Resilient and Sustainable Microgrid Planning on Alderney Island

AEL MG Planning Technical Report

Authors

Dr. Shahab Dehghan
Ms Agnes Nakiganda
Dr. Petros Aristidou

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Executive Summary

Remote rural and islanded communities face many difficulties in adequate and secure energy supply. In many cases, connecting these communities to the bulk electricity grid is economically challenging or impossible due to geographical constraints. Climate change and reliance on fossil fuels make the electrification of these communities more complicated. In this project, the School of Electronic and Electrical Engineering at the University of Leeds (UoL) has collaborated with the Alderney Electricity Ltd (AEL) on the existing microgrid on Alderney Island as the 3rd largest of the Channel Islands to investigate reinforcement and investment solutions increasing its resilience and sustainability through employing and extending the microgrid planning tools developed at UoL. The project was funded through an UKRI EPSRC Impact Accelerator Award and co-funded by Alderney Electricity Ltd.

The project delivered a full investment planning model for Alderney microgrid that can be used for designing and analysing the techno-economic aspects of hybrid microgrids on the island. More specifically:

- A power-flow model of the Alderney island was developed for the first time.
- The load profiles of the island were digitised.
- Using state-of-the-art clustering techniques, a set of representative daily profiles were developed concerning load consumption, wind and solar generation. These profiles can be used for investment or strategy planning.
- An optimisation-based, techno-economic assessment model was developed based on PyE-PLAN able to select technical solutions at the minimum cost.

Based on the current prices of the investment and operation costs and the available technologies, the analysis showed that the lowest cost is provided by a hybrid solar/wind/diesel system (see Section 3.5.2). More specifically, the optimal solution considers one wind and one solar units, in combination to the existing diesel. However, studies made including the worst case realisations of solar/wind/load (robust), showed that a fully renewables-based MG is not economically viable without affecting the system reliability or increasing significantly the cost of storage.

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Chapter 1

Project Overview

1.1 Alderney Energy State

Alderney island is the third largest of the Channel Islands and has a permanent resident population of approximately 2000 residents. The island covers an area of 3 square miles, with most of its population concentrated in the major town of St. Anne. Major economic activities include small businesses, e-trade, healthcare services, and ecotourism especially during the warmer months of the year. Alderney island runs a closed complex energy system that entirely relies on imported fuel oils for electricity, heating and transportation.

The major energy supplier on the island is Alderney Electricity limited (AEL) providing for both the electric and heating loads. The island currently has an approximate annual electricity demand of 6 GWh with a daily base load of 450 kW, approximate peaks of 1.1 MW that may rise to 1.3 MW during the summer, and approximate average daily load of 700 kW. The largest electricity consumers are the small businesses, the hospital, the airport and the auxiliary consumption of the power plant, with total electricity demand however showing a decline of 1.6% between years 2018 and 2019.

Electric power is centrally generated by diesel generators and supplied through an extensive network consisting of underground cables. Similar to the electric load, the heating load on Alderney island is currently entirely met by fossil fuels with kerosene being the major source of heat. The major aim of this research project is to provide a sustainable and resilient electricity network on Alderney island through integrating renewable energy systems as low-carbon technologies, reducing the reliance of the island on fossil fuels.

1.2 Alderney Electricity Limited

AEL operates as a Community Interest Company and is the regulated utility supplying the island's heat and electric demand. Its core policies include the provision of low-cost energy, addressing any challenges that may arise in the system, and the continual enhancement of the energy supply sustainability taking into account economic, environmental, social, ethical, and cultural aspects. AEL is responsible for importing and distributing different fuels, including kerosene, as well as the generation and distribution of electricity. The company manages both the 11 kV primary distribution network consisting of 21 substations as well as the 415 V secondary distribution network.

In recent years, the network generation infrastructure has been upgraded with eight (8) new Perkins engines at 450 kW each, producing 3.96 kWh per litre of diesel replacing the old Blackstones and Paxman engines that were producing 3.56 kWh per litre of diesel. In addition, the 70 year old substation switchgear was replaced with up-to-date infrastructure provided by Schneider Electric. The electricity tariff in Alderney at the time of writing is set at 0.43 £/kWh including a standing charge of 0.27 £/kWh and variable cost of 0.16 £/kWh. As AEL is a non-profit company, the tariff is an indication of the different costs incurred in the supply of electric power. The high tariff of electricity is majorly attributed to its reliance on fossil fuels which are subject to external energy market fluctuations is one of the drivers in the reinforcement of the island's electric generation to include renewable energy systems. This is in line with the strategy of the Island's energy policy to create a secure and sustainable energy future while ensuring the affordability of the energy for all [1].

1.3 Project Objectives

The first goal of this research project was to extend the existing planning tool at UoL (PyEPLAN) to investigate potential solutions for a resilient and sustainable microgrid with low carbon emissions in a real life energy system on Alderney island. Based on the existing network infrastructure, the forecast solar and wind power generation profiles in addition to forecast consumption profiles, a reference model that can be adapted to the requirements of islanded systems was to be implemented.

The second goal of the project was to use PyEPLAN to propose optimal reinforcements to the Alderney microgrid. This considers investment and operation cost analysis, carbon emissions, and system security, in a bid to ensure the enhanced resilience and sustainability of the network.

The third goal of the project thus dealt with the identification of existing barriers to bridge the gap between theoretical and practical planning tools for real-world applications in islanded communities. The versatile test-bed provided by the Alderney network provides a link between academic and practical requirements in system planning.

1.4 Report Outline

The rest of this report is organised as follows. In Chapter 2, the planning tool (PyEPLAN) used to design a sustainable microgrid on Alderney island is reviewed. Moreover, it is described how electrical technical parameters pertaining to the Alderney microgrid were calculated. In Chapter 3, the proposed planning tool is utilised to create a sustainable microgrid on Alderney island under different condition. Finally, Chapter 4 presents the main conclusions and recommendations of this research work.

Chapter 2

Planning Tool for Renewable Integration into AEL

2.1 Overview

Principally, a sustainable electricity network can be created by using different types of renewable energy sources (RES) (e.g., wind energy, solar energy, tidal energy). However, the optimal design for a sustainable electricity network is a function of different inputs, such as weather conditions [2], which significantly affect RES power generation at various locations. In this research project, the open-source Python-based Energy Planning (PyEPLAN) tool, which is developed at UoL, is used to obtain the optimal topology for a sustainable electricity network on Alderney island. In the sequel, more explanations and discussions about PyEPLAN are presented.

