed here. The local community can develop a C- μ Grid system by integrating their existing/newly purchased μ Gen systems. The proposed system has some advantages both technically and economically over the μ Gen and conventional μ Grid systems. The new system could (i) allow greater penetration of RE in the electricity

supply network; (ii) reduce the production COE to achieve sustainability; (iii) empower the energy citizen through active participation of prosumers (producer + consumer) in the energy trading mechanism; (iv) move towards the development of a model and strategy for efficient μ Grid systems.

This chapter discusses the advantages, integration methods, operation, control strategies and issues related to the technical stabilities of the proposed C- μ Grid system. Simple simulation studies are performed to show the energy management systems within the structure. Finally, techno-economic studies are also performed to analyse sustainability of the proposed system.

4.2 Proposed Community μ Grid (C- μ Grid) System

In the μ Grid structure, the energy sources can be closer to the consumer's connection point that would reduce the electrical losses and the impact of individual failures could be reduced. In the proposed C- μ Grid system, few neighborhoods in an area expect to form an integrated energy system with their own μ Gen systems (especially renewable energy sources) for a safe, reliable, energy efficient, cost-effective and dependable supply system. The system can also save capital and investment cost over individual generator owners. For developing a successful C- μ Grid the following points must be considered: site development, cluster development, greenways, minimum disturbance, wildlife reservation and woodland conservation. Some important features of C- μ Grid system are as follows:

- i. The community residents do not have to purchase personal emergency generator.
- ii. Maintenance could be carried out professionally and the cost could be shared.
- iii. There is no requirement for storage at each house separately as C- μ Grid can have a central storage system.

- iv. Through the utility control and monitoring system the utility could be able to monitor remotely the condition of the system.
- v. Benefits can also include lower operating cost for residents, increased comfort and higher perceived value.
- vi. C- μ Grid requires the collaboration with the developer, homeowner and the electric utility.
- vii. The C- μ Grid concept has some restriction regarding technical, legal and regulatory issues that require collaboration between the developer, homeowner and the electric utility.

Fig 4.1(a) shows an electrical network consisting of grid connected multiple μ Gen systems and Fig 4.1(b) shows the proposed C- μ Grid system. In C- μ Grid systems, a number of μ Gen sources are connected together to form a separate grid structure with a central μ Grid converter. Fig 4.2 shows the details of this system. In the proposed C- μ Grid system, each of the community users uses their own micro wind turbine (as μ Gen) and instead of having separated multiple converters, all the wind turbines of the users are connected through a central converter. The rest of the structure of the μ Gen and C- μ Grid remains the same.

4.3 Advantages of C- μ Grid over μ Gen Systems

There are a set of technical and financial reasons to gradually convert from a μ Gen to a C- μ Grid system. In general, most of the μ Grid aspects are present in the proposed C- μ Grid system except the multi-sources integration method. In conventional μ Grid systems, single or multiple distributed generation systems are connected individually in a network to form a μ Grid network and managed by central/distributed controllers. Therefore, consumers/prosumers might not have any

chance to actively participate in the energy management/trading mechanism. Whereas, the proposed C- μ Grid will be able to empower them to become energy active citizens. Therefore, the advantages of C- μ Grid with/without storage are given below together with a short description of the C- μ Grid aspects.

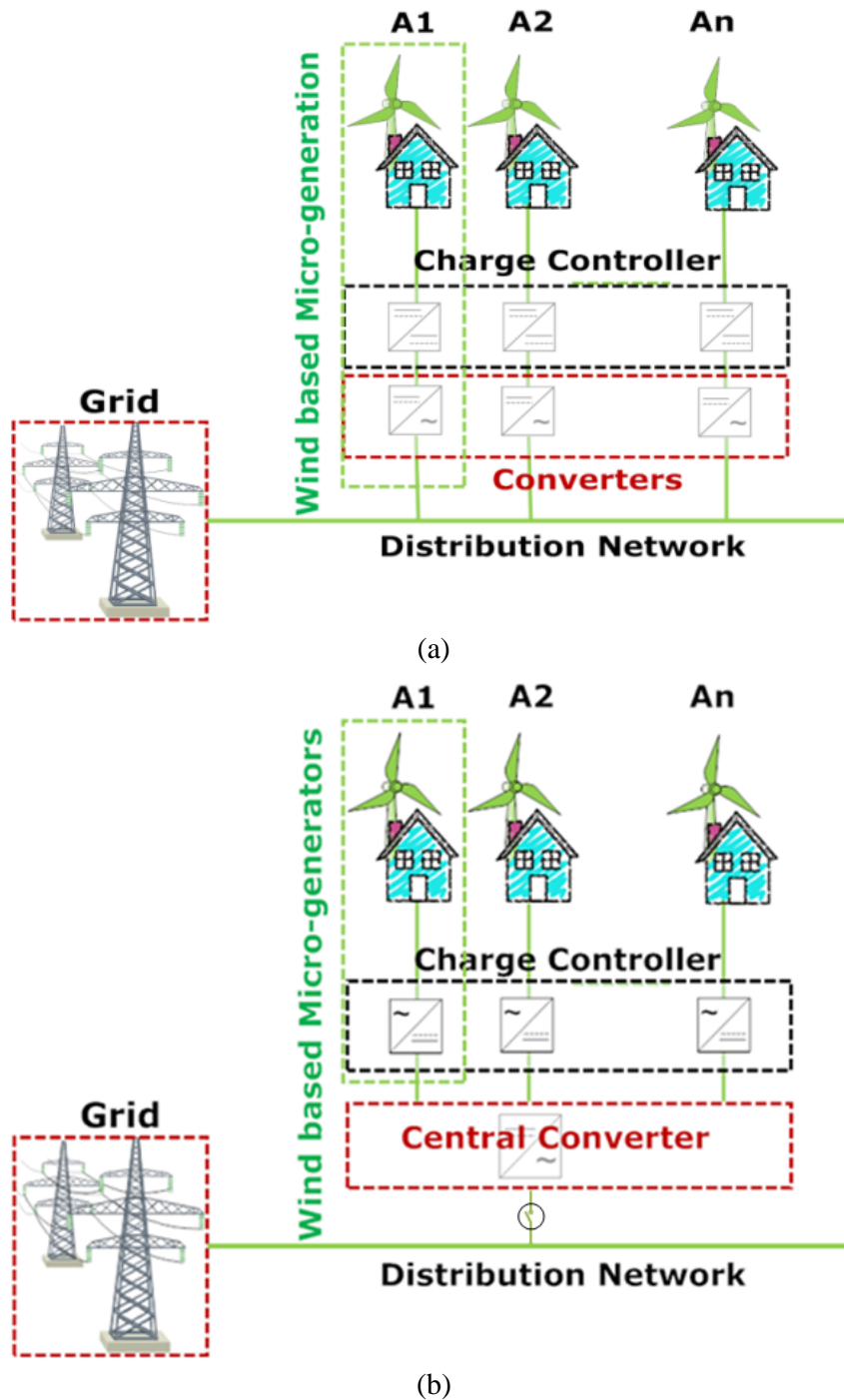


Fig 4.1 (a) μ Gen system (b) proposed C- μ Grid system in distribution network

4.3.1 Technical Aspects

Interfacing μ Gen systems in LV networks has been increasing in recent years. Therefore, the existing distribution system is facing some complex challenges as the system is not capable of handling bi-directional power flow and a large number of micro-generators, and as a result various technical problems associated with protection and control systems arise [105]. A high number of micro inverters connected to the low voltage distribution network could also create voltage disturbances and unbalances leading to deterioration in PQ. On the other hand in a μ Grid system, active network management and multi-directional power flow are also possible [106]. This increases the reliability of power flow to highly sophisticated customers by improving the voltage quality in the μ Grid system through the appropriate control of DG converters [107]. The other advantage of μ Grid system is that it can operate in islanded/autonomous mode and it minimises the interruption of the electricity supply [105]. These advantages of μ Grid systems are also applicable in the proposed C- μ Grid system.

4.3.2 Economic Aspects

μ Gen systems are economically remunerated with a special tariff in most countries, which is absent in most cases for μ Grid systems. If the same tariff/REFIT policy is applied in μ Grid/C- μ Grid systems, the system could show better economic payment [108] and thus it can be commercially acceptable. Due to the need of fewer components and larger inverter size the investment cost can be reduced, as reflected in Fig 3.6 (chapter 3), and thus the production COE can be lower in C- μ Grid systems. Furthermore, financial benefits for GHG reduction in the REFIT policy can also help the C- μ Grid system to be economically viable.

4.3.3 Environmental Aspects

Compared to the conventional power generation system, RES based μ Grid systems reduce the GHG emission and thus can improve the environment [107]. GHG reduction can also be remunerated in government energy policy. Though the RES is not controllable, the inclusion of a storage system and the ability to control its internal load could make the μ Grid system Smart and also environmentally friendly.

4.3.4 Social Aspect

Planning a sustainable Zero Net Energy Community [109] based on a local community can build a civic awareness. Such an environmental friendly project, together with sustainable building management and good home maintenance practice through an active load management system can enhance the quality of life and wellbeing of the community.

4.3.5 Empowering the Energy Citizen

Along with these, the C- μ Grid system will be able to empower the energy citizen by actively participating in the development, energy management and trading of the system. This would also bring the direct saving in their investment as well as will help to make the financial benefit due to the energy exchange mechanism.

4.4 System Structure and Integration Method

Depending on the existing distribution network conditions and its possibility of modification, the development of a C- μ Grid can be of two types: (i) without storage - where the proposed system is always connected to the grid and (ii) with storage - where it can work both in on-grid and off-grid mode. Details are given below.

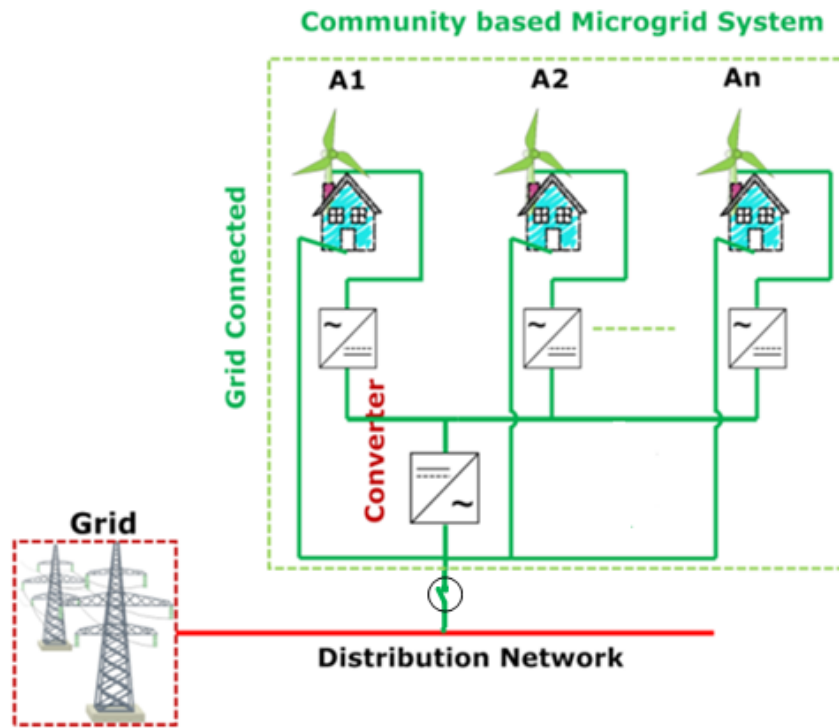
4.4.1 Without Storage

Fig 4.2 shows the C- μ Grid system can and without storage. In the case of without storage condition, the system is always connected to the grid, as shown in Fig 4.2(a). In the case of an existing distribution network, all the consumer loads are directly connected to the grid. μ Gen sources are then connected through a large capacity single unit inverter. Due to the always grid-connected condition, the inverter is flexible to supply the active power only to the load and distribution network. During power failure or fault condition, the inverter is disconnected automatically to maintain the safe network condition.

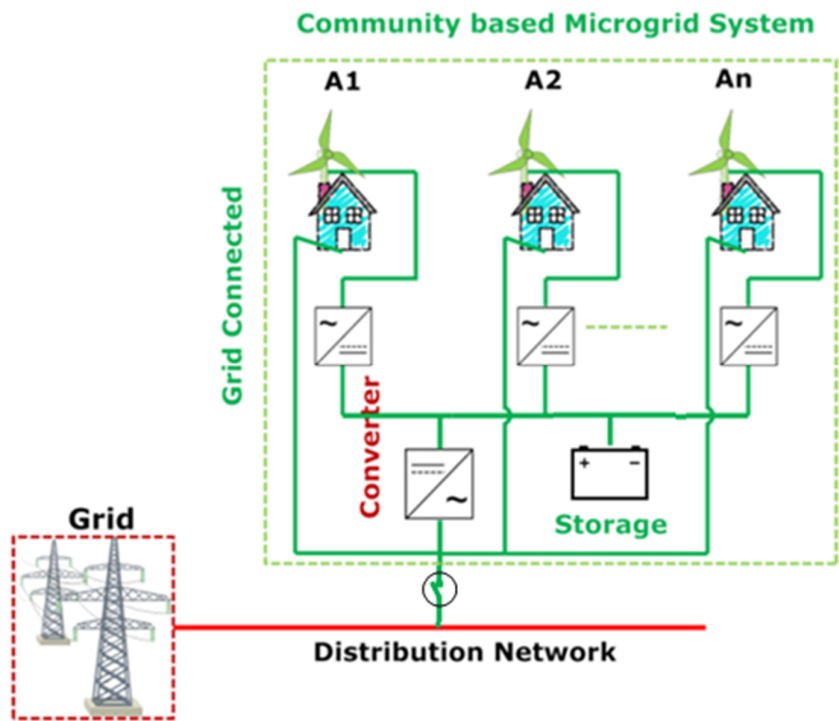
4.4.2 With Storage

Fig 4.2(b) and (c) show the C- μ Grid with storage system. In that case, the system can work both in on-grid and off-grid conditions. Storage capacity is defined according to the requirement to operate the system during islanded condition. To meet the active and reactive power demand during off-grid condition, the inverter here needs to change its control strategy. Connection for μ Gen sources are the same as without storage, but to create a separate network for the off-grid condition, all the consumer loads are connected through a single point of common coupling. This configuration is possible for new prosumers and with an extended grid network. It is also possible to develop the islanded condition in the existing grid network.

The communication system is very important to facilitate the control and energy management of the system. The details of the architecture including placement of sensors and power flow operation are discussed in the following section. Emphasis has also been given on the development of the central controller for the C- μ Grid system (C- μ GCC) which is proposed to manage the power sharing between the prosumers.



(a)



(b)

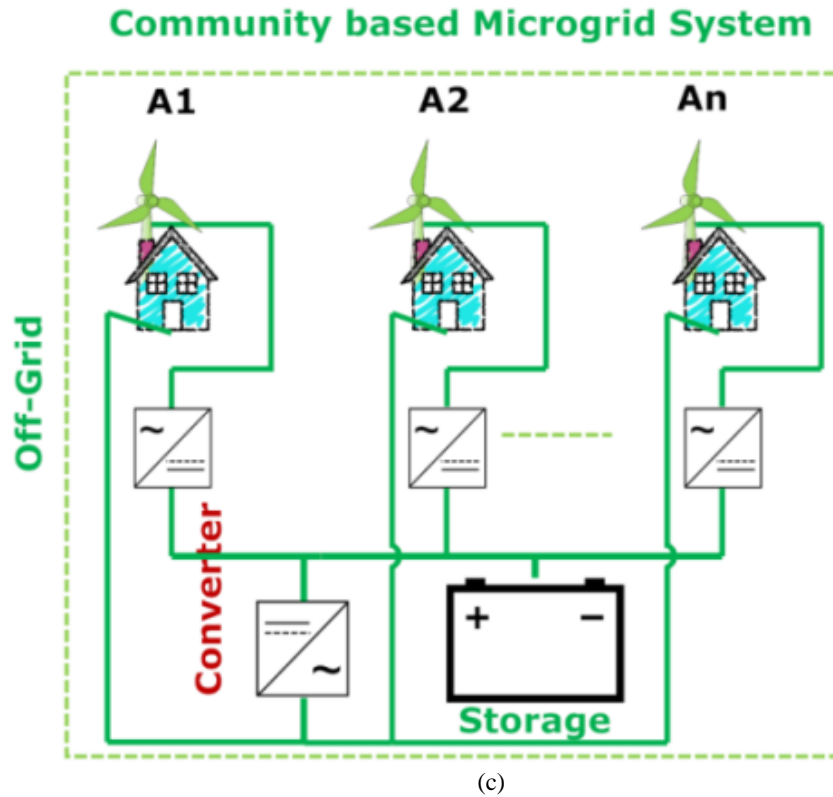


Fig 4.2 C- μ Grid system grid connected (a) without (b) with storage (c) off-grid with storage condition

4.5 Operation

All the μ Gen sources have to be connected in parallel to a common DC bus and have their own Charge Controller (CC). To reduce the operational power and energy loss and improve the stability of the C- μ Grid system, voltage in the DC part of the system should be maintained as high as possible. Therefore, the output of the DG sources are converted to high voltage DC at the source end and assumed to have the same level of DC voltages output. These are then directly connected to the common DC link bus of the central inverter, as shown in Fig 4.3. This helps to reduce the electrical losses before the inverter end. The central inverter, which is managed by the C- μ GCC, is assumed to have high voltage DC input to convert it to AC and to transfer the active power to the grid. Depending on the command from the central controller, central inverter transfers active and reactive energy to the network. It is to be noted

that presently available commercial inverters have some of these features such as high voltage DC input and multi-DC input. As an example, one of the best inverter manufacturers in the present market, SMA has multi-string inverter as well as string combiners to accommodate 24 and 32 string DC inlets [110].

4.6 Control

The control strategy adopted by the C- μ GCC is crucial to facilitate the power flow among the generators, the storage unit and the loads. In this respect, an IF-THEN-ELSE Heuristic control algorithm is proposed for the C- μ GCC to manage the power shared among the prosumers on the basis of the energy demanded at the consumer sides. The energy produced by the μ Gens and the buying/selling tariffs are related to the energy exchange with the external main grid.

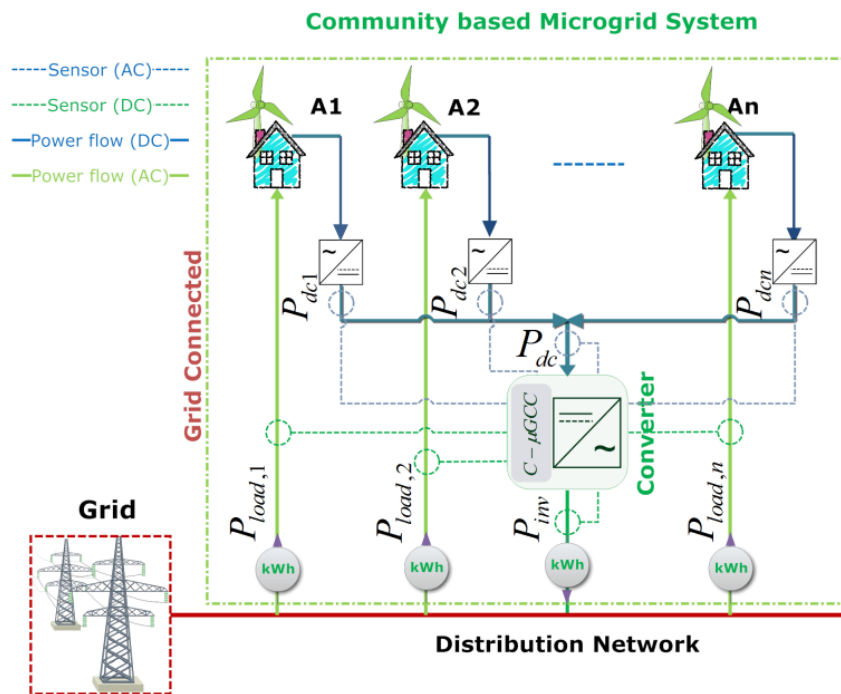


Fig 4.3 Power flow diagram for grid-connected C- μ Grid system without storage in the existing network

4.6.1 Operational Control Statement

The C- μ Grid system under investigation can be described by the model shown in Fig 4.4, where the μ Grid is represented by the interconnection of main components which include: 1) a local consumer; 2) a renewable generator (wind turbine); 3) a storage facility (battery); and 4) an external grid (main grid). In Fig 4.4, the signals $d_l(t)$ (kWh) and $d_s(t)$, collect all the demand required by the consumers and the entire energy produced by the μ Gen sources, respectively. Moreover, $u_b(t)$ denotes the energy transmitted/received to/from the battery storing a certain amount of energy $x(t)$, while $u_g(t)$ represents either the energy bought from the main grid ($u_g(t) > 0$) or the energy sold to the main grid ($u_g(t) < 0$) within the following prefixed bounds:

$$-\underline{u}_g \leq u_g(t) \leq \bar{u}_g \quad (4.1)$$

where \underline{u}_g and \bar{u}_g are the maximum buying and selling energy, respectively. The cost of purchasing energy from the grid varies according to the time-varying buying tariff $\alpha(t) > 0$ while the selling income is regulated by a different time-varying tariff $\beta(t) > 0$. In this work, we assume that $\alpha(t) \geq \beta(t)$.