2.1.1 Platform

PyEPLAN has mainly three different modules for investment and operation planning in microgrids, as depicted in Figure 2.1. However, it can be extended to solve various investment and operation planning problems not only in microgirds, but also in megagrids. In this project, the investment planning module is used to create a sustainable microgrid on Alderney island. Since both investment and operation planning modules include various optimisation problems, the open-source, Python-based, optimisation modelling module Pyomo [3] is used with diverse abilities in formulating, solving, and analysing optimisation problems. The main ability of Pyomo is related to modelling and solving structured optimisation problems, similarly to common notations in mathematics. Moreover, in Pyomo, we may formulate problems with different object-oriented modelling components including: sets, scalars, parameters, variables, constraints, and objectives. It is noteworthy to mention that Pyomo is also able to separate model and data by means of abstract and concrete models. The model can be defined without data in abstract models while the model can be defined with data in concrete models.

Both investment and operation planning modules in PyEPLAN are developed based on a

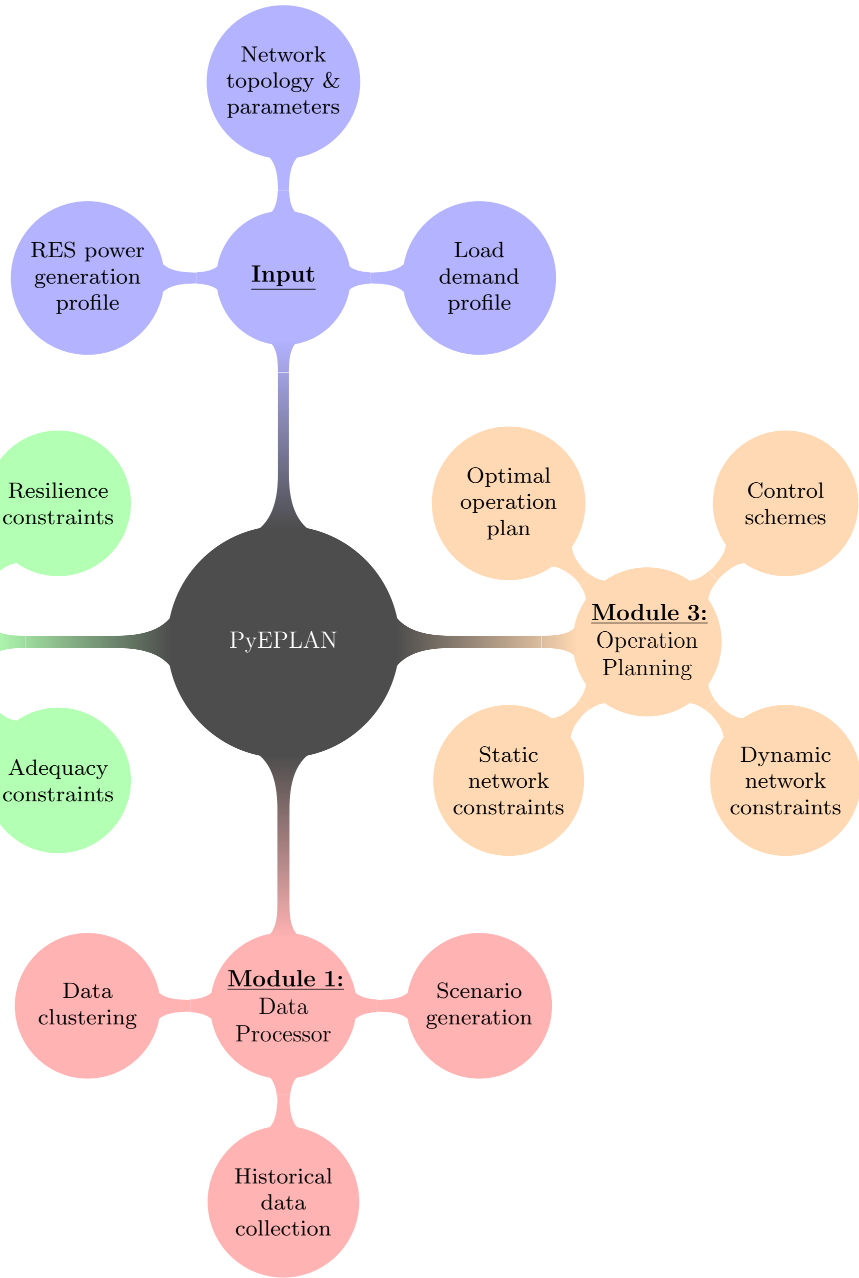


Figure 2.1: Overview of PyEPLAN architecture.

concrete model in Pyomo. Each concrete model in PyEPLAN can be initialised by means of comma-separated values (CSV) files, including input data sets (i.e., different characteristics of various components in microgrids). Since Pyomo can support many open-source, and even commercial, solvers (e.g., CPLEX [4], Gurobi [5], AMPL [6], PICO [7], CBC [8], and GLPK [9]), PyEPLAN can also utilise a broad range of solvers to obtain the optimal solution in both investment and operation planning modules.

2.1.2 Algorithm Description

The investment and operation planning modules in PyEPLAN are outlined in Figure 2.1. The objective of the investment planning module is to minimise both investment and operation costs during a *long-term* planning horizon (i.e., from one year to several years) under both investment and operation related techno-economic constraints, while the objective of the operation planning module is to minimise operation costs during a *short-term* planning horizon (i.e., one day) under operation related techno-economic constraints. However, the investment/operation planning module needs network characteristics (i.e., candidate/existing production technologies, candidate/existing lines) as well as long-term/short-term estimated/forecasted load demands and power generations of RESs to obtain the optimal solution. Accordingly, a data processor is considered in PyEPLAN to provide the input data needed for both investment and operation planning modules.

2.2 Data Processing

In this research project, the data processor in PyEPLAN is customised to find representative days, characterising daily profiles of load demands and power generations of RESs, as discussed in Section 2.2.1, and calculating network parameters for the Alderney microgrid, as discussed in Section 2.2.2.

2.2.1 Representative Days: A Data Clustering Technique

In the investment planning module, it is assumed that the pattern of power generation (obtained from dividing the hourly power generation of each RES by its capacity) as well as the pattern of load demand (obtained from dividing the hourly load demand of each year by its peak) remain unchanged during a one-year period [10]. However, a sufficient number of scenarios are required to characterise power generation of RES and load demand during a one-year period. Therefore, the k-means clustering technique is used in PyEPLAN to obtain representative days from daily profiles of load demands and power generations of RESs during a specific year. Given 365 vectors of historical observations pertaining to 365 daily 24-hour patterns of load demands and power generations of RESs, the application of the k-means clustering algorithm to obtain representative days can be summarised as follows [2]:

Step 1) Define the number of clusters to obtain representative days.

Step 2) Initialise the centroid of all clusters by randomly adding one historical observation to each cluster.

Step 3) Calculate the distance between the centroid of each cluster and all historical observations. In this research project, similar to [2], a quadratic distance is utilised.

Step 4) Add each historical observation to its nearest cluster using distances calculated in Step 3.

Step 5) Update the centroid of all clusters using historical observations added to each cluster in Step 4.

Step 6) Iterate between Steps 3-5 until all clusters remain unchanged in two successive iterations.

After clustering all historical observations, the proposed planning model incorporates the best(risk-seeker), nominal (risk-neutral), and worst (risk-averse) representative days [10]. The nominal representative day corresponds to the centroid of each cluster obtained from the k-means clustering technique. Moreover, the α-quantile of the empirical cumulative probability distribution of each cluster represent the best representative day, while the $(1-\alpha)$-quantile of the empirical cumulative probability distribution of each cluster represent the worst representative day. In this report, without loss of generality, it is assumed that $\alpha = 0.05$.

2.2.2 Network Parameters

In the investment and operation planning modules, the essential network parameters include distribution factors of load demands, network configuration, and line parameters. Since line parameters for the Alderney microgrid were not available, these parameters are calculated in this research project. The main network parameters in steady-state investment and operation planning studies include the line resistance (i.e., R), line reactance (i.e., X), line charging suceptance (i.e., B), surge impedance loading (i.e., SIL), and thermal loading limit (i.e., $S_{\max}$). These network parameters can be calculated using the length, size, and conductor material of each line as given below [11]:

Line resistance (R):

$$R_{dc} = \frac{\rho \cdot l}{A} \quad [\Omega] \tag{2.1}$$

and R_{AC} then computed from tables using R_{DC}.
Line reactance (X):

$$X = \omega \cdot L \quad \xrightarrow{\text{where}} \quad L = \frac{\mu_o}{2\pi}\left(\frac{\mu_r}{4} + \ln\frac{\sqrt[3]{d_{ab}\cdot d_{ac}\cdot d_{bc}}}{r}\right) \quad [mH/km] \tag{2.2}$$

Line suceptance (B):

$$B = \omega \cdot C \quad \xrightarrow{\text{where}} \quad C = \frac{2\pi \cdot \epsilon_o \cdot \epsilon_r}{\ln\frac{\sqrt[3]{d_{ab}\cdot d_{ac}\cdot d_{bc}}}{r}} \quad [\mu F/km] \tag{2.3}$$

Thermal loading limit (S_{max}):

$$S_{max} = \sqrt{3}\cdot V_{rated}\cdot I_{rated} \quad \xrightarrow{\text{where}} \quad I_{rated} = J \cdot A \quad [A] \tag{2.4}$$

where I_{rated}, V_{rated}, and Z_0 represents the rated line thermal current carrying capability, rated line-to-line voltage, and line characteristic impedance, respectively. Moreover, other parameters are described in Table 2.1. It is noteworthy to mention that the thermal loading limit can be also estimated as a function of the SIL through the St. Clair curves [12]. However, it can be calculated by (2.4) short lines.

Table 2.1: Parameter Description

ρ	Resistivity
l	Cable length
A	Cross-sectional area
μ_o, μ_r	Absolute and relative permeability
$\sqrt[3]{d_{ab} \cdot d_{ac} \cdot d_{bc}}$	Geometric mean distance (GMD)
r	Conductor radius
ϵ_o, ϵ_r	Absolute and relative permitivity
J	Current density

2.3 Mathematical Modelling of the Proposed Planning Tool

In this section, the mathematical model of the customised investment planning module in PyEPLAN is presented. Hereafter, $\underline{\bullet}$ and $\overline{\bullet}$ represent the lower and upper bounds of the quantity $\bullet$, respectively. Moreover, all indices, parameters, sets, and variables are presented in the nomenclature.

Nomenclature

n Index of nodes where n' and n'' stand for nodes before and after node n, respectively.

d Index of load demands.

g Index of generation units.

o Index of representative days (scenarios).

t Index of time periods.

e_b^{ini} Initial stored energy of battery unit b (kW).

e_b^{max} Maximum stored energy of battery unit b (kW).

e_b^{min} Minimum stored energy of battery unit b (kW).

pc_d Penalty cost of load demand curtailment (\$/kWh).

pc_r Penalty cost of RES power generation curtailment (\$/kWh).

f_d Power factor of load demand d.

ic_b Annualised investment cost of battery unit b (\$).

ic_g Annualised investment cost of generation unit g (\$).

mc_g Marginal cost of generation unit g (\$/kWh).

$p_b^{\text{max,c}}$ Maximum charging power of battery unit b (kW).

$p_b^{\max,\mathrm{d}}$ Maximum discharging power of battery unit b (kW).

$\bar{p}_{dto}$ Load demand d at hour t in representative day o ($/kWh).

$p_{n'n}^{\max}$ Maximum active power flow from node n' to node n (kW).

$p_g^{\max}$ Maximum active power of generation unit g (kW).

$\overline{p}_{gto}^{\max}$ Maximum power generation of generation unit g at hour t in representative day o (kW).

$q_b^{\max}$ Maximum reactive power of battery unit b (kVAr).

$q_b^{\min}$ Minimum reactive power of battery unit b (kVAr).

$q_{n'n}^{\max}$ Maximum reactive power flow from node n' to node n (kVAr).

$q_g^{\max}$ Maximum reactive power of generation unit g (kVAr).

$q_g^{\min}$ Minimum reactive power of generation unit g (kVAr).

$r_{n'n}$ Resistance of the line connecting nodes (n', n) (ohm).

$v^{\max}$ Maximum permitted voltage magnitude (V).

$v^{\min}$ Minimum permitted voltage magnitude (V).

$x_{n'n}$ Reactance of the line connecting nodes (n', n) (ohm).

$\eta_b^{\mathrm{c/d}}$ Reactance of the line connecting nodes (n', n) (ohm).

Ω^B Set of battery units where Ω^{B_n} indicates set of battery units connected to node n.

Ω^N Set of nodes where Ω^{N_n} indicates set of nodes after and connected to node n.

Ω^D Set of load demands where Ω^{D_n} indicates set of load demands connected to node n.

Ω^L Set of distribution lines connecting nodes.