The interactions among the independent components of the C- μ Grid are allowed by the bus that enables power exchange from the wind turbines and main grid to the battery and loads according to the following algebraic equation:

$$d_l(t) = -u_b(t) + u_g(t) + d_s(t) \quad (4.2)$$

where only the quantities $u_b(t)$ and $u_g(t)$ are assumed to be directly controllable by the supervisor (C- μ GCC) while $d_s(t)$ and $d_l(t)$ are stochastic power flows driven by μ Gen sources and the consumer load demands, respectively.

The battery is modeled as a device capable of storing a certain amount of DC electricity. Limits are specified on how quickly it can be charged or discharged, how deeply it can be discharged without causing damage and how much energy can cycle

through it before it needs replacement. Moreover, it is assumed that the properties of the battery remain constant throughout its lifetime and are not affected by external factors such as temperature.

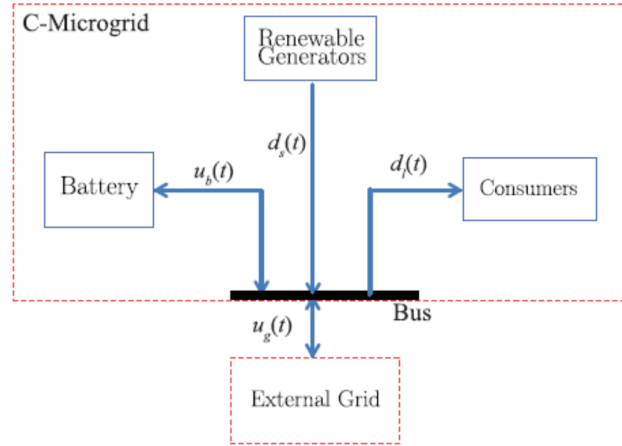


Fig 4.4 C- μ Grid control oriented scheme

In the proposed C- μ Grid setting, for describing the battery operation (the charge and discharge modes), a quasi-kinetic battery model [111] is used, which models the battery as a tank storing a certain amount of energy $x(t)$ at time step t that evolves according to the following discrete-time difference equation:

$$x(t + 1) = \tau x(t) + u_b(t) \quad (4.3)$$

with $\tau \leq 1$ denoting the hourly self-discharge decay. Obviously, the quantity of storable energy is constrained as the capacity of the battery is limited by a quantity \bar{x} :

$$x(t) \leq \bar{x} \quad (4.4)$$

Furthermore, an additional constraint bounding the minimum level of stored energy is taken into account:

$$x(t) \geq \underline{x} \quad (4.5)$$

where \underline{x} is the minimum amount of energy that should be stored in the battery.

Moreover, according to the kinetic battery model, only a certain amount of stored

energy is immediately available for charging or discharging, the remaining being chemically bound. For this reason the following inequalities are considered:

$$\underline{u}_b \leq u_b(t) \leq \bar{u}_b \quad (4.6)$$

in order to limit the amount of transferable energy from/to the battery to/from the other μ Grid components. Finally, in order to include in an explicit way the lifetime of the battery in the supervision scheme, the above battery model is equipped with the following equation:

$$q(t + 1) = q(t) - |u_b(t)| \quad (4.7)$$

where $q(t)$ is the remaining *lifetime throughput* of the battery at time t , which is the amount of energy that can cycle through the battery before failure. In practice, when $q(t) \approx 0$, the battery should be replaced.

4.6.2 IF-THEN-ELSE Heuristic Control

The simple IF-THEN-ELSE heuristic control, hereinafter referred as S-LOGIC, does not make use of any prediction and works according to the following criteria:

- i) battery will not charge from the grid under any circumstances
- ii) generation will first serve the load
- iii) excess electricity ($d_s(t) \geq d_l(t)$) will be stored in the battery
- iv) in a deficit situation, ($d_s(t) < d_l(t)$), the system will take energy from battery
- v) if the battery is full ($x(t) = \bar{x}$), system will export energy to grid
- vi) if the battery is empty ($x(t) = \underline{x}$) and ($d_s(t) < d_l(t)$), the load will import energy from the grid

A flowchart of the algorithm implemented according to the above instructions is shown in Fig. 4.5.

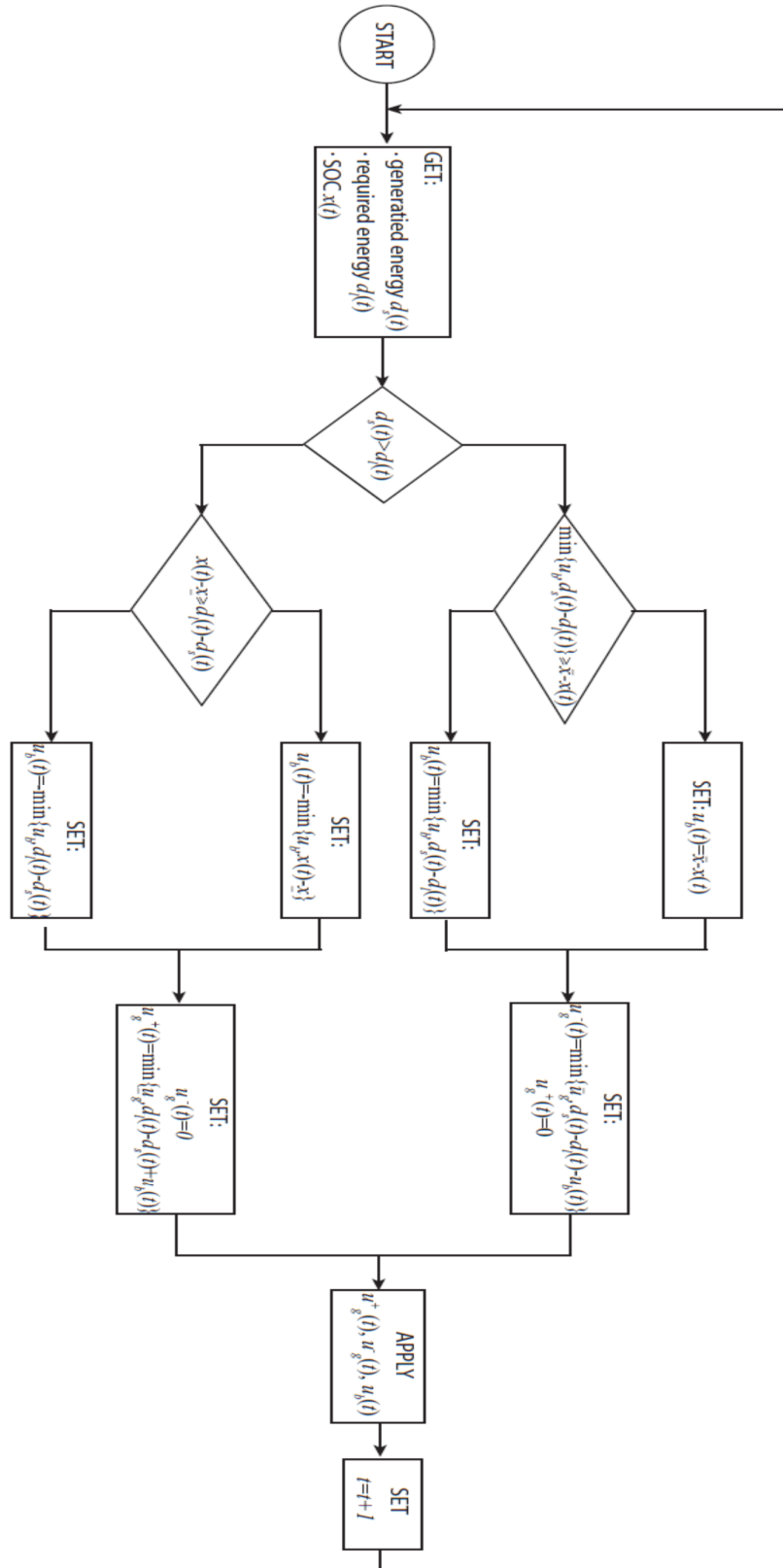


Fig 4.5 S-LOGIC algorithm flowchart

4.7 Technical Stability Issues for C- μ Grid

With more power electronics converters being interfaced for source integration, the stability in a μ Grid largely depends on the control topology of the converters. Along with this, the type of sources, storage, protection and compensation also play a significant role in the system stability. According to [12], the stability issues in a μ Grid are divided into three categories; (i) small signal, (ii) transient and (iii) voltage stability. Small signal stability is related to the feedback controller, continuous load switching and power limit of the DG sources. A fault with loss of power and subsequent island operation poses a transient stability problem. Voltage stability problems occur due to the reactive power limits, load dynamics, under voltage load shading and tap changers voltage regulation. Depending on the types of architecture, Fig 4.6 shows the different stability improvement methods used in μ Grid structures.

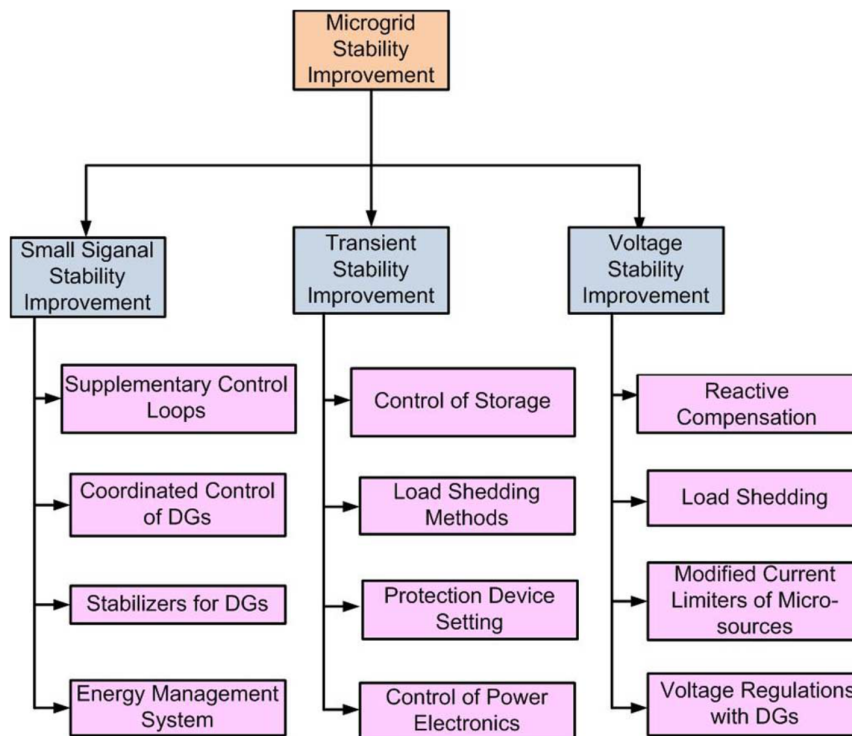


Fig 4.6 Different stability improvement methods in μ Grid [12]

In most of the cases, it is found that stability issues arise more due to the multi-source inverters in a μ Grid network. Therefore, introducing supplementary control loops in each inverter is suitable. Otherwise, a separate stabilizer, custom power devices like STATCOM or energy storage devices are mostly practiced [12].

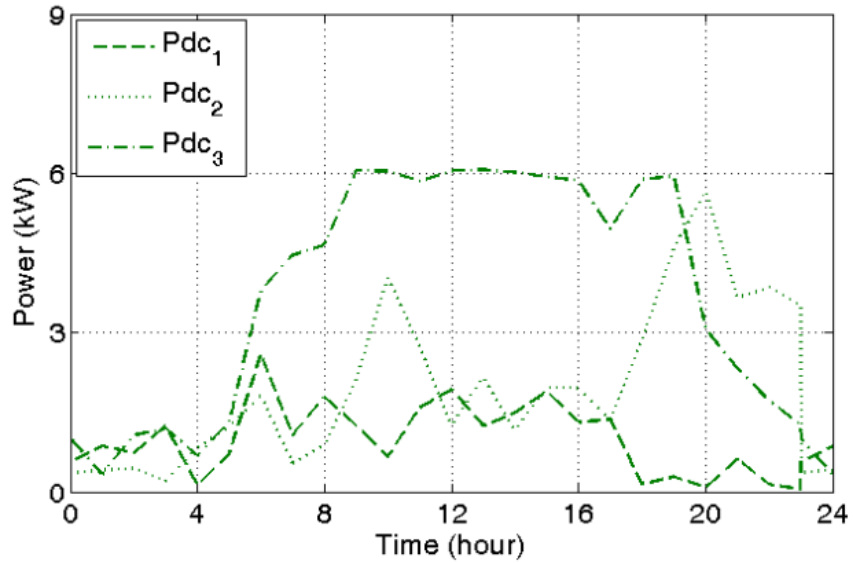
The novelty of C- μ Grid structures is that only one central inverter is considered for each C- μ Grid system and therefore stability control should be comparatively easy. In the case of an always grid connected structure (Fig 4.2), a small capacity storage unit can be introduced that will also help to stabilize the network. On the other hand, C- μ Grid structure for on/off-grid conditions in an existing distribution network can consider additional stabilizer/STATCOM unit to improve the stability of the network. The present thesis considered the top level dynamic energy and power balance situations. Hence the micro level stability issues were assumed to be not causing concern in detail.

4.8 Simulation Study

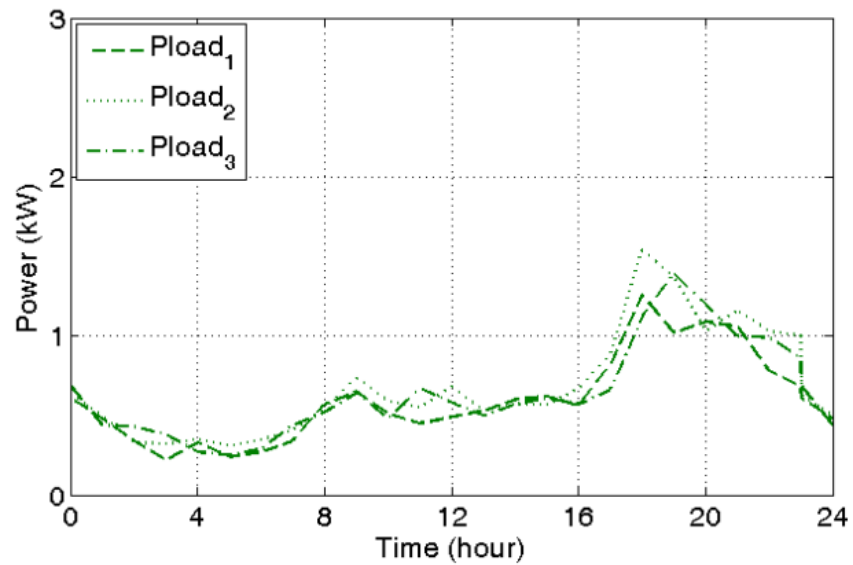
To understand the technical performance of the central controller along with the power sharing mechanism, a simulation model for a grid connected C- μ Grid system consisting of three wind energy based μ Gen systems and measured load demand information is developed in MATLAB Simulink.

Wind speed measured data has been collected from MET Éireann and location is Dublin, Ireland. The generated DC power output (P_{dc}) for a typical day has been calculated from three different wind turbines, as shown in Fig 4.7(a). The load demand for three typical household (P_{load}) in Dublin have also been collected from the respective authorities and is shown in Fig 4.7(b). The grid electricity price, REFIT price has also been taken from the local electricity utility, ESB.

The distinct outputs of three turbines are fed into the central inverter. A simple lookup table is also created for efficiency vs power output to reflect the performance of the central inverter in the system. The total input and output of the inverter along with its efficiency at different time are shown in Fig 4.8. The total export/import condition from the grid (P_{grid}) is also shown in the same Fig 4.8.



(a)



(b)

Fig 4.7 (a) Output from three wind turbines; (b) load demand of three houses on that typical day

Depending on the controlling method and mutual agreement between the prosumers and utility distributor under the C- μ Grid system, the energy management part of the C- μ GCC will decide the power sharing mechanism within the system. At this moment, the C- μ GCC calculates the individual amount of energy that is consumed by each prosumer and supplied to the grid. Fig 4.9 shows the performance and results for individual prosumers. Power generation from each of the μ Gen sources, corresponding output from the central inverter, load demand and power exchange with the grid are shown individually. In the current policy, the prosumers are not benefited by selling their generated excess clean energy to other consumers or in energy market. In future, the energy policy could allow the prosumers to take part in an energy trading mechanism through the buy/sell of their own generated energy to other consumers/prosumers/grid operator. This information then can easily be assessed by the Feed-in-Tariff policy to calculate the details of the economic benefits for each of the prosumers.