Ω^M Set of micro-turbine/diesel units where Ω^{M_n} indicates set of micro-turbine/diesel generators connected to node n.

Ω^R Set of RES units where Ω^{R_n} indicates set of RES units connected to node n.

Ω^T Set of hours.

$p_{bto}^{\mathrm{c/d}}$ Active charging/discharging power of battery unit b at hour t in representative day o (kW).

$p_{n'nto}$ Active power flow from node n' to node n at hour t in representative day o (kW).

p_{gto} Active power generation of generation unit g at hour t in representative day o (kW).

q_{bto} Reactive power of battery unit b at hour t in representative day o (kW).

$q_{n'nto}$ Reactive power flow from node n' to node n at hour t in representative day o (kVAr).

q_{gto} Reactive power generation of generator g at hour t in representative day o (kVAr).

v_{nto} Voltage magnitude of node n at hour t in representative day o (V).

y_{dto} Curtailment status of load demand d at hour t in representative day o (i.e., 1/0: curtailed/not-curtailed).

z_b Investment status of battery unit b (i.e., 1/0: built/non-built).

z_g Investment status of RES unit g (i.e., 1/0: built/non-built).

2.3.1 PyEPLAN Planning Formulation

In this section, the mathematical formulation of the planning model is briefly presented within a single-year planning horizon under different representative days (scenarios) for load demands and RES power generations as given below:

$$\min \mathbf{\Psi}^{\text{inv}} + \mathbf{\Psi}^{\text{opr}} \tag{2.5a}$$

s.t.

$$\mathbf{\Psi}^{\text{inv}} = \sum_{b\in\Omega^B} (ic_b \cdot z_b) + \sum_{g\in\Omega^R} (ic_g \cdot z_g) \tag{2.5b}$$

$$\begin{aligned}\mathbf{\Psi}^{\text{opr}} = &\sum_{o\in\Omega^O}\sum_{t\in\Omega^T}\sum_{g\in\{\Omega^M,\Omega^R\}} (\tau_o \cdot mc_g \cdot p_{gto}) + \\ &\sum_{o\in\Omega^O}\sum_{t\in\Omega^T}\sum_{s\in\Omega^S} (\tau_o \cdot pc_d \cdot \overline{p}_{dto} \cdot (1 - y_{dot})) + \\ &\sum_{o\in\Omega^O}\sum_{t\in\Omega^T}\sum_{g\in\Omega^R} \left(\tau_o \cdot pc_r \cdot \left(\overline{p}^{\text{max}}_{gto} - p_{gto}\right)\right)\end{aligned} \tag{2.5c}$$

$$\begin{aligned}&p_{n'nto} + \sum_{g\in\{\Omega^{M_n},\Omega^{R_n}\}} p_{gto} + \sum_{b\in\Omega^{B_n}} \left(p^{\text{d}}_{bto} - p^{\text{c}}_{bto}\right) = \\ &\sum_{n''\in\Omega^{N_n}} p_{nn''to} + \sum_{d\in\Omega^{D_n}} (\bar{p}_{dto} \cdot y_{dto}) \quad n \in \Omega^N, t \in \Omega^T, o \in \Omega^O\end{aligned} \tag{2.5d}$$

$$\begin{aligned}&q_{n'nto} + \sum_{g\in\Omega^{M_n}} q_{gto} + \sum_{b\in\Omega^{B_n}} q_{bto} = \sum_{n''\in\Omega^{N_n}} q_{nn''t} + \\ &\sum_{d\in\Omega^{D_n}} \tan\left(\arccos\left(f_d\right)\right) \cdot (\bar{p}_{dto} \cdot y_{dto}) \quad n \in \Omega^N, t \in \Omega^T, o \in \Omega^O\end{aligned} \tag{2.5e}$$

$$(r_{n'n} \cdot p_{n'nto} + x_{n'n} \cdot q_{n'nto}) = v_{n'to} - v_{nto} \quad n \in \Omega^N, t \in \Omega^T, o \in \Omega^O \tag{2.5f}$$

$$- p^{\text{max}}_{nn''} \leq p_{nn''to} \leq p^{\text{max}}_{nn''} \ \ (n, n'') \in \Omega^L, t \in \Omega^T, o \in \Omega^O \tag{2.5g}$$

$$-q^{\max}_{nn''} \leq q_{nn''to} \leq q^{\max}_{nn''} \quad (n, n'') \in \Omega^L, t \in \Omega^T, o \in \Omega^O \tag{2.5h}$$

$$0 \leq p_{gto} \leq p^{\max}_{g} \quad g \in \Omega^M, t \in \Omega^T, o \in \Omega^O \tag{2.5i}$$

$$q^{\min}_{g} \leq q_{gto} \leq q^{\max}_{g} \quad g \in \Omega^M, t \in \Omega^T, o \in \Omega^O \tag{2.5j}$$

$$0 \leq p_{gt} \leq \bar{p}^{\max}_{gto} \cdot z_g \quad g \in \Omega^R, t \in \Omega^T, o \in \Omega^O \tag{2.5k}$$

$$q^{\min}_{g} \cdot z_g \leq q_{gto} \leq q^{\max}_{g} \cdot z_g \quad g \in \Omega^R, t \in \Omega^T, o \in \Omega^O \tag{2.5l}$$

$$e^{\min}_{b} \cdot z_b \leq e^{\text{ini}}_{bo} + \sum_{\tau=1}^{t} \left(\eta^{\text{c}}_{b} \cdot p^{\text{c}}_{b\tau o} - \frac{1}{\eta^{\text{d}}_{b}} \cdot p^{\text{d}}_{b\tau o} \right) \leq e^{\max}_{b} \cdot z_b \quad b \in \Omega^B, t \in \Omega^T, o \in \Omega^O \tag{2.5m}$$

$$\sum_{\tau=1}^{T} \left(\eta^{\text{c}}_{b} \cdot p^{\text{c}}_{b\tau o} - \frac{1}{\eta^{\text{d}}} \cdot p^{\text{d}}_{b\tau o} \right) = 0 \quad b \in \Omega^B, t \in \Omega^T, o \in \Omega^O \tag{2.5n}$$

$$0 \leq p^{\text{c}}_{bto} \leq p^{\max,\text{c}} \cdot z_b \quad b \in \Omega^B, t \in \Omega^T, o \in \Omega^O \tag{2.5o}$$

$$0 \leq p^{\text{d}}_{bto} \leq p^{\max,\text{d}} \cdot z_b \quad b \in \Omega^B, t \in \Omega^T, o \in \Omega^O \tag{2.5p}$$

$$v^{\min} \leq v_{not} \leq v^{\max} \quad n \in \Omega^N, t \in \Omega^T, o \in \Omega^O \tag{2.5q}$$

$$v_{1to} = 1 \quad t \in \Omega^T, o \in \Omega^O \tag{2.5r}$$

The objective function (2.5a) minimises the total investment and operational costs, where $\mathbf{\Psi}^{\text{inv}}$ calculates the total investment costs of battery and RES units, as indicated in (2.5b), and $\mathbf{\Psi}^{\text{opr}}$ represents the total operational costs of micro-turbine/diesel and RES units as well as curtailment costs of load demands and RES power generations, as indicated in (2.5c). For simplicity, all existing and candidate technologies are considered as investment candidates, where the investment costs (resp. decision variables) of existing technologies (i.e., micro-turbine/diesel units) are set to 0 (resp. 1).

PyEPLAN offers different ways to include the network constraints. In this report, the linearised approximation of the DistFlow formulation is selected for the AC power flow equations [13] and the quadratic power flow limitations are linearised by means of a polygon approximation [14]. Accordingly, constraints (2.5d) and (2.5e) ensure active and reactive power balance at each node of every hour of all representative days, respectively. Constraint (2.5f) denotes the difference of voltage magnitudes between two neighbor nodes connected. Constraints (2.5g) and (2.5h) bound the active and reactive power flows between two connected neighbor nodes, respectively.

Constraints (2.5i) and (2.5j) ensure the limits on active and reactive power generation for micro-turbine/diesel units, respectively, while constraints (2.5k) and (2.5l) ensure the limits of active power generation for RES units.

Constraint (2.5m) bounds the stored energy of each battery unit at every hour of all representative days. Moreover, constraint (2.5n) ensures the initial and final stored energy of battery units for each representative day. Constraints (2.5o) and (2.5p) bound the charging and discharging power of each battery unit at every hour in all representative days, respectively. Constraint (2.5q) limits the allowed variation bound of the nodal voltage magnitude. Also, constraint (2.5r) sets the voltage magnitude at the main AEL substation on one.

The proposed mathematical model in (2.5a)-(2.5r) is a mixed-integer linear programming (MILP) problem, which can be solved by off-the-shelf optimisation packages.

Chapter 3

Case Study

3.1 Overview

In this chapter, PyEPLAN is used on the Alderney microgrid to obtain a sustainable electricity network using different types of RESs. Also, all date sets are collected from AEL and online resources.

3.2 Network Configuration and Parameters

The 11 kV primary distribution network in the Alderney microgrid is currently run as four radial feeders, fed through feeders E1, E2, W1, and W2, as depicted in Figure 3.1. In the future, the Alderney microgrid will eventually be run as two separate rings (East and West). The topology of the network with East and West rings is depicted in Figure 3.2. Power is generated solely at the power station by the eight 450 kW Perkin's generators. The power station is connected to the 11 kV primary distribution network via two 2500 kVA transformers and the 11 kV primary distribution network is connected to the 415 V secondary distribution network by 500 kVA transformers at the different substations and locations. The AEL distribution network consists of three types of underground, copper core cables including 16 mm^2 steel-wrapped PILC cables, 25 mm^2 PILC cables, and 70 mm^2 XLPE cables. The conductor parameters for each cable are given in 3.1, while the line lengths, parameters for the network topology are provided in 3.2.

Table 3.1: Installed cable conductor parameters [15]

Size (mm^2)	R_{DC} **at 20°C (Ω/km)**	R_{AC} **at 70/90°C (Ω/km)**	X_L **at 50Hz (Ω/km)**	**C (μF/km)**
16	1.15	1.47	0.141	0.18
25	0.727	0.870	0.107	0.360
70	0.2680	0.3420	0.110	0.289