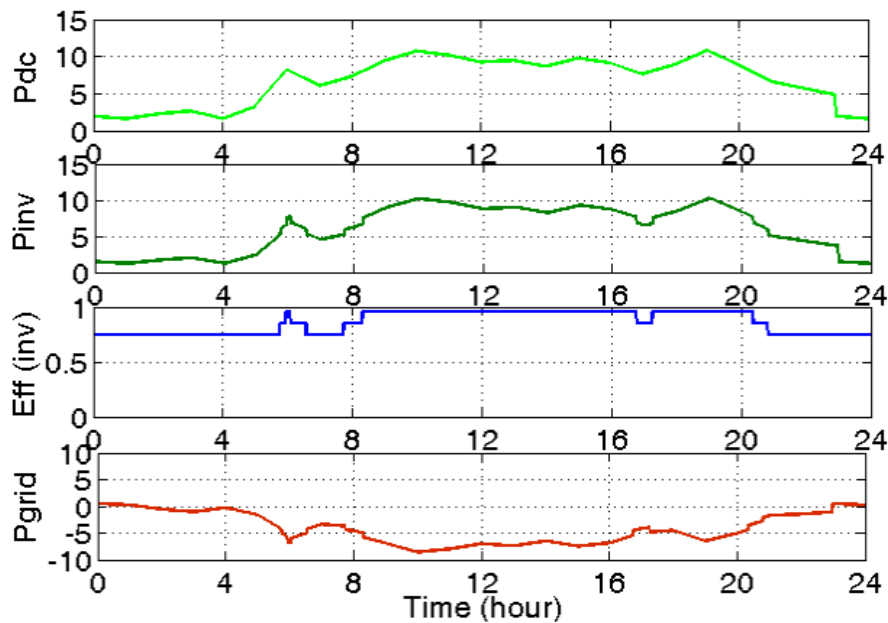
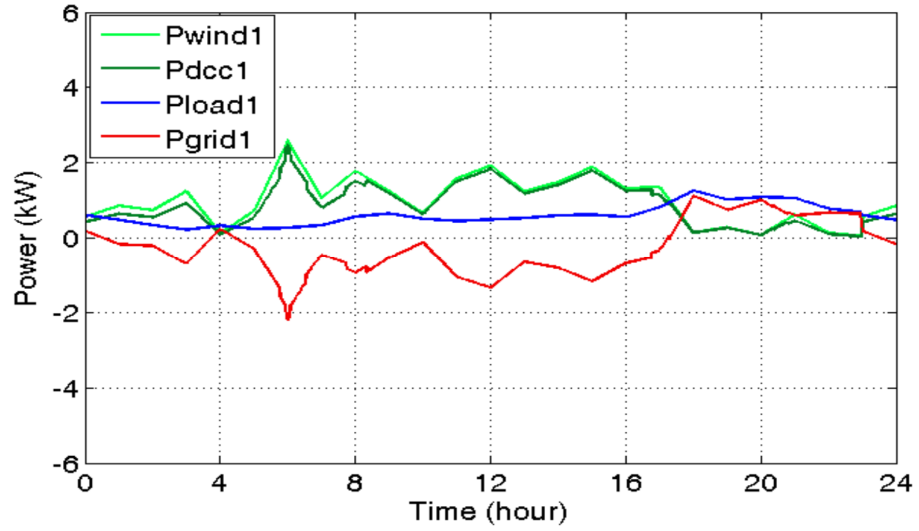
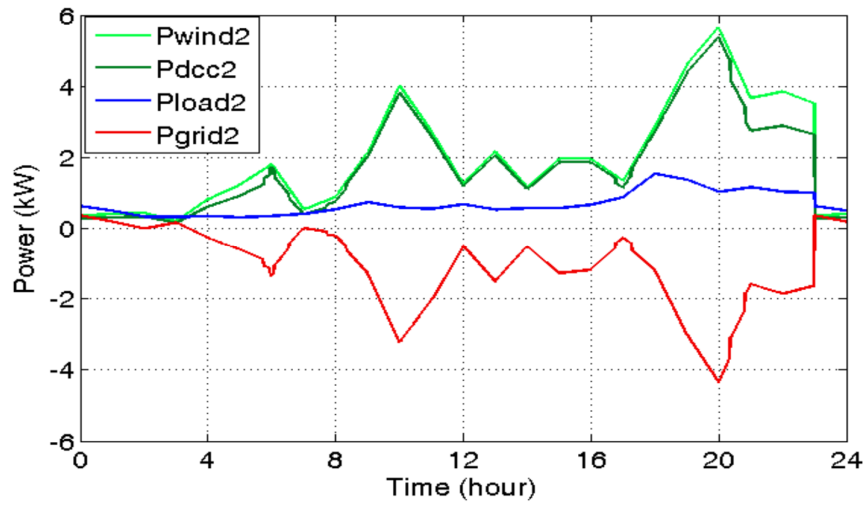


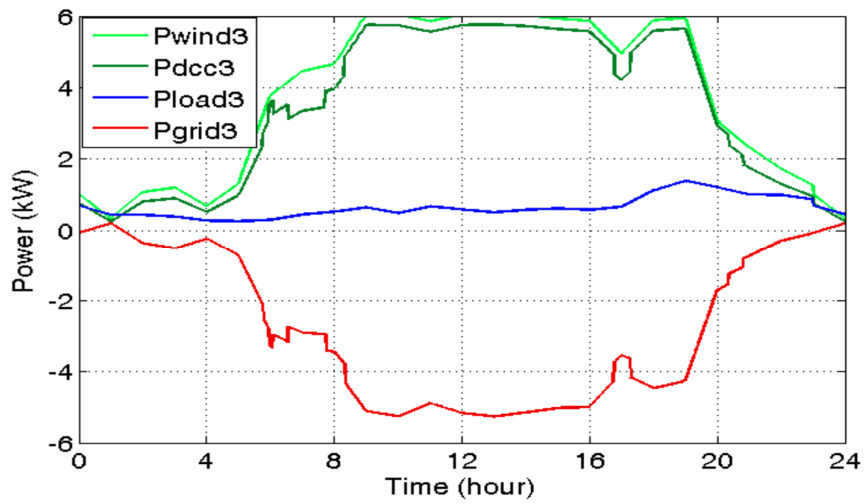
Fig 4.8 Total input and output power of inverter with efficiency and grid power



(a)



(b)



(c)

Fig 4.9 Power sharing information for (a) house1 (b) house2 and (c) house3

4.9 Economical Sustainability Study

4.9.1 Case Study Description

The system shown in Fig. 4.1 has been set in an Irish context. To understand the economical sustainability of the proposed C- μ Grid system, a virtual community area in Dublin, Ireland consisting of 50 houses has been considered. It has been assumed that each of the 50 houses have their own wind energy based μ Generators. In a μ Gen system, each consumer has one CC and a micro converter in their own system. While in the proposed C- μ Grid system, their micro wind turbines are considered to be connected together through their own CC to a total capacity single unit inverter. One of the important criteria of the system is that the consumers of the community would have to agree to share the investment and benefits of the system equally. Both the systems have been designed and simulated partly in HOMER and MATLAB.

Specific grid electricity bills for day time and night time (Table 4.1) are taken from the local authority of electricity, ESB. Details of system parameters and economical information can be found in Table 4.1 also. Here it is worth commenting that the decay τ is tuned such that the battery losses 2% of the stored energy after one month.

4.9.2 C- μ Grid Without Storage

Figure 4.2 (a) shows the C- μ Grid without a storage system which is always grid connected. Table 4.2 shows the energy purchase and selling information for a C- μ Grid system from and to the grid. It is noted that at the end of the year, net purchase of the system is negative. That is, the system is selling more energy to the grid. Table 4.3 shows the techno-economical information of 50 individual μ Gen systems and a C- μ Grid system consisting of 50 houses. From the study it is found that the initial

investment and total system cost are lower in the C- μ Grid concept compared to μ Gen systems. Thus the COE (€0.09/kWh) for grid sale becomes lower than the REFIT price which is €0.10/kWh. Therefore, according to the analysis it can be stated that the system could become economically viable for the community users in an Irish context.

Table 4.1 System parameters and cost info

House	
Number of house	50
Average load demand/house	14kWh/day
Turbines	
Maximum achievable power/turbine	6kW
Cost/Turbine	18k€
Battery	
Capacity/house, \bar{x}	14.4kWh
Decay factor, τ	0.9997
Initial Lifetime Throughput, $Q(0)$	25×10^3 kWh
Minimum storable energy, \underline{x}	$0.3\bar{x}$
Maximum and Minimum Charge rate, $(\bar{u}_b, \underline{u}_b)$	5kW/h
Initial and Replacement cost	(200 and 120) €/kWh
Maintenance Cost	160€/year
Converter	
Capacity	6kW/house
Initial and Replacement cost	(1340 and 760) €/kW
Grid	
Day and Night time buying tariff	(0.233 and 0.153) €/kWh
Day and Night time selling tariff	(0.10 and 0.10) €/kWh

4.9.3 C- μ Grid With Storage

C- μ Grid can operate either in grid connected or autonomous mode. To maintain the operational reliability and flexibility, system management should be able to accommodate the power produced by the sources without compromising the security of the system [112]. As a solution, the technology that is projected to increase its penetration in future power systems is the Energy Storage System (ESS). To restore system voltage and frequency in several cycles, storage devices are integrated in the system. Despite the high price of battery or ESS, the technology is projected to increase usage in the coming years [113,114]. C- μ Grid system with storage can

support islanding condition when power outage occurs in the grid network. In the event of power outage, homeowners can automatically experience a smooth and safe transition to the emergency backup.

Table 4.2 Energy purchased from and sold to the grid for C- μ Grid system consisting of 50 houses

Month	Energy Purchased	Energy Sold	Net Purchases
	(kWh)	(kWh)	(kWh)
Jan	4216	58737	-54521
Feb	3918	54227	-50308
Mar	4929	54619	-49690
Apr	5290	36549	-31259
May	6424	30247	-23823
Jun	6092	25890	-19798
Jul	6607	25255	-18647
Aug	6436	26802	-20366
Sep	5651	31722	-26071
Oct	4448	45601	-41145
Nov	4330	43652	-39323
Dec	4164	52034	-47870
Annual	62505	485335	-422830

Table 4.3 Techno-economic aspects of μ Gen and C- μ Grid system

Aspect	Parameters	μ Gen System	C- μ Grid System
		50 Houses (50 unit)	1 Microgrid (1 unit = 50 houses)
Technical	Wind Turbine	6 kW/unit	6*50 = 300 kW
	Converter	6 kW/unit	300 kW
Economical	Initial cost	€12000	€600000
	Total cost	€14630	€90000
	Cost of energy	€0.11/kWh	€0.09/kWh

To implement the proposed C- μ Grid system with storage, the previous analysis has been extended with a storage system. Three cases have been considered for the overall analysis: (i) off-grid μ Gen system, (ii) off-grid C- μ Grid system and (iii) grid connected C- μ Grid system. All the systems have their own required storage. Detailed technical information is given in Table 4.4.

In off-grid conditions, to maintain the technical stability and to meet the peak load demand, the required storage capacity becomes high. It is found that the primary load demand of a single user is around 14 kWh/day, with a peak load of 1.7 kW. To

meet the demand, the 50 units of off-grid μ Gen system require 1440 kWh of battery storage capacity, as shown in Table 4.4. This storage capacity can be reduced but in that case the peak load demand may not be met and thus a capacity shortage could occur.

Table 4.4 Technical information of off-grid/grid connected C- μ Grid system with storage

Grid integration	Off-grid		On-grid
System	μ Gen System	C- μ Grid System	C- μ Grid System
	50 Houses (50 unit)	1 Microgrid (1 unit = 50 houses)	1 Microgrid (1 unit = 50 houses)
Wind Turbine	6*50 = 300 kW	6*50 = 300 kW	6*50 = 300 kW
Converter	6*50 = 300 kW	300 kW	300 kW
Storage			
Battery Capacity	28.8*50 = 1440 kWh	935 kWh	14.4 kWh to 935 kWh
Autonomy	24 hr	23 hr	1 hr to 23 hr
Expected life	20 yr	20 yr	20 yr
Project life	25 yr	25 yr	25 yr

Analysis shows that, in the case of an off-grid C- μ Grid system, the storage capacity can be reduced to 935 kWh. Because of the central storage system, each of the houses would not need separate storage. The community can share the common battery bank, thus its size can be reduced. For both the off-grid cases, autonomy is maintained for around 1 day. One of the drawbacks of RE based off-grid systems is to utilize the excess energy. In both the cases, excess energy from wind turbine is very high. This occurs due to the mismatch of supply and demand. Therefore the COE in an off-grid system is also high, as shown in Table 4.5. In the case of an off-grid μ Gen system with storage, the COE is found to be €0.22/kWh. This cost goes down to €0.16/kWh for the off-grid C- μ Grid system. In the case of a grid connected C- μ Grid system this cost goes down to €0.11/kWh. This cost reduction occurs due to i) the reduction of storage capacity ii) the lower cost of a large capacity single unit converter and iii) selling excess electricity to the grid.

Table 4.5 Economic aspects of off-grid/grid connected C- μ Grid system with storage

Grid integration	System	Off-grid		On-grid
		μ Gen System	C- μ Grid System	C- μ Grid System
Economic aspect	Initial investment cost	€19430*50	€757260	€662460
	Total system cost	€26064*50	€833355	€802566
	COE	€0.22/kWh	€0.16/kWh	€0.11/kWh

4.10 Conclusion

A new structure of a μ Grid system, called as C- μ Grid, is proposed here to maximise the benefits of μ Gen systems to empower energy citizens. The techno-economic advantages of the proposed system over the conventional μ Gen and μ Grid systems are also discussed and analysed. A simple S-LOGIC control algorithm for the central controller of the system is developed to understand the performance including the energy sharing mechanism of the system. Both the technical and economic performance of the system is verified through the simulation study.

Techno-economic results show that without changing the government incentive/REFIT policy, community users can convert their μ Gen system towards the development of a C- μ Grid system with/without storage. It is found that the initial investment and total system cost are lower in the C- μ Grid concept compared to the μ Gen system, thus the COE can also become lower for the C- μ Grid system. This step forward could help the community users to move towards making their RE system sustainable and economically viable in an Irish context.

Energy Efficient C- μ Grid through DSM

5.1 Introduction

The previous chapter proposes design, development, operation and control of new and cost-effective C- μ Grid systems through the innovative method of integrating μ Gens to encourage the prosumers to take part in energy trading mechanism. Techno-economic sustainability of the systems with/without storage is also presented. To cope with smart grid network or to work independently in future, the proposed C- μ Grid system with storage could be an attractive solution to the end users as well as to the utility operators. Furthermore, introducing storage in the system can improve the efficiency and stability of the network. At the same time, storage can be another viable option to implement Demand Side Management (DSM) strategy that has been proposed as a key component for future smart grid systems [115-118].

The energy efficiency of C- μ Grid system could further be improved by efficient energy management system through supply or demand side control. This chapter investigates the possibility of implementing DSM strategy to the proposed C- μ Grid system with storage. This might help to (i) further improve the efficiency of the system by reducing peak load demand and (ii) maximise the utilisation (self-consumption) of renewable energy by shifting the load demand. This will also extend the overall benefits of implementing C- μ Grid, such as (i) grid operator to improve

distribution network efficiency and stability, (ii) decrease the cost of energy of the proposed C- μ Grid system by reducing the required storage capacity, (iii) active participation of prosumers in energy management.

The analysis of this chapter is a continuation of the case study that has been considered for the techno-economic sustainability, as discussed in the previous chapter. The following part briefly discusses the DSM technique and followed by the load pattern and characteristics analysis. This case study is carried out for a selected location in response to evaluate the possibility of applying DSM technique to make the C- μ Grid system more responsive and energy efficient for Irish context.

5.2 Demand Side Management (DSM)

DSM is the methodology of planning, implementing and monitoring the utility activities that are designed to influence customer's electricity usage. The main objective of DSM is to encourage the consumers to consume less power during peak time or to shift some loads to off-peak hours to flatten the demand curve. Furthermore it is sometimes more desirable to follow the pattern of the generation system. For both cases control over the consumers' energy usage is a vital point, whereas, the classical concept is to supply the required demand whenever needed. Therefore, the main tasks of the DSM techniques are to reduce the peak load and the ability to control load consumption according to generation [119].

On the other hand, the reliable operation of the grid is initially dependent on perfect balance between supply and the demand. When penetration of RE to the grid increases it becomes difficult to maintain the network stability. Renewable generation is weather dependent and the output cannot be forced to follow a particular load shape. Furthermore peaks in RE would not always coincide with the peak demand. While there are many research and demonstration experiences available in optimising

energy generation and distribution, DSM receive increasing attention recently [120]. DSM can help to adjust operating time of the flexible loads to match with the RE generation. This can be accomplished by developing different load shaping patterns. These are peak clipping, valley filling, load shifting, strategic conservation, strategic load growth and flexible load shape, as shown in Fig 5.1(a) [119].

DSM includes everything that is done on the demand side, ranging from implementing compact fluorescent lights up to a sophisticated dynamic load management system. Depending on the timing and the impact of the applied measures on the customer process, DSM can be categorized into the following as shown in Fig 5.1(b) [120].

- a) Energy Efficiency (EE)
- b) Time of Use (TOU)
- c) Demand Response (DR)
- d) Spinning Reserve (SR)

EE generally aims to reduce overall energy demand. ToU tariff system is developing recently to encourage the consumer to shift/turn-off their load during the peak demand period. On the other hand DR concentrates more on shifting the energy consumption during peak times and thus it helps to balance the supply and demand. Currently most consumers have no means of receiving information that would reflect the state of the grid and thus cannot react accordingly to increase efficiency. Due to the unpredictable nature of RESs, it is not possible to control or guarantee energy supply as required. Therefore, the goals of introducing the DR systems are to reduce the peak load demand and to control the consumption in line with generation [120]. Hence, DSM in terms of DR is very important to achieve a more energy efficient C- μ Grid system.

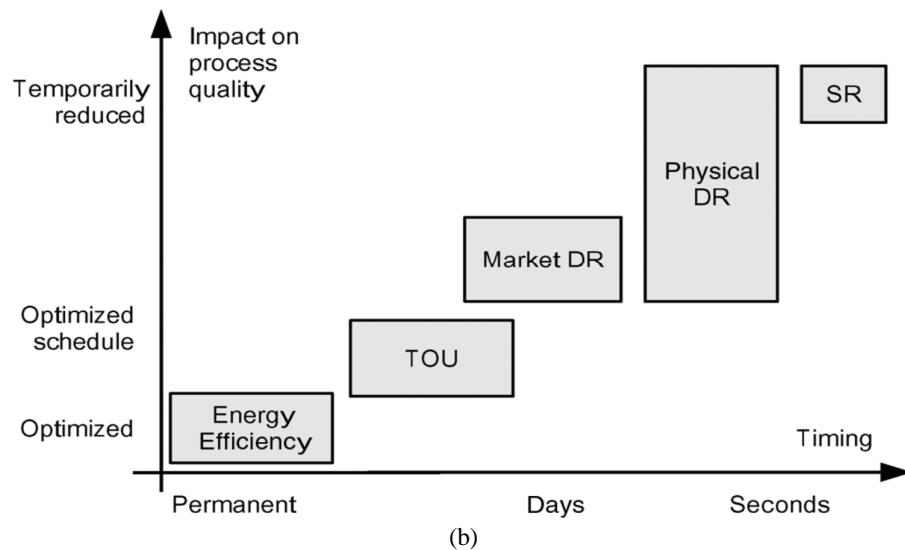
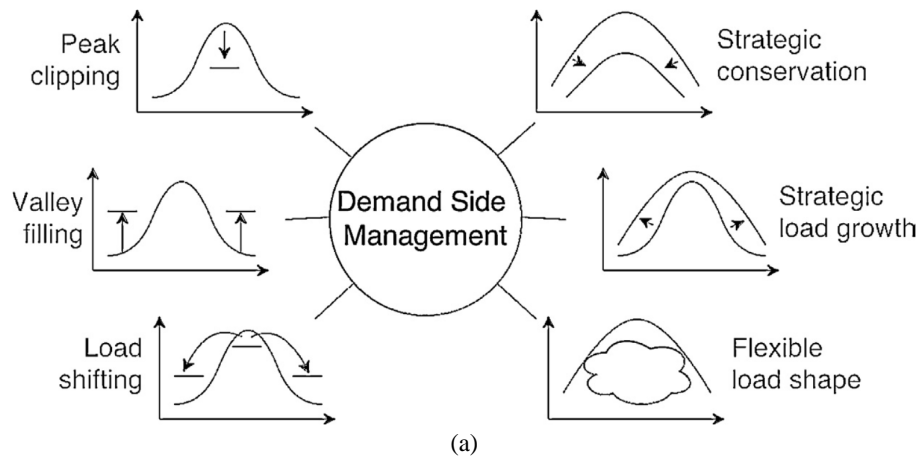


Fig 5.1 (a) Basic load shaping techniques [119]; (b) categories of DSM [120]

5.3 Residential Load Study for DSM

In the previous chapter, simple techno-economic analysis has been carried out for the proposed C- μ Grid system where normalised data for a type of residential house was considered and scaled up for 50 houses to consider a virtual C- μ Grid system. It is also difficult to get the time series data for all of these houses in real-case. Even, if possible to get all the data, it requires high computation system to analyse in details. Therefore, some of the time series measured data were extracted from [93] and analysed to perform the DSM study here.

5.3.1 Load Pattern

Details of the time series data for the combined load profile of the selected 10 houses in the C- μ Grid structure has been studied. From the combined load pattern it is found that:

- The monthly average hourly load demand profile indicates that peak load demand occurs during the morning and evening time, as show in Fig 5.2. It is found in the analysis that the proposed C- μ Grid (based on 10 houses) consumes 50770 kWh of energy per year (139 kWh/day).
- Total load duration curves based on the 15 min interval time series data, as shown in Fig 5.3(a), reveals that the peak demand could go upto 53.84kW.
- Fig 5.3(b) uncovers that load shifting for 2% of time can reduce up to 21.53kW (from 53.84kW to 32.31kW) or 40% of peak demand.

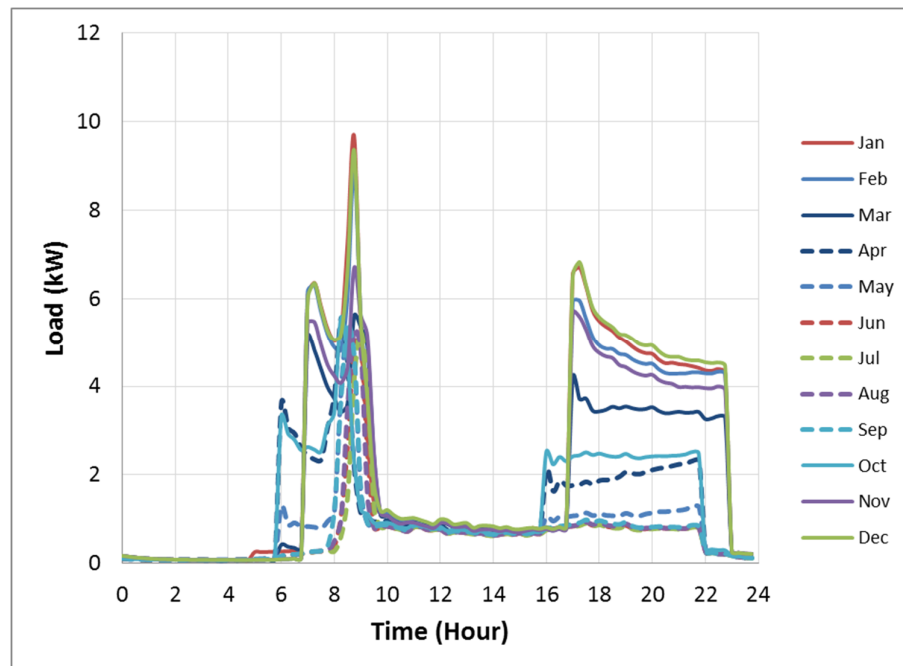


Fig 5.2 Monthly average hourly total load profile for the selected houses in the case study

This initial study indicates that if it is possible to shift the operating hours for some of the loads (appliances) then an appropriate DSM strategy could be implemented. This will then help to reduce the peak demand and thus DSM can play a vital role to improve the distribution network efficiency and stability. By shifting the load to follow the renewable energy generation pattern could also reduce the required storage capacity. Thus the efficiency of the proposed C- μ Grid could further be improved.

5.3.2 Operational Flexibility

The possibility of DSM through the load shifting depends on the operational flexibility of the individual loads. Consumers' behavior, level of occupancy, weather conditions and renewable energy sources play an important role in the use and to achieve the operational flexibility of the load [121-126]. In general, depending on the control and operation, the household loads can be divided into two groups: (i) fixed (un-controllable) – operating time is fixed over the year; (ii) flexible (controllable) – operating time can be shifted. In some cases, time and amplitude (peak power) can also be changed [125]. Refrigerator, TV, lights, computers can be categorized as fixed loads. Whereas washing machines, water heaters, space heaters, vacuum cleaners, dish washers can fall into the flexible category.

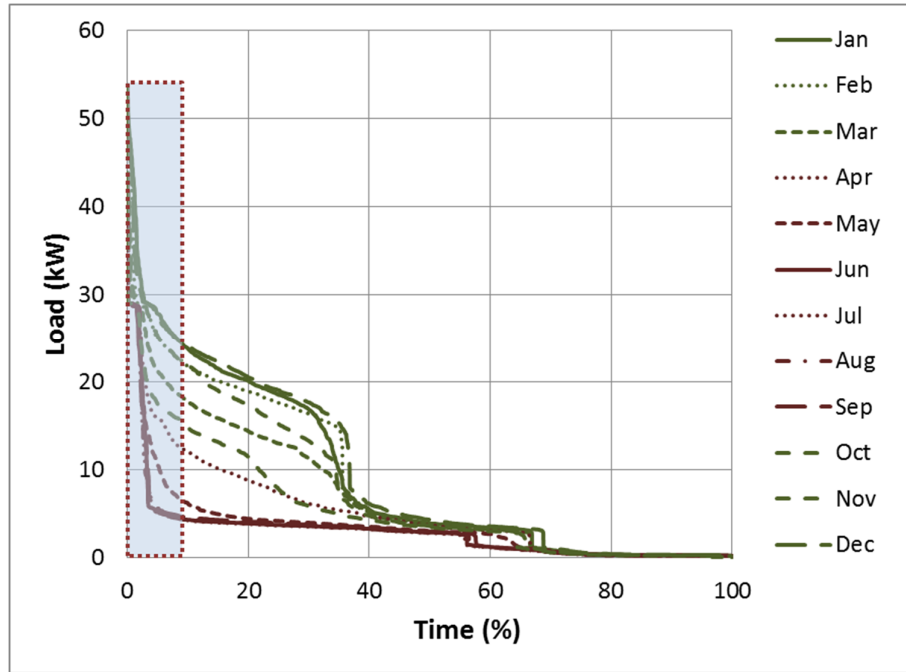
Table 5.1 Considered fixed and flexible appliances for the case study and their power consumption

Fixed Load	Power (Watt)	Flexible Load	Power (Watt)
Deep Fridge/Freezer	160 - 190	Room heater	1000 - 2800
Refrigerator	110 - 130	Water heater	3000
TV	100 - 120	Dish washer	1200
PC	120 - 140	Tumble dryer	2000 - 2500
Hob	1000 - 2400	Washer dryer	700 - 800
Wifi	30	Washing machine	450 - 600
Oven	2200	Lights	15-35
Microwave	1250	Iron	1000
Kettle	2000	Vacuum cleaner	750 - 1200
Lights	15-35	DVD Player	50

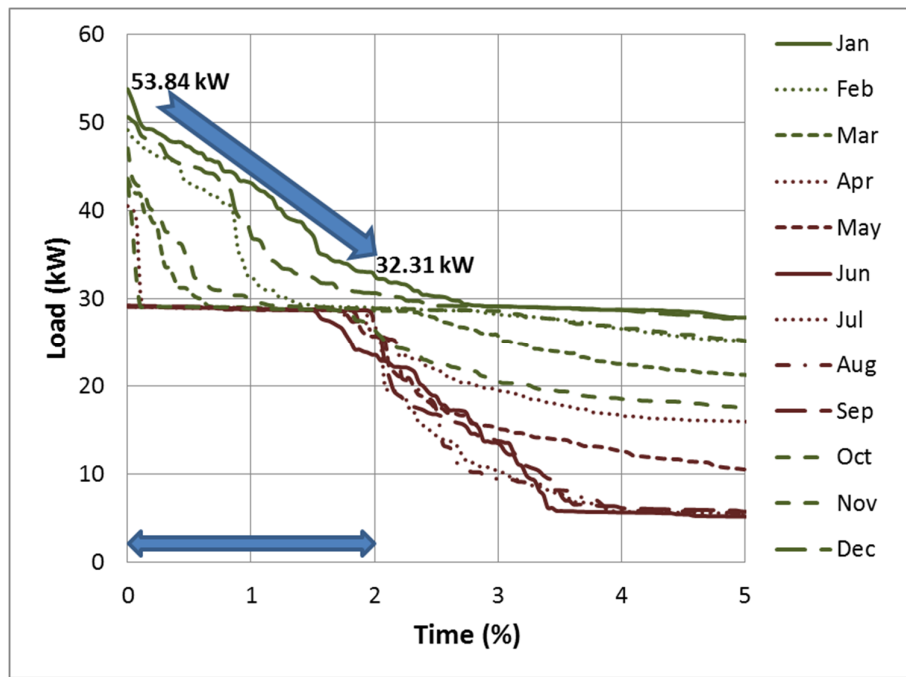
Introducing energy storage and applying operational flexibility through the appropriate appliance scheduling scheme means that the consumer can realize more cost savings [127]. This can be achieved through an intelligent energy management framework where the flexible appliances are scheduled for power consumption during the low peak hours. With energy storage this allows the consumers to purchase energy during off-peak hours when electricity prices are low and satisfy their demands when prices are high by discharging the energy from storage [123].

Based on this research, detailed of power consumption and probable time of use information for the appliances/loads have been extracted from the time of use [93] and personal survey. Table 5.1 shows the considered appliances for the residence in the proposed C- μ Grid system and their power consumption. Some random values from the ranges have been chosen for the appliances. The demand profiles for the fixed and flexible loads are then generated and shown in Fig 5.4. Fig 5.5 also shows the monthly energy consumption and the peak demand by the fixed and flexible loads.

Analysis also shows fixed load consumes around 10930kWh/year whereas for flexible load (mainly space, water heating and washing) it is 39840kWh/year which is around 78% of the total consumed energy. It is also found that around 70% of the total energy is consumed only for space and water heating.

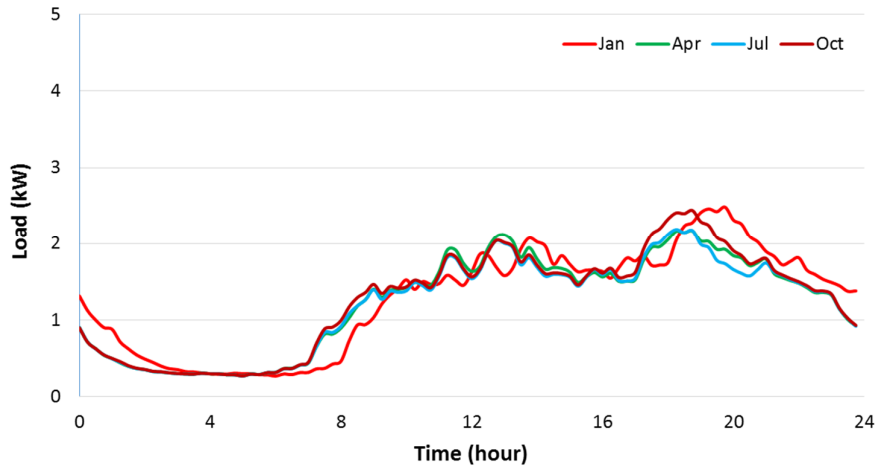


(a)

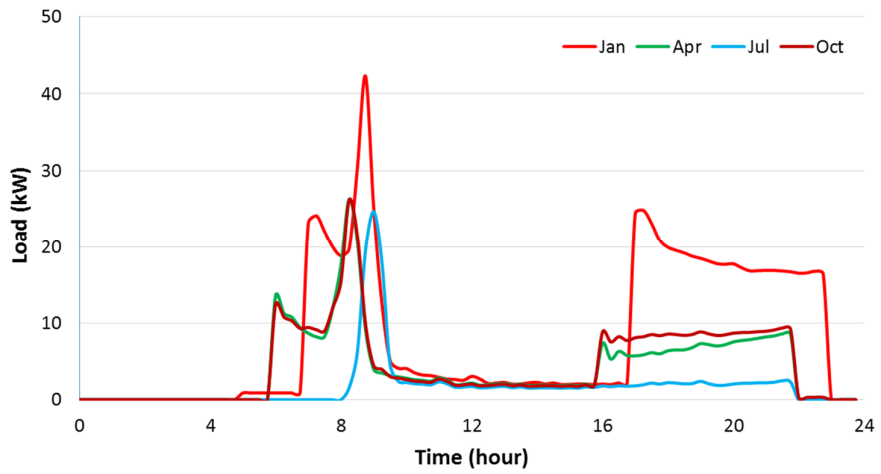


(b)

Fig 5.3 Load duration curve for the case study; (a) Duration 100% (b) zoom in to 5%

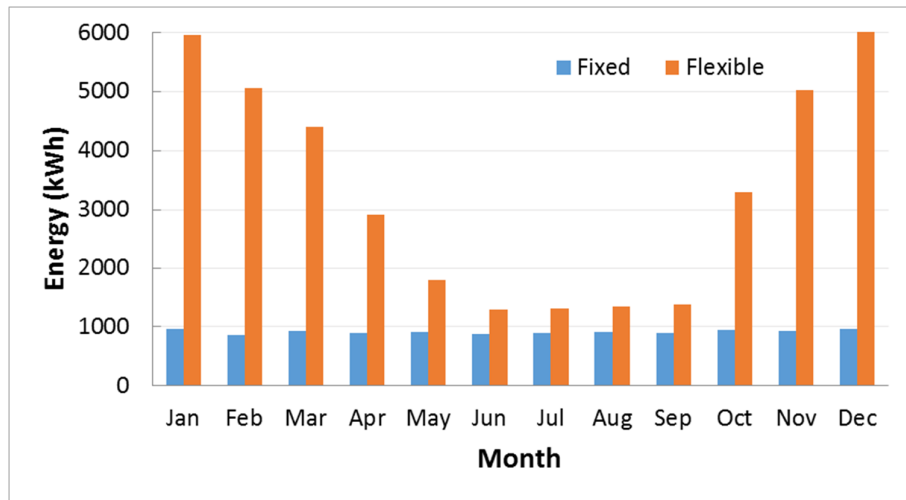


(a)

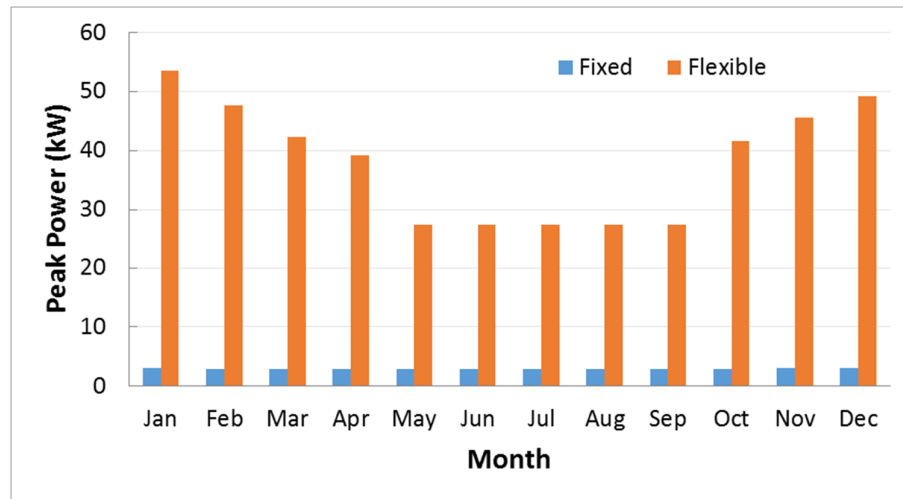


(b)

Fig 5.4 Combined load profile for (a) fixed loads and (b) flexible loads



(a)



(b)

Fig 5.5 (a) Monthly energy consumption; (b) peak demand by the fixed and flexible loads

Advanced technologies are helping to develop smart and efficient heater [128] which uses low-cost, off-peak energy, making it the most economic electric heating system in the market today. Along with this, smart electrical energy storage solution is also in the market [129] to provide backup power during utility outages and natural disasters and ready to integrate seamlessly with solar, enabling self-power home and even go for off-grid. This indicates that it will be possible to achieve full flexibility in storing electrical energy for electricity and thermal energy usage. At the same time intelligent algorithms for home energy/demand side management as well as demand response analysis are also being developed [123, 130-133]. Therefore it is expected that the control and management technologies will be available to maximise the operational flexibility of the demand side appliances to synchronise with the future smart grid network.

5.4 DSM Strategy

The main purpose of implementing a demand side management strategy is to investigate the improvement of energy efficiency of the proposed C- μ Grid system.

The strategy is to identify the possibility of shifting the peak load demand so that DSM can:

- (a) Reduce peak demand from the grid
- (b) Reduce purchased energy from the grid
- (c) Increase RE utilisation by the load
- (d) Lessen the energy storage capacity
- (e) Decrease the unit cost of energy

Research has already been done on the impact of demand side management strategies due to manual or automatic shifting of appliances based on energy tariff [122, 134], shifting the peak load demand [130, 135] as well as active control of heating/cooling systems in the context of smart grid with high penetration of renewable energies [136]. Thus DSM also helps to increase the penetration of renewable electricity [137], reducing the CO₂ emission and thus benefiting the environment [138].

In most of the mentioned articles, the DSM controller deals with the individual loads, their control and shifting according to the requirement. Therefore, it is assumed here that the technology and control devices of the individual appliances for DSM are available or will be available in near future. Thus the communication and operational infrastructure will facilitate obtaining the maximum operational flexibility of the appliances.

Hence, rather than dealing with the individual loads, their control and shifting, a simple algorithm has been introduced here, as shown in Fig 5.6, to generate a new load profile by shifting of flexible power and energy demand to follow the RE generation. Thus it will maximise the RE consumption by the load and therefore it will decrease the required storage capacity as well as reduce the peak demand from

the grid. With the technological advancement, it is considered here that both the thermal and electrical storage devices will also be able to synchronise with RE generation time so that they can store maximum energy during the RE generation, low peak or low cost energy time. Storage will be able to supply energy to the load during the peak demand or the peak price time. The algorithm also considers the following constraints:

- i) battery will not charge from the grid under any circumstances
- ii) generation will first serve the fixed load power ($p_{l,fixed}(t)$) and energy ($d_{l,fixed}(t)$)
- iii) excess power ($p_s(t) > p_{l,fixed}(t)$) and energy ($d_s(t) > d_{l,fixed}(t)$) will then serve the flexible power ($p_{l,flex}(t)$) and energy demand ($d_{l,flex}(t)$); additional energy will be stored in the battery
- iv) if generated power and energy are less than the total demand ($p_s(t) < p_l(t)$ and $d_s(t) < d_l(t)$); shift flexible demand and update $d_{l,flex}(t) = d_{l,flex}(t) + d_{l,flex}(t + 1)$
- v) in a deficit situation, ($d_s(t) < d_l(t)$), the system will take energy from the battery
- vi) if the battery is full ($x(t) = \bar{x}$), system will export energy to grid
- vii) if the battery is empty ($x(t) = \underline{x}$) and ($d_s(t) < d_{l,flex}(t)$), the load will import energy from the grid
- viii) as the annual averaged daily energy consumption is 139kWh/day, this has been considered as the value for maximum daily energy consumption
- ix) as for most of the summer months, the peak demand is around 30kW, the maximum grid purchase is restricted to 30kW round the year.

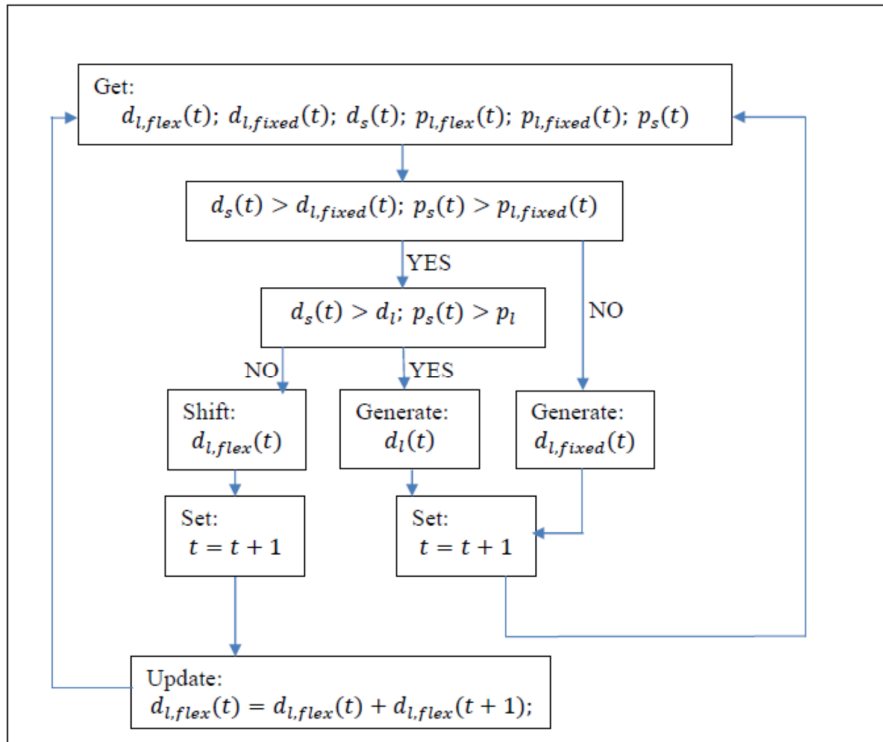


Fig 5.6 Flexible load shifting flowchart to implement DSM strategy

5.5 Simulation Study

Based on the developed simple algorithm, peak power and energy demand by the flexible loads have been shifted and adjusted so that DSM strategy can be achieved. The generated new load profile (dash lines) along with the original load profile for the four months is shown in Fig 5.7. This total load profile is then transferred to the S-LOGIC algorithm (as discussed in chapter 4, section 4.6) to carry out the analysis. Thus the performance of DSM for the proposed C- μ Grid system has been studied.