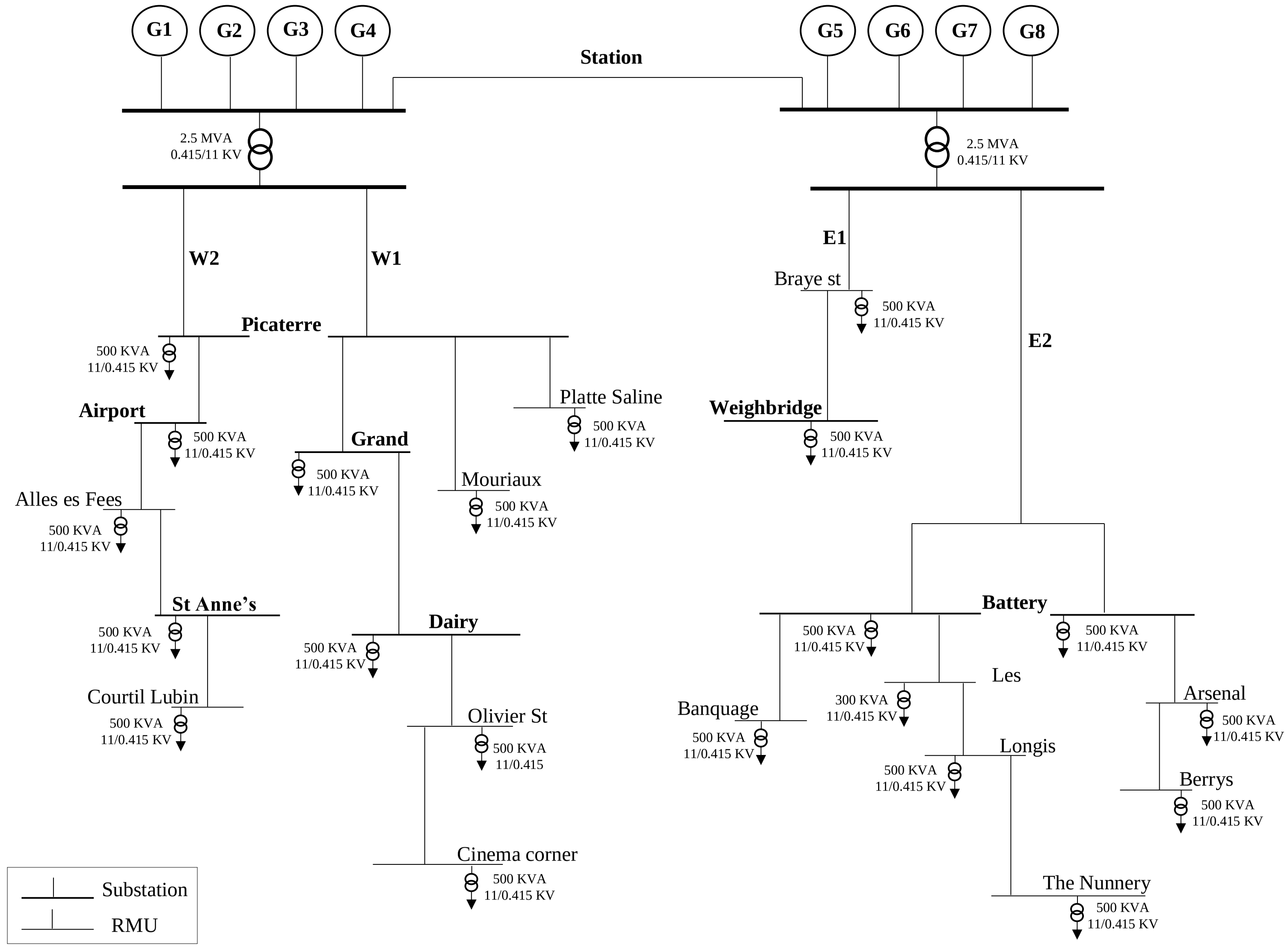


Figure 3.1: Alderney radial network topology.

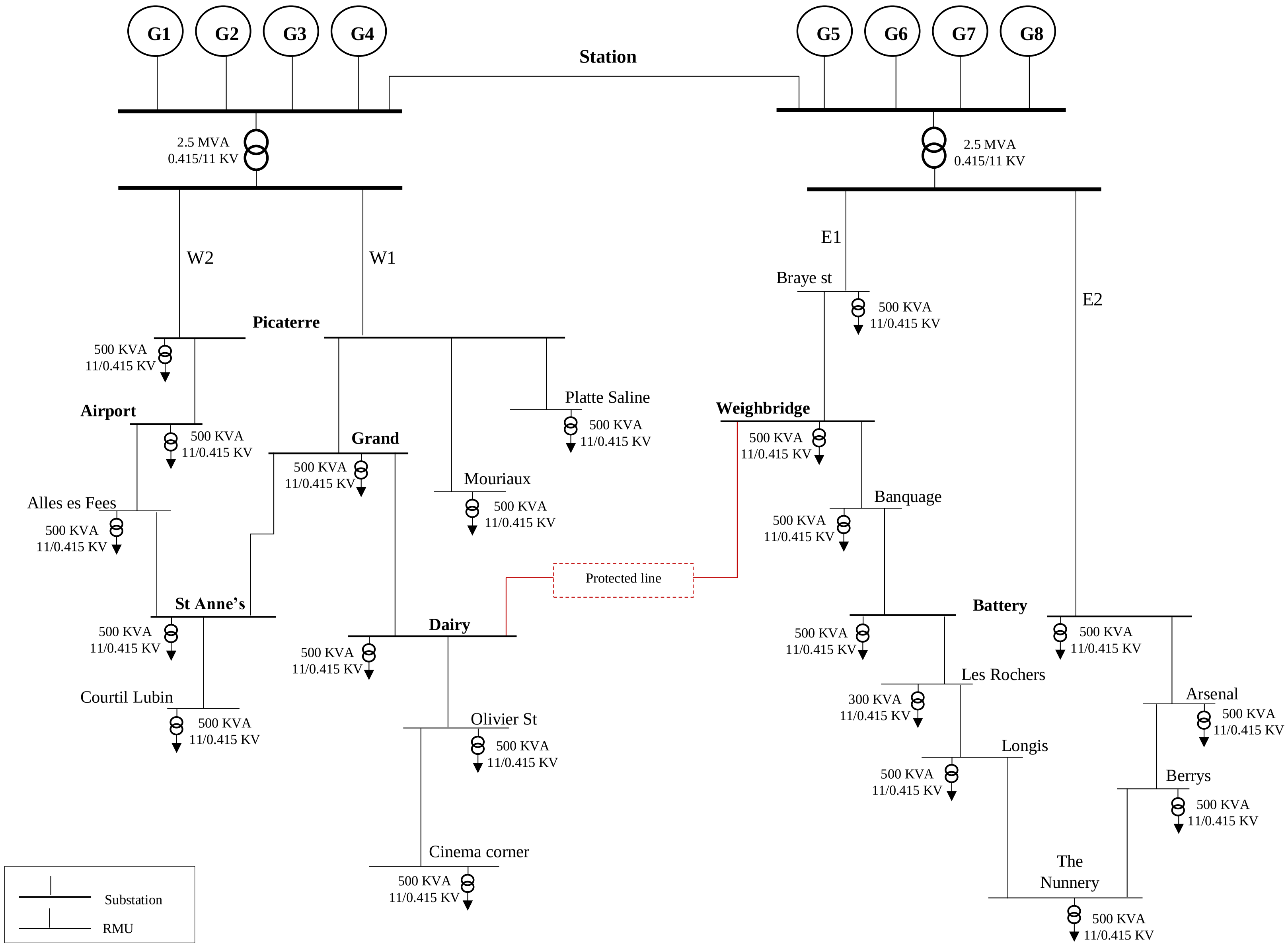


Figure 3.2: Alderney ring network topology.