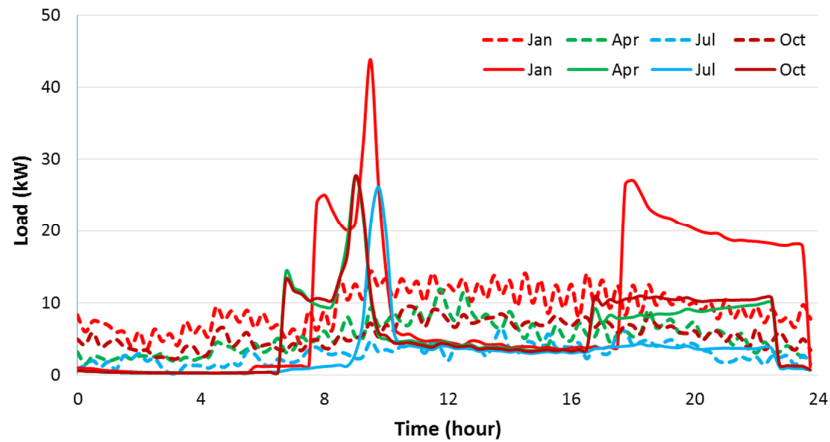


Fig 5.7 Total load profile before (solid line) and after (dash line) the implementing DSM algorithm

5.5.1 Reduced Peak Demand from the Grid

One of the key purposes of implementing DSM technique is to improve the grid network efficiency by reducing the peak purchased demand from the grid. It can help the grid to become more stable. As shown in Fig 5.5, for most of the summer months the peak demand by the combined load is just below 30kW, therefore the constraint is applied to restrict the peak demand from the grid to 30kW. It is reflected in Table 5.2 where the purchased peak demand during day and night period for each of the months from the grid are given.

Table 5.2 Peak demand (kW) purchase from the grid

Month	Without DSM		With DSM	
	Day	Night	Day	Night
Jan	45	51	0	1
Feb	27	30	0	1
Mar	17	24	0	1
Apr	0	30	0	2
May	3	29	0	1
Jun	0	29	0	2
Jul	0	28	0	2
Aug	0	28	0	2
Sep	0	29	0	1
Oct	15	22	0	1
Nov	20	22	0	1
Dec	25	27	0	1
Ann	45	51	0	2

The analysis reveals that without implementing DSM technique, purchased peak power demand for the C- μ Grid system can reach upto 53kW for January (at night time) and for rest of the period it is below 30kW peak. The performance of DSM technique shows that the system acquires only 2kW peak maximum during the summer period from the grid and mostly at night time (off-peak). With more accurate and real-time control, the performance could even be better. Thus the study clearly indicates the reduction of peak demand from the grid.

5.5.2 Reduce Purchased Energy from the Grid

Analysis shows that the DSM technique can help to reduce energy purchase from the grid. Table 5.3 shows the results of purchased energy from the grid for each month with and without implementing the DSM technique. It shows that without DSM, the system purchases more energy at night time whereas for the summer months the system purchases almost zero energy at day time.

Table 5.3 Energy (kWh) purchased from the grid

Month	Without DSM		With DSM	
	Day	Night	Day	Night
Jan	167	335	0	14
Feb	206	219	0	11
Mar	94	189	0	11
Apr	0	469	0	21
May	1	274	0	22
Jun	0	117	0	36
Jul	0	71	0	30
Aug	0	116	0	31
Sep	0	173	0	19
Oct	21	211	0	15
Nov	162	197	0	13
Dec	193	233	0	10
Ann	844	2604	0	233
Total	3448		233	

Moreover due to DSM technique, the day time purchased energy can become zero and night time required energy can also reduce significantly. In most of the months (except Jun-Aug) it reduces the grid purchase around 95% whereas annually it decreases the grid energy purchase from 3448 kWh to 233 kWh.

5.5.3 Increase RE Utilisation by the Load

The other purpose of applying DSM technique is to increase the RE utilisation by the load, so that it can also reduce the grid dependency. Fig 5.7 shows that DSM algorithm can shift the flexible energy demand and thus generate new load profile to follow the RE generation. Tables 5.2 and 5.3 also explains the possible reduction of grid dependency and thus it indicates that the flexible load demand can follow the RE generation pattern. Thus the utilisation of RE by the load can be increased. Fig 5.8 shows the monthly increase of RE utilisation by the load. It is calculated that RE utilisation by the load increases from 93% (without DSM) to 99.5% with DSM technique.

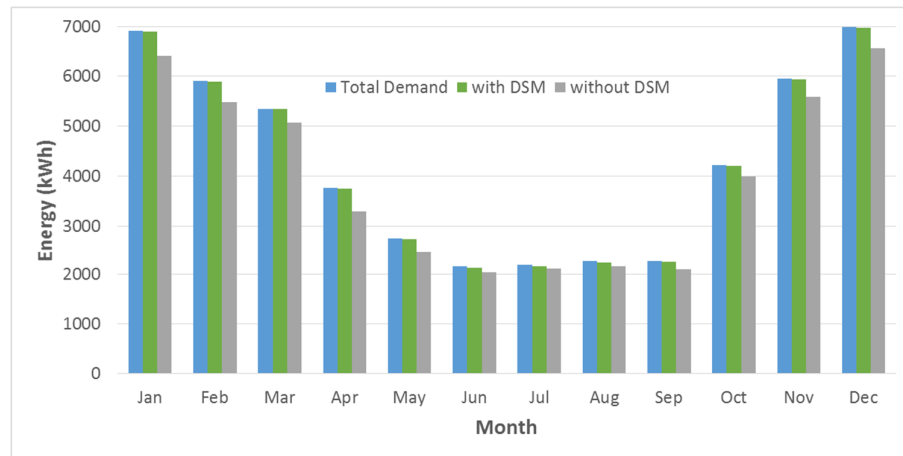


Fig 5.8 Total demand and RE consumption by the total load with and without DSM technique

5.5.4 Lessen the Energy Storage Capacity

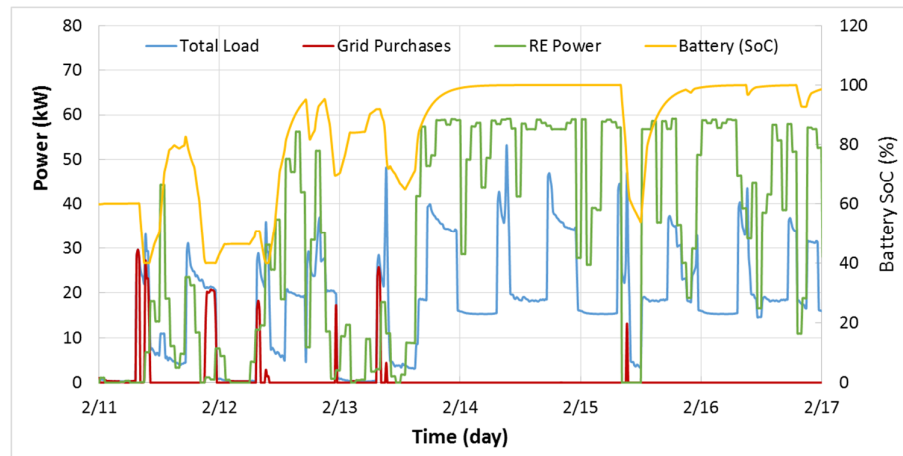
Synchronisation of flexible load with RE production and increase in RE utilisation, reduction of purchased power and energy from the grid confirms that

DSM could help the system to reduce its energy storage capacity. From the analysis, it is found that due to the DSM technique the modified load profile can strongly follow the RE generation profile. This can help to reduce the purchase energy from the grid. Due to the demand and RE supply synchronisation process, it also can help to reduce the utilisation of storage system and thus the storage capacity can be reduced. This situation is reflected in the Fig 5.9 which shows the total load demand, purchased energy from the grid, RE production and State-of-Charge (SoC) of the battery for some typical days in the month of February. Fig 5.9(a) shows the performance of S-LOGIC control without implementing DSM technique whereas Fig 5.9(b) shows the performance with DSM technique.

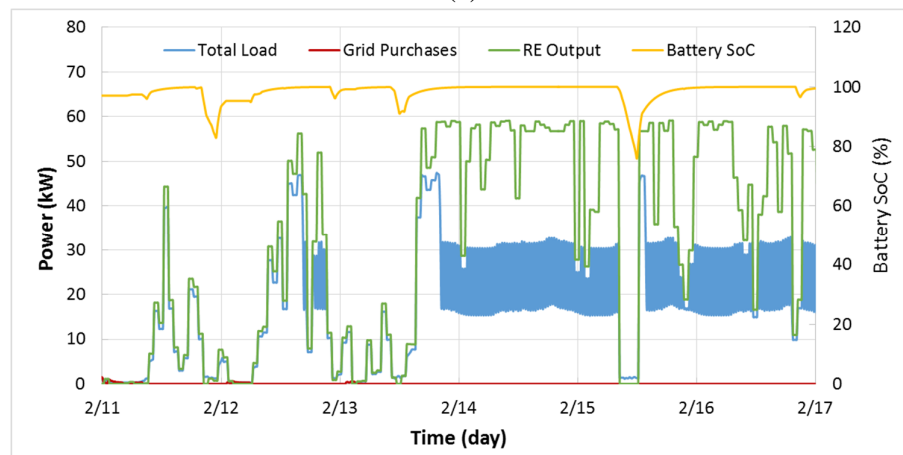
Fig 5.9 also confirms that DSM can facilitate the shifting of flexible energy demand to follow the RE generation, thus the peak demand can be modified and met by the RE peak generation. This could help to reduce the grid purchase and also improve the battery performance (charging/discharging) as shown in Fig 5.10.

Fig 5.10 shows yearly data for the SoC with 15 minutes interval for both cases, with and without DSM. Fig 5.10(a) shows performance of the battery without the DSM technique where the required storage capacity is calculated as 144kWh for the case study. Fig 5.10(b) shows the results after implementing the DSM technique and it demonstrates that the battery remains fully charged for most of the time period. Hence, it may be possible to reduce the storage capacity. Fig 5.10(c) shows the performance of reduced storage capacity (72kWh) after applying DSM technique to the system. It is also possible to further reduce the storage capacity, but in that case charging/discharging might increase and thus periodic replacement could be needed. This will then increase the overall cost of the system and as well as the COE also may increase. Results also reveal that due to the DSM technique the performance of

storage becomes more stable and uniform compared to without the DSM technique. Thus it can help to improve overall stability of the C- μ Grid system. Therefore, from the analysis, it can be stated that with appropriate technology, control and the DSM mechanism it will be possible to decrease 50% of total storage capacity as compared to the capacity without the DSM technique.



(a)



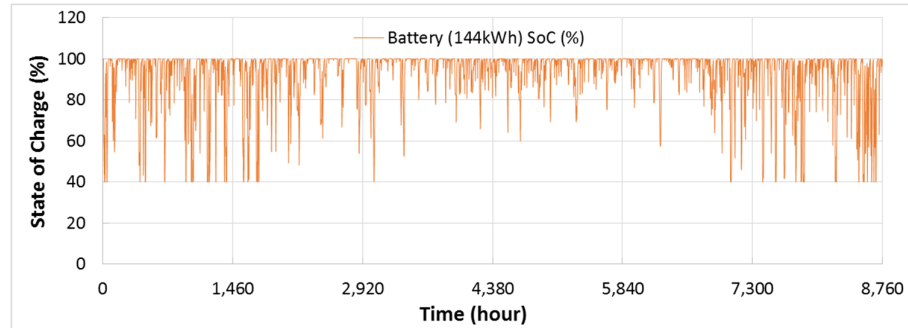
(b)

Fig 5.9 Total load demand, purchased energy from grid, RE output and battery condition for some typical days in February; (a) without DSM and (b) with DSM

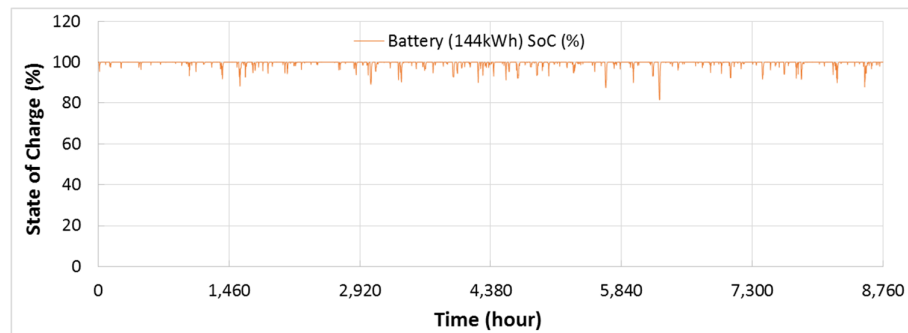
5.5.5 Decrease the Unit COE

It is confirmed by the study that the DSM technique can reduce the peak demand and energy purchase from the grid and increase RE utilisation by the load. Therefore it is expected that the overall COE for the prosumers in the proposed C- μ Grid system

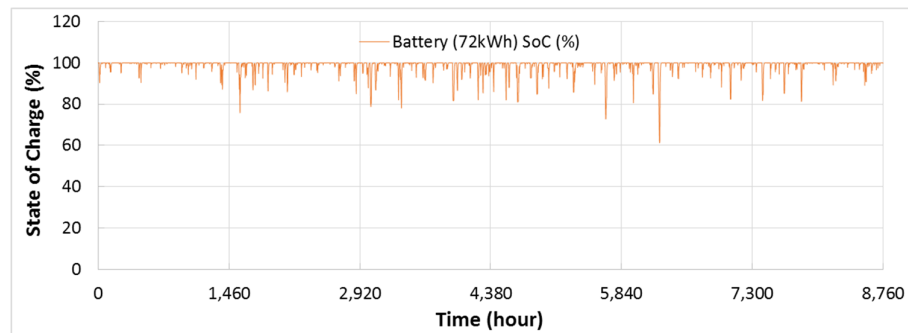
can be reduced. Considering all the economic information in the previous chapters for the development of such a system, the overall COE is found to be 0.08 €/kWh, as given the Table 5.4.



(a)



(b)



(c)

Fig 5.10 Yearly data with 15minute interval for battery state of charge; (a) without DSM (b) with DSM (c) with DSM and reduced storage capacity

Table 5.4 Energy exchange and cost of energy information applying DSM

Parameter	Value
Energy consumption by the load	50770 kWh/year
Energy purchase from the grid	233 kWh/year
RE utilisation by the load	50535 kWh/year
Storage Capacity	72 kWh
Cost of Energy	0.08 €/kWh

5.6 Conclusion

The study in this chapter concluded that the possibility of implementing DSM technique can further increase the energy efficiency of the distribution network and the proposed C- μ Grid system. By applying the DSM technique, reduction of peak load demand can help to maximise the utilisation of RE and thus can reduce the energy purchase from the grid. Based on the existing utility tariff and renewable energy fed-in-tariff systems, DSM shows that it can shift some loads to follow the RE production and use during off-peak/low tariff hours. Thus it helps to lessen the required storage capacity, increase the energy efficiency and then further reduce the COE of the system. Utilizing the existing technology and recent development on storage systems along with its integration and control can help to synchronise the C- μ Grid system with future smart grid network.

Chapter 6

Economic Optimisation

6.1 Introduction

Community-based microgrid systems (C- μ Grid) are increasingly gaining importance nowadays because of the lack of μ Grid public investment and management policies. Techno-economic analysis shows that C- μ Grid based on a cluster of μ Gens could be an effective solution when individual systems are not feasible. Study in the previous chapter also shows that applying a demand side management technique within the proposed C- μ Grid system could improve its efficiency as well as reduce the required storage capacity. To implement the DSM technique, advanced smart metering and building energy management systems with load demand control capability is required. These can be implemented in the near future when the devices are available.

In this chapter, the controlling capability of the central controller of the C- μ Grid (C- μ GCC) is further improved through an Economic Model Predictive Control (EMPC) approach operating at the pricing level that can fulfill the goal of the operational control of the cluster. With a central controller it is capable of satisfying the demand at the prosumer side and, at the same time, optimising the various μ -Grid contrasting constraints. Emphasis here has been given to the operational constraints

related to the battery lifetime, so that the maintenance and replacement costs would be reduced. Thus the economic optimisation could be achieved for the proposed C- μ Grid system.

Therefore, this chapter briefly discusses the approaches of the EMPC. A comparative analysis has been carried out between the performances of two systems; one based on IF-THEN-ELSE heuristic supervision logic (S-LOGIC) and the other one is the proposed EMPC strategy.

6.2 Model Predictive Control (MPC)

The Central Controller of a μ Grid (μ GCC) system is one of the most critical components in a μ Grid architecture. It controls the power and energy flow, manages controllable loads and optimises the system operation based on information of PQ requirement, energy cost, demand-side request and special grid need. The overall control becomes more complicated if the generation capacity of DG sources is significant, which asks for advanced modeling, optimisation and control techniques. MPC is being practiced as one of the most efficient methodologies to optimise different tasks of a μ GCC. Its optimisation strategy is based on a prediction model which is employed to predict the behavior of the controlled plants over a finite receding horizon in future, as shown in Fig 6.1 [139]. In each discrete time step an open loop optimal control (u) problem is formulated by measured and predicted inputs/outputs (y) under certain objective functions. In the optimal solution, only the control action for current time step (k) is implemented in the plant. This routine is repeated in subsequent intervals with new measurements and updated plant information. MPC is technically favorable because it naturally incorporates prediction model and constraints that can ensure the μ Grid is operating along the desired path [140].

6.3 Economic Model Predictive Control (EMPC)

EMPC is a Receding Horizon Control (RHC) strategy that differs from standard MPC in that its action is computed on-line by minimising an objective function that is related to some economical aspects of the system management rather than control objectives, such as stability or tracking performance. The potential of EMPC for power management has been investigated in [141], where such a method was used to operate a portfolio of power generators and consumers so that the cost of producing the required power is minimised. Following the same lines, the above problem has been investigated in the presence of massive energy storage facilities in [142]. A more efficient formulation of EMPC has been presented in [143] for the minimisation of the production cost. A supervisory control system via MPC has been applied in [144] that minimises a suitable cost function while computing power references for wind and solar PV systems at each sampling time. A mathematical model of a μ Grid system has been presented in [145] and this is used for the on-line optimisation of the μ Grid running cost via an MPC scheme. Wang et al. in [146] focused on a moving horizon optimisation strategy in charge of ensuring the match between RE generation and demand. An optimisation approach used to satisfy the demand side fluctuations via the active use of the intermittent resources has been proposed in [147]. A generic MPC scheme has been developed in [148] to decide the optimal number of generators to meet the load demand and minimise the operational cost based on unit commitment. A balance of power sharing between decentralised energy generators, load demand and integration to the grid has been achieved in [149] by using a MPC approach. In [150] a tiered power management system, including an advisory layer and a real-time layer to address optimisation, reliability and feasibility of the system

has been proposed. An energy management system for RE based μ Grid is proposed in [151] where a control RHC strategy has been used for the unit commitment.