Table 3.2: Alderney HV network connections and line parameters

Node from	**Node to**	**Size (mm^2)**	**Length (m)**	**R (Ω)**	**X (Ω)**	**B (μS)**	**Short circuit rating (kA)**	**Current-carrying capacity (A)**	**Thermal loading (MVA)**
Power Station	Picaterre (W1)	25	630	0.5481	0.0674	71.251	3.1	125	1.375
Power Station	Picaterre (W2)	70	630	0.2155	0.0693	57.199	9.7	245	2.695
Picaterre	Mouriaux (RMU)	16	572	0.8408	0.0807	32.346	2.3	112	1.232
Picaterre	Airport	70	1832	0.6265	0.2015	166.331	9.7	245	2.695
Airport	Allees es Fees (RMU)	70	1105	0.3779	0.1216	100.325	9.7	245	2.695
Allees es Fees	St Annes	70	485	0.1659	0.0533	44.034	9.7	245	2.695
St Annes	Mouriaux	70	270	0.0923	0.0297	24.514	9.7	245	2.695
St Annes	Grand	70	530	0.1813	0.0583	48.120	9.7	245	2.695
St Annes	Coutil Lubin (RMU)	70	534	0.1826	0.0587	48.483	9.7	245	2.695
Coutil Lubin	Cinema Corner (RMU)	16	341	0.5012	0.0481	19.283	2.3	112	1.232
Picaterre	Grand	70	527	0.1802	0.0580	47.847	9.7	245	2.695
Grand	Dairy	70	100	0.0342	0.0110	9.079	9.7	245	2.695
Dairy	Ollivier St (RMU)	16	205	0.3014	0.0289	11.593	2.3	112	1.232
Ollivier St	Cinema Corner	16	225	0.3308	0.0317	12.724	2.3	112	1.232
Power Station	Braye St (RMU)	16	480	0.7056	0.0677	27.143	2.3	112	1.232
Braye St	Weighbridge	25	191	0.1827	0.0225	23.750	3.1	125	1.375
Weighbridge	Banquage	25	210	0.8700	0.1070	113.097	3.1	125	1.375
Banquage	Battery	25	1000	0.5220	0.0642	67.858	3.1	125	1.375
Weighbridge	Dairy	70	600	0.2052	0.0660	54.475	9.7	245	2.695
Power Station	Battery	70	1000	0.3420	0.1100	90.792	9.7	245	2.695
Battery	Arsenal (RMU)	70	475	0.1625	0.0523	43.126	9.7	245	2.695
Arsenal	Berrys Switch (RMU)	70	400	0.1368	0.0440	36.317	9.7	245	2.695
Berry's Switch	The Nunnery (RMU)	70	600	0.2052	0.0660	54.475	9.7	245	2.695
Battery	Les Rochers (RMU)	70	260	0.0889	0.0286	23.606	9.7	245	2.695
Les Rochers	Longis (RMU)	70	246	0.0841	0.0271	22.335	9.7	245	2.695
Longis (RMU)	The Nunnery	70	1095	0.3745	0.1204	99.417	9.7	245	2.695

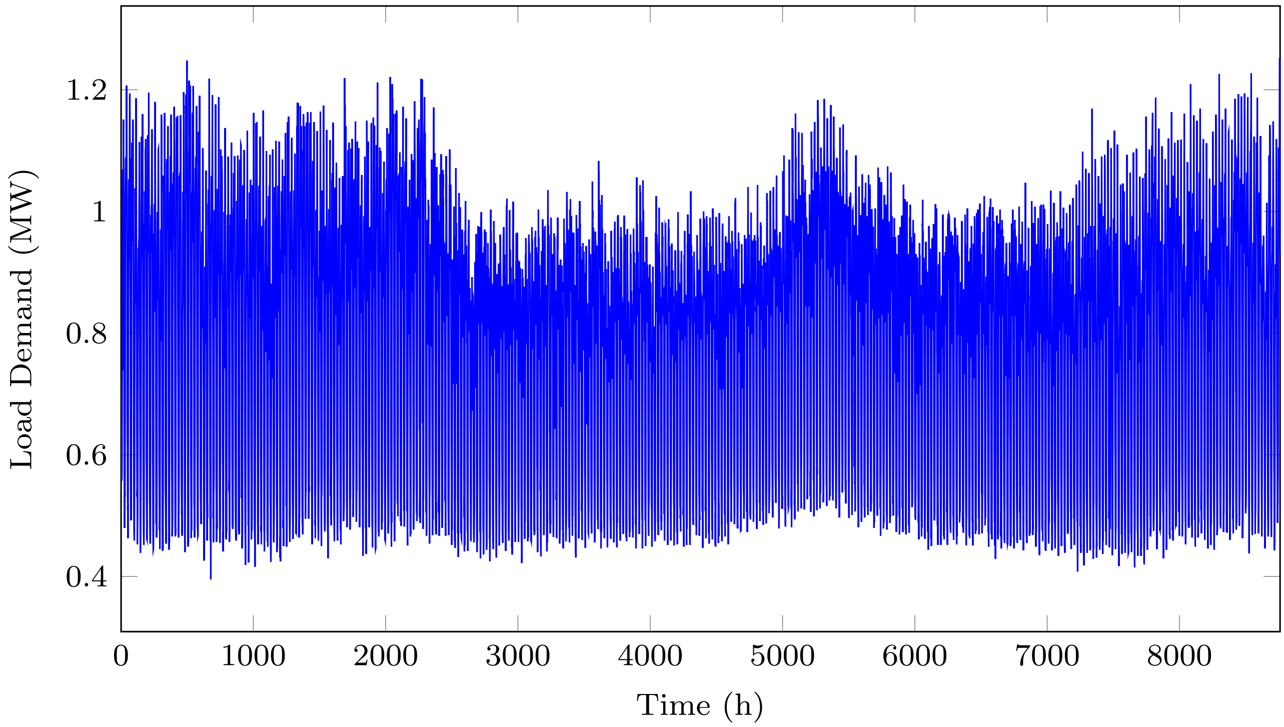


Figure 3.3: The yearly profile of load demand on Alderney island in 2013.

3.3 Production and Consumption Profiles

In this study, the AEL yearly load demand profile in 2013, as depicted in Figure 3.3, is used to obtain representative days by means of the k-means clustering technique, as discussed in Section 2.2.1. The peak load is equal to 1.252 MW. In addition, the solar irradiation and wind speed on Aldenery island in 2013 are taken from `https://www.meteoblue.com`. Given a 1.8 MW solar farm with a 2-hectare land used to construct this power plant and a 1.8 MW wind farm, the yearly power generation profiles of solar and wind farms in 2013 are depicted in Figures 3.4 and 3.5, respectively. In this research project, it is assumed that the efficiency of candidate solar panels/modules in solar farm is equal to %10 [16] and the cut-in speed, the rated speed, and the cut-out speed of candidate wind turbines (i.e., Vestas V90 1.8 MW) in the wind farm are equal to 4 m/s, 12 m/s, and 25 m/s, respectively. Also, the hub height of each wind turbine is equal to 80 m.

The capacity factor of both solar and wind farms are presented in Table 3.3. By definition, capacity factor represents the ratio of the electrical energy produced by a specific production technology to the electrical energy, which could have been produced at continuous rated capacity during a one-year period (or other specific periods) [17]. Accordingly, the capacity factor of wind technology is significantly higher than the capacity factor of solar technology while the land needed by wind turbines to create a 1.8 MW wind farm is significantly less of the land needed by solar panels/modules to create a 1.8 MW solar farm (i.e., approximately 2 hectares). For more clarification, the land needed by a 1.8 MW solar farm on Alderney island is approximately equal to three football pitches [18].