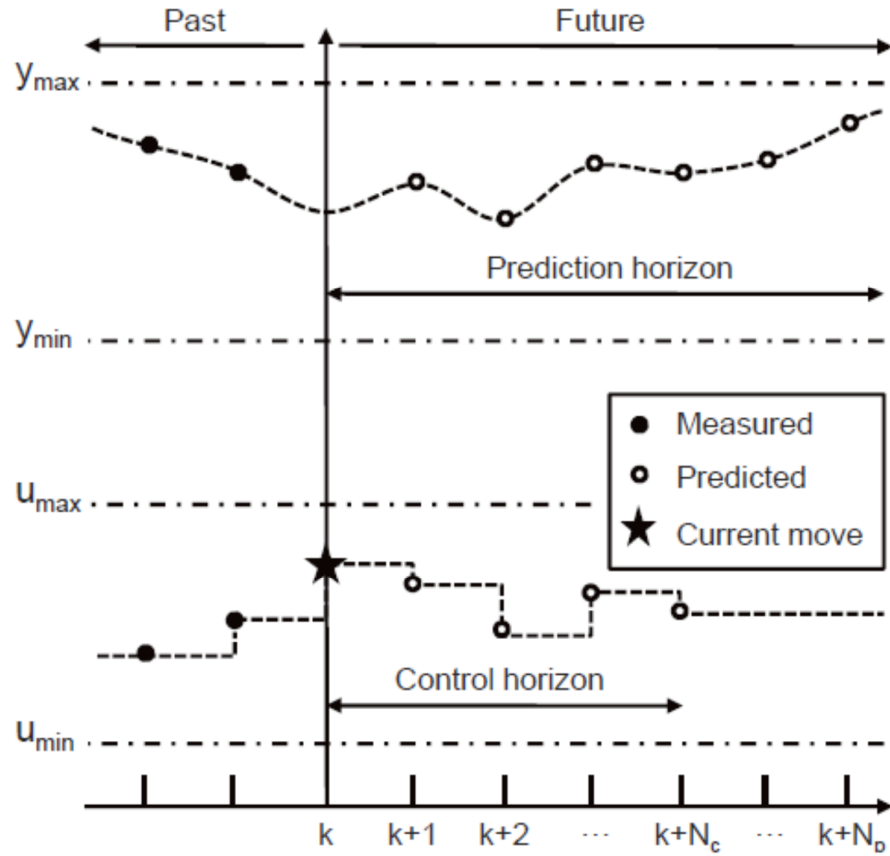


Fig 6.1 Basic MPC scheme

6.4 Optimisation

The control strategy adopted by the C- μ GCC is crucial to facilitate the power flow among the generators, the storage unit and the loads. In this respect, the control algorithm for C- μ GCC has to manage the power shared among the prosumers on the basis of the energy demand at the consumer sides, the energy produced by the μ Gens and the buying/selling tariff related to the energy exchange with the external main grid. The controlling capability of the C- μ GCC is being improved through an EMPC approach operating at the pricing level, as shown in Fig 6.1 that can fulfill the goal of the operational control of the cluster. With a central controller it is capable of

satisfying the demand at prosumer side and, at the same time, optimising the various C- μ Grid contrasting constraints. Emphasis here is being given to the operational constraints related to the battery lifetime, so that the maintenance and replacement cost would be reduced.

Notice that none of the mentioned works consider in an explicit way any constraints related to component lifetime. However, a proper management of the components of the system aimed at alleviating their degradation should lead to benefit in terms of reduction of both maintenance and replacement cost.

From this perspective, in this chapter, an EMPC framework is developed for the optimal real time power dispatch in a C- μ Grid while minimising the operational costs of the energy system. Unlike other existing works on the topic, the proposed strategy comes equipped with the capability of taking into account in an explicit way the lifetime of the battery during the computation of the control commands.

Two distinct features of this analysis are: (i) introducing an economic cost index to the optimisation problem and (ii) adding an explicit constraint on the desired lifetime of the battery in the optimisation problem.

6.4.1 Operational Goals

Different criteria may be taken into account for managing a C- μ Grid. The model of C- μ Grid here has been considered same as chapter 4, section 4.6.1. In this chapter and according to a given context, the operational goals in the management and optimisation of the C- μ Grid system are of three kinds: 1) *economics*; 2) *safety*; and 3) *durability*. They are stated, respectively, as follows:

1) to provide a reliable electricity supply minimising the power purchased from the external grid

2) to guarantee the availability of enough energy in the battery to satisfy the consumers' stochastic demand under the stochastic power flow provided by the wind turbines

3) to plan an optimised battery schedule that guarantees a sufficiently long lifetime.

As stated in chapter 4, section 4.6.1; Fig 4.4; the economic goal of the C- μ Grid could be achieved by minimising $\alpha(t)u_g(t)$ when buying and maximising $-\beta(t)u_g(t)$ when selling. As a consequence, a supervisor for the grid must also decide if $u_g(t)$ has to be positive or negative. All these requirements lead to the following optimisation problem formulation involving both Boolean and real variables. In order to avoid a mixed-integer program, the above criteria into a standard optimisation problem is encoded first by recasting $u_g(t)$ as:

$$u_g(t) = u_g^+(t) - u_g^-(t) \quad (6.1)$$

where

$$0 \leq u_g^+(t) \leq \bar{u}_g$$

$$0 \leq u_g^-(t) \leq \underline{u}_g \quad (6.2)$$

In this way, the energy exchanged with the grid $u_g(t)$ is split into two virtual flows: 1) the sold energy $u_g^-(t)$ and 2) the bought energy $u_g^+(t)$. Secondly, the above formulation allows the adoption of the following performance indicator:

$$J_E(t) \triangleq \alpha(t)u_g^+(t) - \beta(t)u_g^-(t) \quad (6.3)$$

where J_E is a pure economic cost as it is directly related to the buying/selling operations of the C- μ Grid. Interesting enough, it can be proved that by minimising the above cost $\alpha(t)u_g(t)$ and $\beta(t)u_g(t)$ can be minimised and maximised respectively depending on the sign of $u_g(t)$. In fact, J_E enjoys the following property:

Proposition 1: $J_E(t)$ is an upper bound for the actual cost $\alpha(t)u_g(t)$ during a purchase operation. On the contrary, $-J_E(t)$ is a lower bound for $-\beta(t)u_g(t)$ during a selling operation;

$$J_E(t) \geq \alpha(t)u_g(t) > 0, \quad \text{if } u_g(t) > 0 \quad (6.4)$$

$$0 \leq -J_E(t) \leq -\beta(t)u_g(t), \quad \text{if } u_g(t) < 0 \quad (6.5)$$

Proof: Because $\alpha(t) \geq \beta(t)$, one has that

$$-\beta(t)u_g^-(t) \geq -\alpha(t)u_g^-(t) \quad (6.6)$$

Then, by adding the same quantity $\alpha(t)u_g^+(t)$ to both sides of the above inequality it can be obtained

$$J_E(t) = \alpha(t)u_g^+(t) - \beta(t)u_g^-(t) \geq \alpha(t)u_g^+(t) - \alpha(t)u_g^-(t) = \alpha(t)u_g(t) \geq 0$$

Analogously, (6.5) can be proved by considering again $\alpha(t) \geq \beta(t)$ and $u_g(t) < 0$. In fact $-\alpha(t)u_g^+(t) \leq \beta(t)u_g^+(t)$ results and by adding $\beta(t)u_g^-(t)$ to both sides of the above equation, it is obtained:

$$\begin{aligned} 0 \leq -J_E(t) &= -\alpha(t)u_g^+(t) + \beta(t)u_g^-(t) \leq -\alpha(t)u_g^+(t) + \alpha(t)u_g^-(t) \\ &= -\beta(t)u_g(t) \end{aligned}$$

The safety goal could be achieved by enforcing the safety constraint (6.7), which can be conveniently reformulated as a soft constraint in the following way:

$$x(t) \geq \underline{x} - \xi(t) \geq 0 \quad \forall t \quad (6.7)$$

where $\underline{x} \in \mathbb{R}$ is a safety threshold on the minimum level of energy stored in the battery always to be ensured. It is empirically estimated and kept at a desired larger value to avoid the risk of a deep discharge of the battery due to the uncertainty in predicting the future energy demand. As a result, a corresponding safety performance index

$$J_s(t) \triangleq \xi^2(t) \quad (6.8)$$

is stated.

Finally, the third goal (durability) can be achieved by considering the following performance index:

$$J_D(t) \triangleq u_b^2(t) \quad (6.9)$$

which aims at reducing the charge/discharge operation.

6.4.2 EMPC for C- μ Grid Operational Goal

The main goal of the operational control of μ Gird at a pricing level is to satisfy the demand at the consumer side and optimise, at the same time, the management policies expressed as a multi-objective optimal control problem. Hence, MPC seems to be suitable to control a C- μ Grid because of its capability to efficiently deal with multivariable dynamic constrained systems and compute proper actions to achieve the optimal performance according to a user-defined cost function. Moreover, the MPC design follows a systematic procedure [152], which generates the control input signals to the plant by combining a prediction model and a RHC strategy.

In particular, two EMPC strategies have been introduced here that deal with the economics and safety goals in the same way but adopt different criteria to cope with the durability goal. Both strategies are based on the control scheme depicted in Fig. 6.2, where the C- μ GCC of the μ Grid to be designed makes use of the current state of the battery and wind generation and load demand forecasts. Although forecasts usually differ from real data, there has been assumed in this chapter for simplicity that the supervisor has perfect knowledge of the future evolutions of the mentioned quantities (the forecasting error is assumed to be zero).

The first EMPC algorithm will be referred to hereafter as MPC_1 . Given a prediction horizon $H_p = 48$, and control objectives [see (6.3) and (6.8)] aggregated in

a performance index $J : \mathbb{R}^{H_p \times (H_p - 1)} \rightarrow \mathbb{R}$, the MPC₁ design problem consists of solving the following finite-horizon optimal control problem:

$$J_1^* \triangleq \min_{u_g^+, u_g^-, u_b, \varepsilon} \sum_{k=t}^{t+H_p-1} [\gamma_E J_E(k) + \gamma_S J_S(k) + \gamma_D J_D(k)] \quad (6.10a)$$

$$x(k+1|t) = \tau x(k|t) + u_b(k|t) \quad \forall k \in \mathbb{I}_{t:t+H_p} \quad (6.10b)$$

$$d_l(k|t) = -u_b(k|t) + u_g(k|t) + d_s(k|t) \quad (6.10c)$$

$$x(k+1|t) \leq \bar{x} \quad \forall k \in \mathbb{I}_{t:t+H_p} \quad (6.10d)$$

$$-\underline{u}_b \leq u_b(k|t) \leq \bar{u}_b \quad \forall k \in \mathbb{I}_{t:t+H_p-1} \quad (6.10e)$$

$$0 \leq u_g^+(k|t) \leq \bar{u}_g \quad \forall k \in \mathbb{I}_{t:t+H_p-1} \quad (6.10f)$$

$$0 \leq u_g^-(k|t) \leq \underline{u}_g \quad \forall k \in \mathbb{I}_{t:t+H_p-1} \quad (6.10g)$$

$$x(k+1|t) \geq \underline{x} - \xi(k+1|t) \geq 0 \quad \forall k \in \mathbb{I}_{t:t+H_p} \quad (6.10h)$$

$$(x(t|t), d_l(t|t), d_s(t|t)) = (x(t), d_l(t), d_s(t)) \quad (6.10i)$$

Then, according to the RHC strategy, one applies only the first samples $u_g^+(t|t)$, $u_g^-(t|t)$ and $u_b(t|t)$ of the optimal sequences:

$$\overset{u^+}{\rightarrow}_g(x(t)) \triangleq [u_g^+(t|t), \dots, u_g^+(t+H_p-1|t)]$$

$$\overset{u^-}{\rightarrow}_g(x(t)) \triangleq [u_g^-(t|t), \dots, u_g^-(t+H_p-1|t)]$$

$$\overset{u_b}{\rightarrow}(x(t)) \triangleq [u_b(t|t), \dots, u_b(t+H_p-1|t)]$$

respectively. At the next time instant, the prediction horizon is shifted one time instant ahead and the optimisation is restarted with new feedback measurements and

updated prediction to compensate unmeasured disturbances and model inaccuracies. This procedure is repeated at each future time instant (see Fig. 6.3).

Note that in the above optimisation problem, the durability goal is enforced by including the term $\gamma_D J_D(t)$ in the optimisation cost (6.10a). In a different approach, such a goal can be dealt with by including explicit constraints involving the battery lifetime as in the following second EMPC formulation, denoted hereafter as MPC₂:

$$J_2^* \triangleq \min_{u_g^+, u_g^-, u_b, \varepsilon} \sum_{k=t}^{t+H_p-1} [\gamma_E J_E(k) + \gamma_S J_S(k)] \quad (6.11a)$$

$$q(k+1|t) = q(k|t) - |u_b(k|t)| \quad \forall k \in \mathbb{I}_{t:t+H_p-1} \quad (6.11b)$$

$$\frac{D(t)}{2} \sum_{k=t}^{t+H_p-1} (|u_b(k|t)|) \leq q(t) \quad (6.11c)$$

where the quantity $D(t)$ is the desired remaining amount of days at time t before the battery needs replacement. Roughly speaking, the above solution is computed in such a way that if the same quantity of energy $\sum_{k=t}^{t+H_p-1} (|u_b(k|t)|)$ was transferred to/from the battery from time t onward, the battery would have a lifetime at least equal to $D(t)$. Even in this case the RHC approach applies and, furthermore, the $D(t)$ should be decreased by 1 at each time t instant, i.e, $D(t+1) = D(t) - 1$.

Remark 1: Despite the intuitive formulation of the RHC strategy, the on-line tuning of an EMPC controller is not trivial or systematic. The EMPC tuning parameters for the given cost function are usually the prediction horizon H_p and the weighting terms γ_E, γ_S and γ_D . In this respect, it is worth remarking that a 48-h prediction horizon has been chosen because two days is a reasonable time for wind forecasting. Longer prediction horizons could lead to obtain solutions with better performance, anyway the underlying optimisation problem would result more complex and it would not be realistic to assume the availability of accurate long-time

wind forecast. For a discussion on the effect of different horizons for MPC in μ Grids please refer to [153].

Remark 2: It is worth commenting that in problem (6.11) $|u_b(k|t)| \rightarrow 0$ when $D(t) \rightarrow \infty$. This means that the activity of the battery results in very limited or may be nonexistent if the desired remaining amount of days before its replacement is too high.

Remark 3: Although several and more complex battery models exist for the battery, in this work, we chose a simple linear model with the aim to deal with low-computationally demanding programs. In fact, thanks to the simplicity of the battery model, the above-introduced optimisation problems belong to the family of quadratic programming problems that can be solved in polynomial time with interior-point methods. For this reason, we were able to perform the deep economic analysis presented in the next section by performing several simulations over a period of one year. Each simulation required about 3 h of CPU time for its completion.

Thus, the use of a more complicated model for the battery would have increased the simulation time further. For instance, if we considered two different dynamical models for the charging and discharging phases, respectively, the above MPC schemes would be based on a mixed-integer program [154]. As is well known, including integer variables enormously increases the modeling power, at the expense of more demanding numerical complexity. In fact, the use of integer programming leads in general to Nondeterministic Polynomial-complete optimisation problems and there is no known polynomial-time algorithm which is able to solve it and even small problems may be hard to solve. In this case, we would have to include 48 binary variables and, as a consequence, the EMPC algorithm should have to select the best system operating trajectory among 2^{48} possible configurations.

Remark 4: As far as the wind forecasting is concerned, the assumption of perfect forecast is not very unrealistic because we deal with two-day-long prediction horizon only, that is a reasonable period to get good forecasts for wind [155]. Relaxing this assumption would slightly increase the complexity of the optimisation problem in order to deal with uncertainties due to the forecast error. In particular this scheme can be extended by following the approach presented in [149] where such an aspect has been taken into account to solve a similar MPC problem for μ Grid management. Usually in the case where uncertainty is present, a robust MPC scheme should be considered (in this respect [156] is an exhaustive work on the topic).

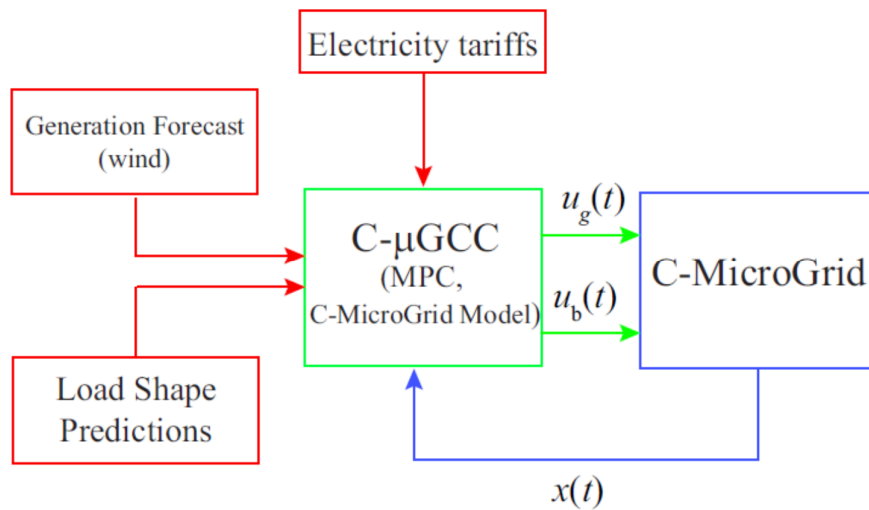


Fig 6.2 C- μ GCC scheme with EMPC

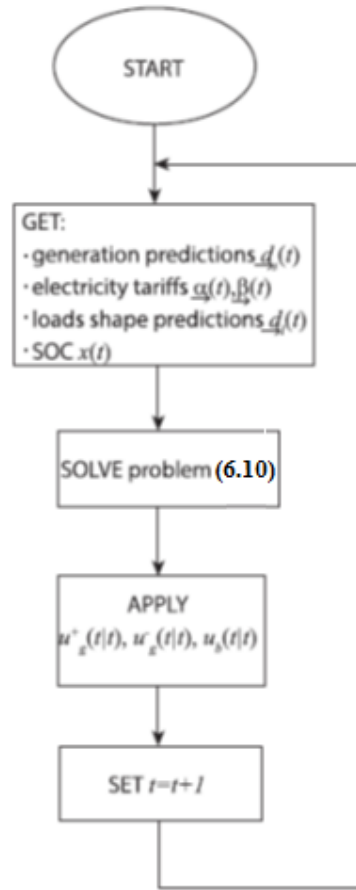


Fig 6.3 EMPC-based algorithm flowchart

6.5 Simulation Study

All results have been obtained by considering a one year real-demand scenario (with 1 hour of sampling time), and $H_p = 48$. For all MPC strategies, the control objectives in (6.11a) have been prioritized with $\gamma_E = 1$, $\gamma_S = 0.001$ and $\gamma_D = 0.0001$, which proved to be suitable after a trial-and-error tuning strategy. The network has been simulated by using the same model used to design the EMPC controller but fed with real energy demand. All simulations have been undertaken by using the Yalmip interpreter and the CPLEX solver, all running in MATLAB c8.2 environment, running on an Intel Core i5-3330 machine with 3.3 GHz and 8 GB RAM.

The control strategies proposed in this chapter have been compared with a simple IF-THEN-ELSE heuristic supervision logic hereinafter referred as S-LOGIC that does not make use of any prediction and works according to the criteria discussed in section 4.6.1.

A simulation campaign has been carried out where an increasing number of turbines have been considered in order to test the robustness of the following algorithm:

- MPC₁: solving problem (6.10)
- MPC_{2-10y}: solving problem (6.11) with desired lifetime for the battery equal to 10 years ($D(0) = 10 \times 365$)
- MPC_{2-20y}: solving problem (6.11) with desired lifetime for the battery equal to 20 years ($D(0) = 20 \times 365$)
- S-LOGIC: described in 4.6.1

In Fig 6.4 incomes derived by the exchange of energy between C- μ Grid and main grid are depicted when the number of turbines increases. Incomes are computed as:

$$\sum_{t=0}^{365 \times 24} \begin{cases} -\alpha(t)u_g(t), & u_g(t) \geq 0 \\ -\beta(t)u_g(t), & u_g(t) < 0 \end{cases} \quad (6.12)$$

In the worst case where only 3 turbines were installed the C- μ Grid is constrained to buy more energy to satisfy the load demand. As a consequence, the income arising from energy exchange is negative, as shown in Fig 6.4.

In Fig 6.5 the time before battery replacement (i.e the time before $q(t) \approx 0$) is depicted. Interesting enough, only the MPC_{2-20y} strategy is able to guarantee a 20 years lifetime for the battery, thus avoiding its replacement while keeping similar performance with respect to its competitors. Such an aspect has a positive impact on the overall operational costs of the C- μ Grid over a horizon of 20 years (see Fig 6.6 – 6.9).

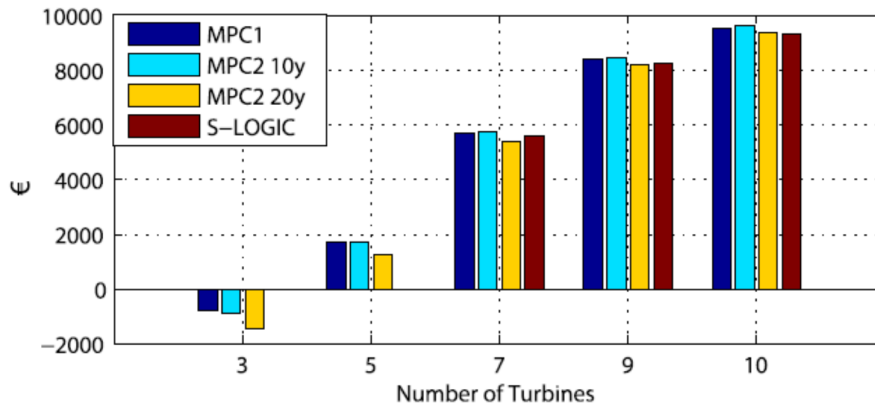


Fig 6.4 Annual income derived by energy exchange between the grid and C-μGrid

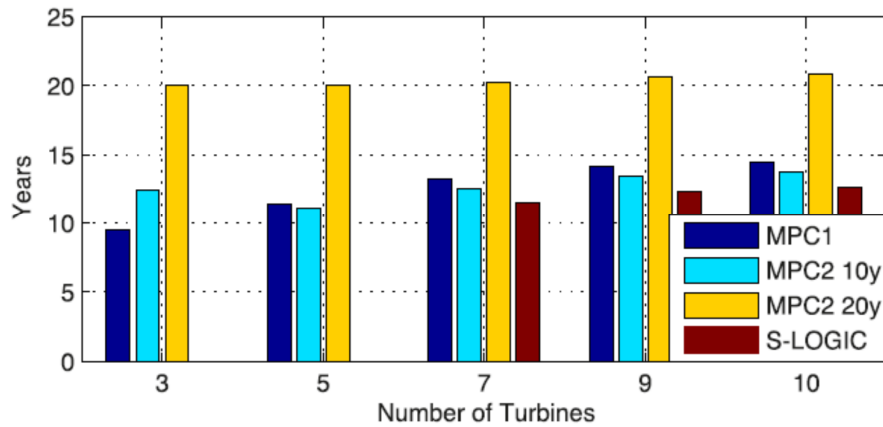


Fig 6.5 Expected battery lifetime

Fig 6.6 and 6.7 analyses the economic impact of the C-μGrid from the external Grid point of view. In this case the C-μGrid can be seen as a generator. In particular, Fig 6.6 depicts the annualised system cost, which is the annual loan payment, collecting both components price and maintenance costs. Fig 6.7 shows the COE related to the C-μGrid (sold energy plus served energy to the load).

In order to analyse the economic impact with respect to the C-μGrid point of view, the total cost arising from C-μGrid management (including the incomes derived from the energy export as a negative cost) in Fig 6.8. Such cost has been used to

compute the cost of demanded load energy in the C- μ Grid (μ COE), which represents the price of a kWh for the consumers in the C- μ Grid. It is evident from the above described Figs (6.7 – 6.9) that, the C- μ Grid shows better economic performance with the maximum number of turbines. Moreover, it is worth pointing out that in the case of MPC2-20y both the COE and the μ COE are reduced by 25% with respect to S-LOGIC. Hence, the strategy used to manage the C- μ Grid has not a marginal impact on the economic aspects. It is evident that even in the best case; the payback period is no shorter than 10 years, as shown in Fig 6.10.

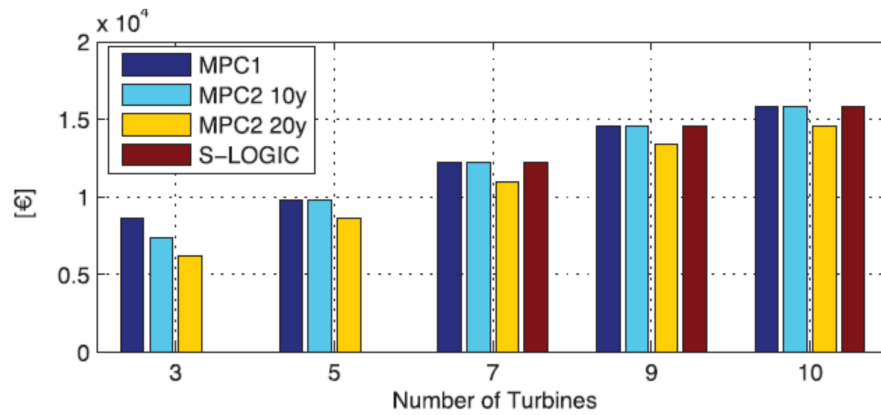


Fig 6.6 Annualised system cost (including component and maintenance costs)

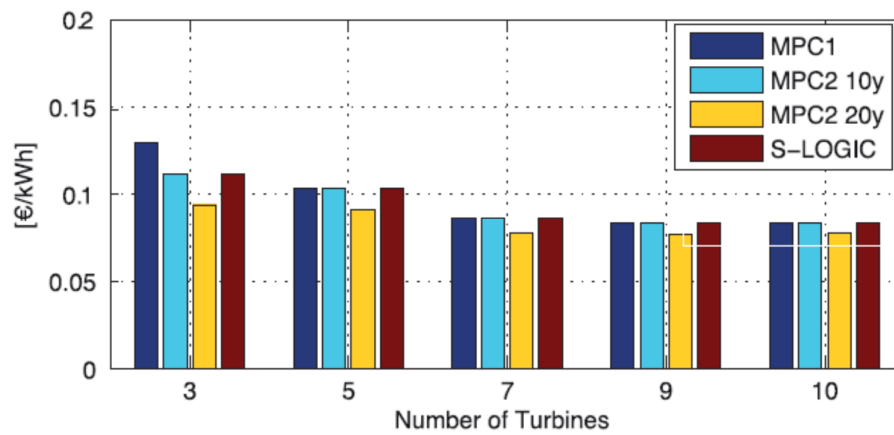


Fig 6.7 Cost of energy

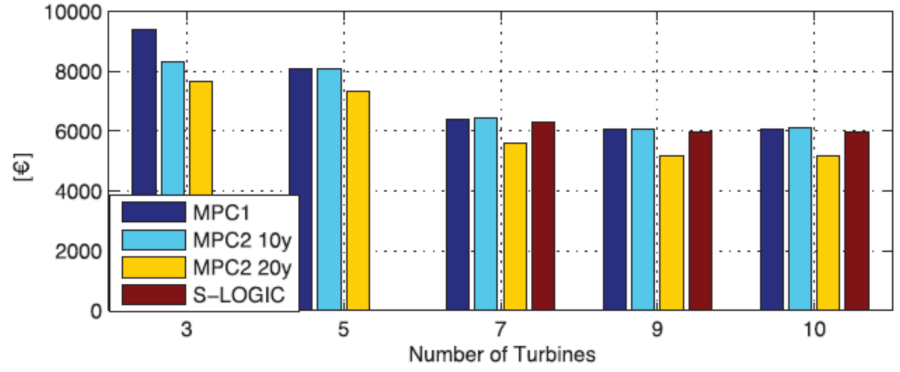


Fig 6.8 Annual net total cost (system cost minus income)

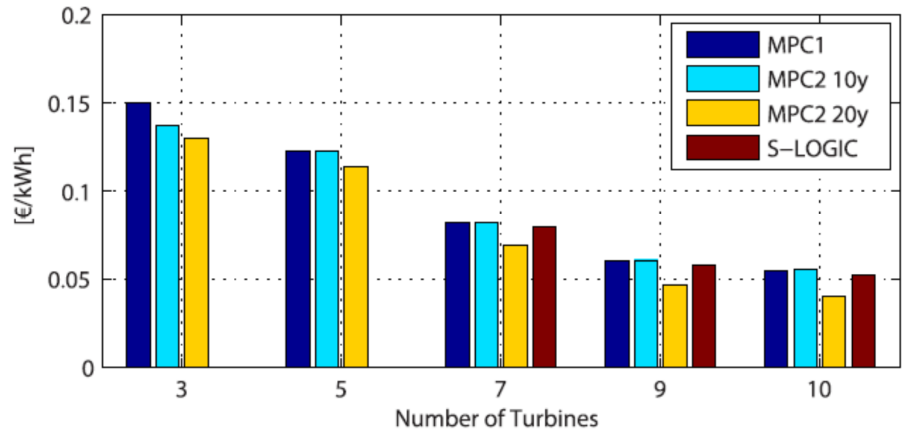


Fig 6.9 μCOE perspective that is equivalent to the price of demanded kWh for the consumers

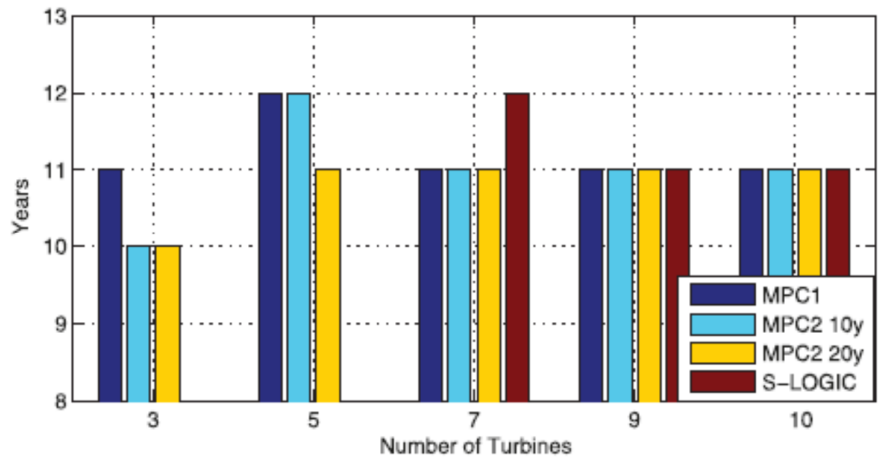


Fig 6.10 Payback curve with respect to traditional scenario

To confirm the effectiveness of the EMPC approach, the time-domain plots pertaining to the first week of the simulation horizon are also included, as shown in Fig (6.11 - 6.13). There, only MPC2-20y and S-LOGIC have been compared in the case of only seven turbines operating. It is evident from Fig 6.13 (a) that for the

MPC_{2-20y} case the C- μ Grid buys energy only when the purchasing tariff $\alpha(t)$ is low, as shown in Fig 6.13 (b). On the contrary, the S-LOGIC buys energy when the battery is almost empty and gets a higher annual income thanks to a deeper usage of the battery.

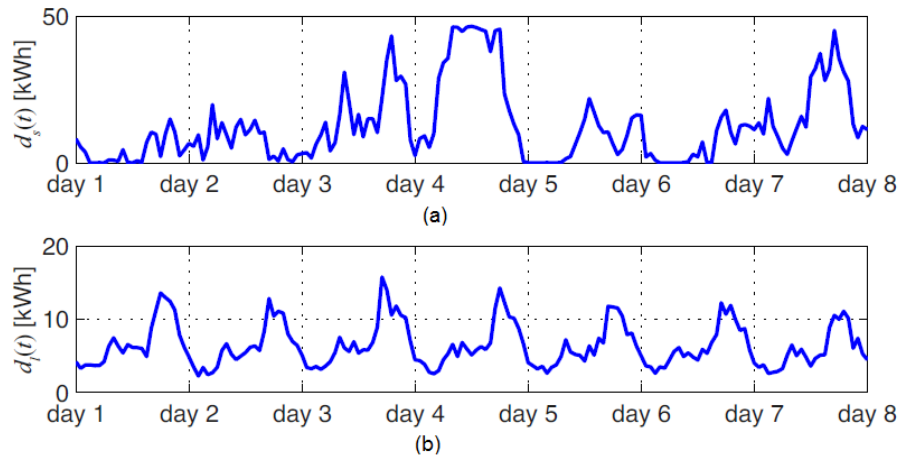


Fig 6.11 (a) Generated energy by the μ Gens and (b) load demand by the consumers

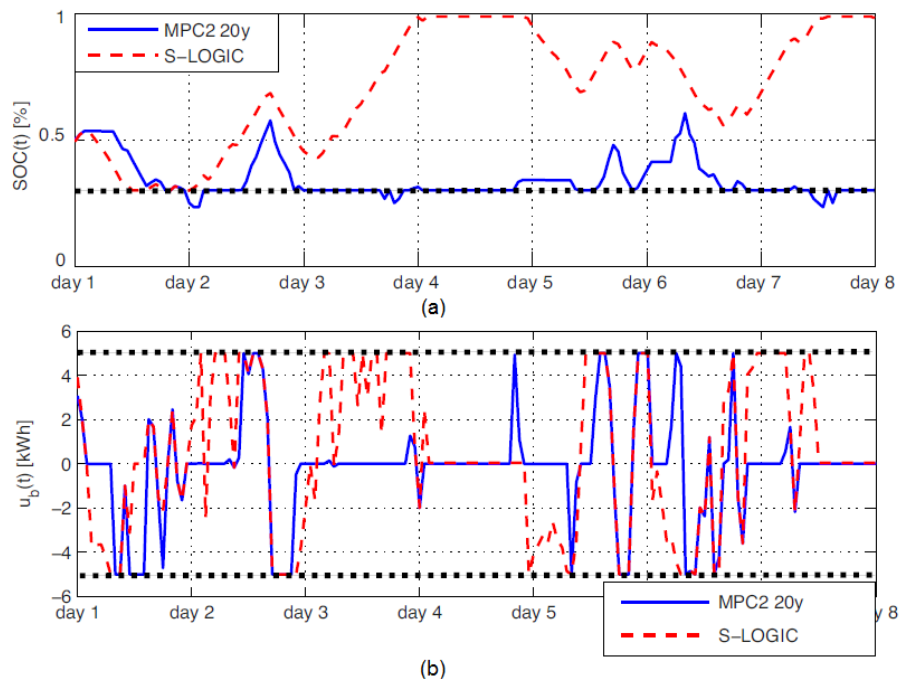


Fig 6.12 (a) State of charge (SOC); (b) energy transferred to/from battery

However, the advantages of the MPC_{2-20y} strategy rely on the systematic battery degradation reduction, robustness, and design flexibility when the problem setup changes. In Fig 6.13(c), the optimisation cost $J_E(t)$ related to economic goal is

depicted in order to verify Proposition 1. In fact, it effectively behaves as an upper bound for both $\alpha(t)u_g(t)$ and $\beta(t)u_g(t)$.

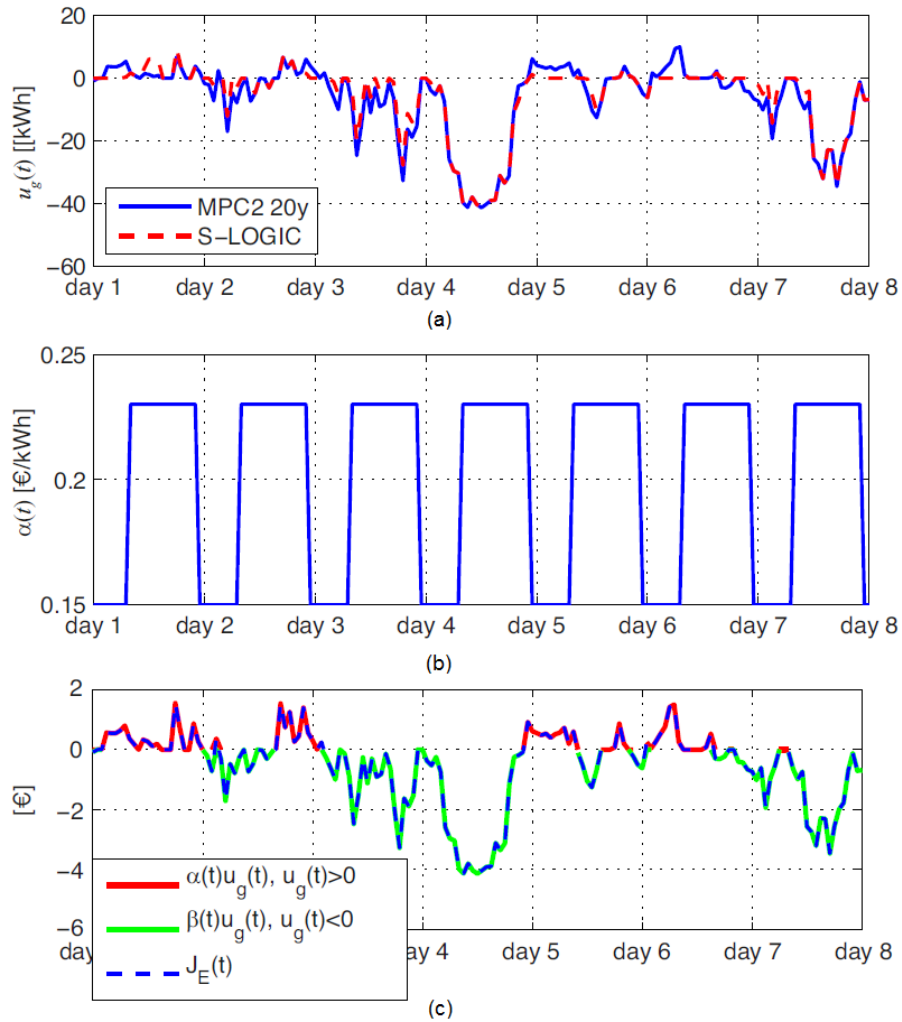


Fig 6.13 (a) Energy exchanged with the grid; (b) buying tariff $\alpha(t)$; (c) optimisation cost $J_E(t)$

6.6 Conclusion

C- μ Grid can become a transitional solution in countries where policies for μ Gens are present while for μ Grid do not exist yet. An EMPC approach has been applied here to design the central controller of a C- μ Grid system. It has been shown that it has the capability to efficiently deal with multivariable dynamic constrained systems and

predicts its actions properly in order to achieve the optimal performance according to the user defined cost functions.

A comparative analysis undertaken for the same proposed system and has shown that a heuristic approach is not feasible when the number of μ Gen systems is less than seven. On the contrary, the control actions provided by the EMPC approach were able to practically operate the C- μ Grid also for a lower number of wind turbines (three in the examples considered). The EMPC approach was shown to be able to guarantee a 20-year lifetime for the battery avoiding its replacement while satisfying the other required criteria. In particular, it has been shown that the control strategy may have a strong impact on the overall cost of the system, as the EMPC approach reduced the COE remarkably.

Chapter 7

Conclusion and Future Work

7.1 Conclusion

To achieve the goal of decarbonising the electric grid by 2050 and empowering the energy citizen as set out in Irish energy policy, importance has been given to increase the clean energy penetration from renewable energy based distributed generation systems. Therefore, strategies that will ensure the most efficient, reliable and economic operation and management of μ Grids are envisaged.

As a part of this research, a details literature review is performed on the existing μ Grid systems. It is realised that reducing the number of system components, improving the system integrity with storage, improving source and load efficiency, reducing the installation and management cost can enhance the efficiency, stability and viability of μ Grid systems. The review also shows that PV based μ Gen system is not economically viable option for Ireland. Along with this, the REFIT cost for PV μ Gen system is also opted out.

Analysis started with a proposed methodology to achieve the sustainability of RE based μ Gen systems. Results show that reducing the component cost (PV/Wind), waiving VAT or increasing REFIT cost could make the systems economically viable for Irish condition. On the other hand, due to interfacing a large number of μ Gen

systems with multiple inverters, the low voltage distribution network is facing some complex challenges as the system is not capable of handling bi-directional power flow and a large number of μ Gen. As a result, various technical problems associated with protection and control systems arise.

The review identifies that μ Grid has technical advantages over the μ Gen systems and also can take part in demand response and local energy market programs to increase its value stream. Therefore, a new structure/integration method for RE-based μ Gen systems in the distribution network, termed as Community- μ Grid (C- μ Grid), has been proposed here. The local community can develop a C- μ Grid system by integrating their existing/newly purchased μ Gen systems. The new system could (i) allow for the greater penetration of RE in the electricity supply network with improved stability; (ii) reduce the production cost of energy to achieve sustainability; (iii) empower the energy citizen through active participation of prosumers in the energy trading mechanism; (iv) move towards the development of a model and strategy for an efficient μ Grid system. Where μ Grid policy does not exist, the present study shows that C- μ Grid system proposes an improved solution to utilize the μ Gen REFIT policy in Ireland.

Analysis also confirms that a C- μ Grid system can reduce the number of system components and cost, also improves the system integrity. Moreover introducing storage in the system can improve the efficiency and stability of the distribution grid as well as μ Grid network. Thus the energy efficient and cost-effective μ Grid system for Ireland (objective I as mentioned in section 1.6) can be achieved by the proposed μ Grid structure, called C- μ Grid. It was found that with a simple IF-THEN-ELSE heuristic supervision control, the sustainability of C- μ Grid system can be reached.

The energy efficiency of the proposed C- μ Grid can be improved by introducing an efficient energy management system through the supply or demand side control. Therefore a simple DSM strategy is applied to the proposed system where the flexible energy demand is shifted to follow the RE generation pattern. This helps to maximise the RE consumption by the consumers/prosumers and thus it reduces the peak power and energy purchase from the grid. It is expected that the control and management technologies are or will be available in future to maximise the operational flexibility of the demand side appliances to synchronise with the smart grid network. Furthermore, it is found that the storage capacity of the system can be reduced up to 50% as compared to the case without DSM technique. All these steps help to decrease the COE of the system. This has strengthened the research to obtain the objective (II) as mentioned in section 1.6.

Optimisation of the battery storage can further reduce the COE and thus the system can become economically more viable. Therefore, controlling the capability of the C- μ GCC is further improved through an EMPC approach operating at the pricing level that can fulfil the goal of the operational control of the proposed system. The operational constraints related to the battery lifetime is applied, so that the maintenance and replacement cost would be reduced. It helps to improve the battery performance with optimised storage and thus can reduce COE of the system. Thus optimisation of the uncontrollable RE based C- μ Grid energy management system (objective III) with storage has been achieved.

7.2 Future Work

Several important points needs to be investigated but could not be included in the scope of this research work. The following issues have been identified as possible topic of further research work in this area:

- Sustainability of a C- μ Grid system including various uncontrollable RE sources such as (solar PV, micro hydro, bio-mass) could be analysed. Hybrid C- μ Grid system could be another topic of research where different RE sources can be installed. Also DC and AC lines could be combined in the same C- μ Grid system for better reliability.
- Different REFIT prices from other countries could be implemented in the system and new REFIT price could be proposed for the policy.
- Feed-in-tariff could be varied and investigated to determine the feasible option for the system.
- As in Ireland there is no μ Grid/C- μ Grid policy, few technical and economical policies could be proposed.
- Performance of different kinds of storage system could be investigated.
- Islanding operation of the C- μ Grid system could be investigated.
- Power electronic operation has not being considered in this research work. This could be a promising topic to investigate in future research.

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Appendix

Code for C- μ Grid System with S-LOGIC Controller

```
clear %cleaning program memory
close all %close all the previous figures
clc %clean the command window
load real_data_one_year
%% Simulation paramters
%Tmax = length(is); % simulation period [h]
Tmax = 365*24; % 6 days simulation
tsim = 0:Tmax-1; % simulation time [h]
%NH = 10; %number of houses
%Iimax = 1.8; %maximum amount of power for on house
%Iismax = 60; %maximum amount of power for the source
reducing_factor=0.75;
loss_factor=0.9997;
is=reducing_factor*is; %reducing produced energy (worst case
scenario)
alpha = Tarif(1:length(tsim),1); % buying tarif
beta = Tarif(1:length(tsim),2); % selling tarif
epsilon=10e-15;
%% Initial conditions %%

X0 = 144*0.5; % initial energy stored in the battery

% il = (NH*Iimax/2)+(NH*Iimax/2)*sin(2*pi*1/(24)*tsim); %load profile
% is = (Iismax/2)+(Iismax/2)*sin(2*pi*1/(24)*tsim+2*pi*1/(12));
%source profile

%% Constraints

xmin = 144*0.3; %minimum stored energy
xmax = 144; %maximum stored energy
ib_max = 5; %maximum energy transferred in an hour to the battery
ib_min = 5; %maximum energy transferred in an hour from the battery
id_max_s = 60; %maximum amount of sold energy energy per our
id_max_b = 10; %maximum amount of baught energy energy per our

%% Simulation

xt = zeros(1,length(tsim)); %state of charge profile during the
simulation
xt(1) = X0;
Ib = zeros(1,length(tsim)); %energy from/to the battery profile
Id_sold = zeros(1,length(tsim)); %
Id_baught = zeros(1,length(tsim));

for t=0:Tmax-1

    [ib_t id_s_t id_b_t] =
    simple_logic_fnc_constraints(xt(t+1),il(t+1),is(t+1),xmax,xmin,ib_max
    ,ib_min,id_max_s,id_max_b,loss_factor);
    xt(t+1+1) = loss_factor*xt(t+1)+ib_t; %state of charge updating
    Ib(t+1) = ib_t;
    Id_sold(t+1) = id_s_t ;
    Id_baught(t+1) = id_b_t;
```

```

    t/Tmax*100
    if abs(il(t+1)+Ib(t+1)+Id_sold(t+1)-Id_baught(t+1)-
is(t+1))>epsilon

        disp('energy loss!!!')

        -Ib(t+1)-Id_sold(t+1)+Id_baught(t+1)+is(t+1)
        il(t+1)
        pause
    end
end

subplot(5,1,1), plot(tsim(1:length(tsim)),xt(1:length(tsim))/xmax)
hold on
subplot(5,1,1), plot(tsim(1:length(tsim)),ones(1,length(tsim)),'r')
grid
ylabel('storage')
subplot(5,1,2), plot(tsim(1:length(tsim)),Ib(1:length(tsim)))
grid
ylabel('energy from battery')
subplot(5,1,3), plot(tsim(1:length(tsim)),Id_baught(1:length(tsim))-
Id_sold(1:length(tsim)))
grid
ylabel('sold/baught energy ')
subplot(5,1,4), plot(tsim(1:length(tsim)),is(1:length(tsim)))
grid
ylabel('prodeced energy')
subplot(5,1,5), plot(tsim(1:length(tsim)),is(1:length(tsim))-
il(1:length(tsim)))
grid
ylabel('excess energy')

figure
subplot(3,1,1), plot(tsim(1:length(alpha)),alpha)
grid
ylabel('buying price')
subplot(3,1,2), plot(tsim(1:length(beta)),beta)
grid
ylabel('selling price')
subplot(3,1,3),
plot(tsim(1:length(tsim)),alpha(1:length(tsim)).*Id_baught(1:length(t
sim))'-beta(1:length(tsim)).*Id_sold(1:length(tsim))')
grid
hold on
subplot(3,1,3),
plot(tsim(1:length(tsim)),alpha(1:length(tsim)).*(Id_baught(1:length(
tsim))'-Id_sold(1:length(tsim))'),'r')
subplot(3,1,3),
plot(tsim(1:length(tsim)),beta(1:length(tsim)).*(Id_baught(1:length(t
sim))'-Id_sold(1:length(tsim))'),'g')
legend('Optimisation cost','buying cost','selling cost')

cost=0;
for i=1:length(tsim)
    if (Id_baught(i)-Id_sold(i)>0)
        cost=cost+alpha(i)*(Id_baught(i)-Id_sold(i));
    else
        cost=cost+beta(i)*(Id_baught(i)-Id_sold(i));
    end
end
end

```

```

disp('----- Costes after at the end of simulation -----')
cost
disp('----- Battery usage -----')
sum(abs(Ib))
disp('----- Battery lifetime -----')
lifetime = (250000*(Tmax/(365*24))/ans)
% simple_logic_fnc

function [ib_t id_s_t id_b_t]=simple_logic_fnc(x,il,is,x_max)
%x state of charge
%il demanded energy
%is produced energy

if is>il
    if x+is-il>=x_max
        ib_t=x_max-x+is-il;
        id_s_t= is-il-ib_t;
        id_b_t=0;
    else
        ib_t=is-il;
        id_s_t= 0;
        id_b_t=0;
    end
else
    if x>=il-is
        ib_t=-(il-is);
        id_s_t= 0;
        id_b_t=0;
    else
        ib_t=-x;
        id_s_t= 0;
        id_b_t=il-is-ib_t;
    end
end

% simple_logic_fnc_constraints

function [ib_t id_s_t
id_b_t]=simple_logic_fnc(x,il,is,x_max,x_min,ib_max,ib_min,id_max_s,i
d_max_b,loss_factor)
%INPUT
%x state of charge
%il demanded energy
%is produced energy
%x_max maximum storable energy in the battery
%ib_max maximum energy towards the battery
%ib_min maximum energy from the battery

%OUTPUT
%ib_t exchanged energy with battery
%id_s_t sold energy
%id_b_t bought energy

if is>il
    if min(ib_max,is-il)>=x_max-x % battery almost full

        ib_t=x_max-x;

```

```

else
    ib_t=min(ib_max,is-il);

end
id_s_t= min(id_max_s,is-il-ib_t);
id_b_t=0;
else
    if x-x_min>=il-is
        ib_t=-min(ib_min,(il-is));
    else
        ib_t=-min(ib_min,x-x_min);

    end
    id_s_t= 0;
    id_b_t=min(id_max_b,il-is+ib_t);
end

```

Code for C-uGrid System with EMPC Controller

```

clear
close all
clc
load real_data_one_year
%% Simulation paramters
Tmax = length(is); % simulation period [h]
Tmax = 365*24; % 364 days simulation
tsim = 0:Tmax-1; % simulation time [h]
reducing_factor=0.5;
loss_factor=0.9997;
is=reducing_factor*is; %reducing produced energy (worst case
scenario)
Ws=1;
Wb=1;
%Wx=0.001;
Wx=0.0001;
xs=144*0.4;
epsilon=10e-5;
%% Initial conditions %%

X0 = 144*0.5; % initial energy stored in the battery

alpha = Tarif(:,1); % buying tarif
beta = Tarif(:,2); % selling tarif

%% Control Parameters

Hp = 48; % prediction horizon 0<Hp<=24

%% Constraints

xmin = 144*0.3; %minimum stored energy
xmax = 144; %maximum stored energy
ib_max = 5; %maximum energy transferred in an hour to the battery

```

```

ib_min = -5; %maximum energy transferred in an hour from the battery
id_max_s = Inf; %maximum amount of sold energy energy per hour
id_max_b = 10; %maximum amount of bought energy energy per hour

%% Simulation

xt = zeros(1,length(tsim));
xt(1) = X0;
Ib = zeros(1,length(tsim));
Id_sold = zeros(1,length(tsim));
Id_bought = zeros(1,length(tsim));

for t=0:Tmax-Hp
    [ib_t id_s_t id_b_t] =
mGCC(xt(t+1),il,is,xmin,xmax,xs,ib_max,ib_min,id_max_s,id_max_b,alpha
,beta,Hp,t,Ws,Wb,Wx,loss_factor);
    xt(t+1+1) = loss_factor*xt(t+1)+ib_t;
    Ib(t+1) = ib_t;
    Id_sold(t+1) = id_s_t ;
    Id_bought(t+1) = id_b_t;
    t/Tmax*100
    if abs(il(t+1)+Ib(t+1)+Id_sold(t+1)-Id_bought(t+1)-
is(t+1))>epsilon

        disp('energy loss!!!')

        -Ib(t+1)-Id_sold(t+1)+Id_bought(t+1)+is(t+1)
        il(t+1)
        pause
    end
    yalmip('clear')
end

subplot(5,1,1), plot(tsim(1:length(tsim)),xt(1:length(tsim))/xmax)
hold on
subplot(5,1,1), plot(tsim(1:length(tsim)),ones(1,length(tsim)),'r')
grid
ylabel('storage')
subplot(5,1,2), plot(tsim(1:length(tsim)),Ib(1:length(tsim)))
grid
ylabel('energy from battery')
subplot(5,1,3), plot(tsim(1:length(tsim)),Id_bought(1:length(tsim))-
Id_sold(1:length(tsim)))
grid
ylabel('sold/bought energy ')
subplot(5,1,4), plot(tsim(1:length(tsim)),is(1:length(tsim)))
grid
ylabel('prodeced energy')
subplot(5,1,5), plot(tsim(1:length(tsim)),is(1:length(tsim))-
il(1:length(tsim)))
grid
ylabel('excess energy')

figure
subplot(3,1,1), plot(tsim(1:length(tsim)),alpha(1:length(tsim)))
grid
ylabel('buying price')

```

```

subplot(3,1,2), plot(tsim(1:length(tsim)),beta(1:length(tsim)))
grid
ylabel('selling price')
subplot(3,1,3),
plot(tsim(1:length(tsim)),alpha(1:length(tsim)).*Id_baught(1:length(t
sim))'-beta(1:length(tsim)).*Id_sold(1:length(tsim))')
grid
hold on
subplot(3,1,3),
plot(tsim(1:length(tsim)),alpha(1:length(tsim)).*(Id_baught(1:length(
tsim))'-Id_sold(1:length(tsim))'),'r')
subplot(3,1,3),
plot(tsim(1:length(tsim)),beta(1:length(tsim)).*(Id_baught(1:length(t
sim))'-Id_sold(1:length(tsim))'),'g')
legend('Optimization cost','buying cost','selling cost')

cost=0;
for i=1:t
    if (Id_baught(i)-Id_sold(i)>0)
        cost=cost+alpha(i)*(Id_baught(i)-Id_sold(i));
    else
        cost=cost+beta(i)*(Id_baught(i)-Id_sold(i));
    end
end
disp('----- Costes after a week -----')
cost
disp('----- Battery usage -----')
sum(abs(Ib))
disp('----- Battery lifetime -----')
lifetime = (250000*(Tmax/(365*24))/ans)
%save last_sim

% mGCC function

function [ib_s id_s id_b J] =
mGCC(xt,il,is,xmin,xmax,xs,ib_max,ib_min,id_max_s,id_max_b,alpha,beta
,Hp,t,Ws,Wb,Wx,loss_factor)

%% Decision variables definitions
Ib_k=sdpvar(1,Hp);
Id_s=sdpvar(1,Hp);
Id_b=sdpvar(1,Hp);
cnc_ib=0;

%%
const = []; %constraints vector
J = 0; %cost
for k=0:Hp-1
    xt=loss_factor*xt+Ib_k(k+1);
    const = [const il(t+k+1)=-Ib_k(k+1)-
Id_s(k+1)+Id_b(k+1)+is(t+k+1)];
    const = [const xmin<=xt<=xmax];
    const = [const ib_min<=Ib_k(k+1)<=ib_max];
    const = [const 0<=Id_s(k+1)<=id_max_s];
    const = [const 0<=Id_b(k+1)<=id_max_b];
    const = [const is(t+k+1)>=Ib_k(k+1)]; % it is assumed that
battery cannot be charged from the grid
    %const = [const Id_s(k+1)<=xt-xs]; % it is assumed that energy
can be sold only if the battery is almost full

```

```

    J = J + Wb*alpha(t+k+1)*Id_b(k+1)-
Ws*beta(t+k+1)*Id_s(k+1)+Ib_k(k+1)*Wx*Ib_k(k+1);
    %J = J + Wb*alpha(t+k+1)*Id_b(k+1)-Ws*beta(t+k+1)*Id_s(k+1)+(xt-
xs)*Wx*(xt-xs);
    %J = J + Wb*alpha(t+k+1)*Id_b(k+1)-Ws*beta(t+k+1)*Id_s(k+1);% +
(Ib_k(k+1)*Ib_k(k+1))/(250000*(Hp/(365*24)));
    % %soft constraints, to be considered if xmin=0
    %cnc_ib=cnc_ib+Ib_k(k+1)*Ib_k(k+1);
end
%const = [const cnc_ib/(250000*(Hp/(365*24)))<=1/19];%constraints on
the guaranteed battery lifetime
%pp=solvesdp(const,J,sdpsettings('solver','cplex','verbose',0));
pp=solvesdp(const,J);
if pp.problem~=0
    disp('infeasible problem!!')
    pp.problem

end
ib_s=double(Ib_k(1));
id_s=double(Id_s(1));
id_b=double(Id_b(1));

```


List of Publications

- [1] L Mariam, M Basu and M F Conlon, Techno-economic Analysis of Community based μ Grid (C- μ Grid) Systems, ESEIA 2018, Dublin, Ireland
- [2] L Mariam, M Basu and M F Conlon, Energy Efficient Community based Microgrid (C- μ Grid) through Demand Side Management, ESEIA 2018, Dublin, Ireland
- [3] L Mariam, M Basu and M F Conlon, Microgrid: Architecture, Policy & Future Trends, Renewable & Sustainable Energy Reviews, Vol 64, pp 477-489, 2016
- [4] F Tedesco, L Mariam, M Basu, A Casavola, M F Conlon, Supervision of Community Based Microgrids: an Economic Model Predictive Control approach, RE&PQJ, No.14, pp. 172-177, 2016
- [5] F Tedesco, L Mariam, M Basu, M F Conlon, A Casavola, Economic Model Predictive Control based Strategies for Cost-effective Supervision of Community Microgrids Considering Battery Lifetime, IEEE Journal of Emerging and Selected Topics in Power Electronics (JESTPE), vol 3(4), pp. 1967 -1077, 2015
- [6] L Mariam, M Basu and M F Conlon, Development of a simulation model for a Community Microgrid system, UPEC 2014, Romania.
- [7] L Mariam, M Basu and M F Conlon, Sustainability of grid-connected Community Microgrid based on micro wind-Generation system with storage, International Symposium on Industrial Electronics, ISIE2014, Istanbul, Turkey
- [8] L Mariam, M Basu and M F Conlon, Community microgrid based on micro wind generation system, UPEC 2013, Dublin, Ireland
- [9] L Mariam, M Basu and M F Conlon, Sustainability of grid-tie micro-generation system, UPEC 2013, Dublin, Ireland
- [10] L Mariam, M Basu and M F Conlon, A Review of Existing Microgrid Architectures, Journal of Energy and Power Engineering, vol. 2013, Article ID 937614, 8 pages, 2013
- [11] L Mariam, M Basu and M F Conlon, A Review of Existing Micro Grid Architectures, Proceedings of SEEP2012, 05-08 June 2012, DCU, Dublin, Ireland