Now, the k-means clustering technique is used to obtain representative days using the yearly profiles pertaining to load demand, solar power generation, and wind power generation. The

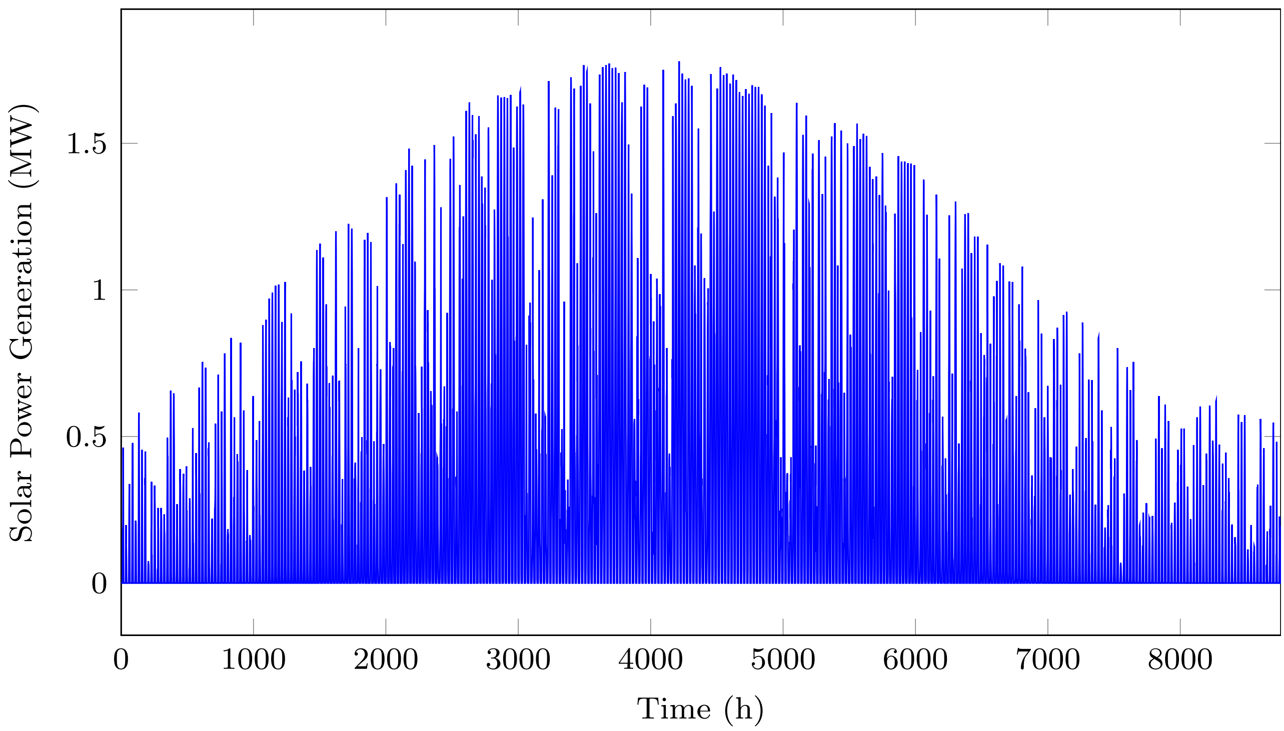


Figure 3.4: The yearly profile of solar power generation on Alderney island in 2013.

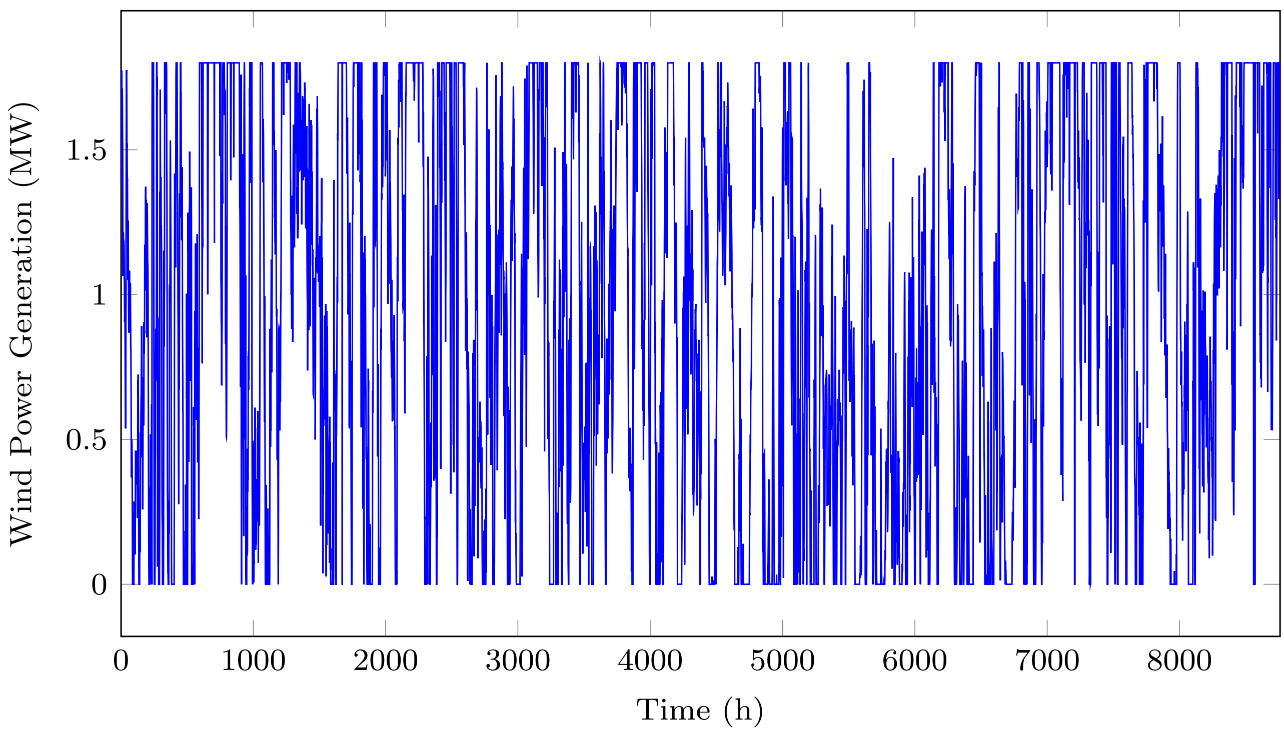


Figure 3.5: The yearly profile of wind power generation on Alderney island in 2013.

Table 3.3: Capacity Factor for Solar and Wind Farms on Alderney island

Technology	**Installed Capacity (MW)**	**Capacity Factor (%)**
Solar	1.8	16.27
Wind	1.8	54.39

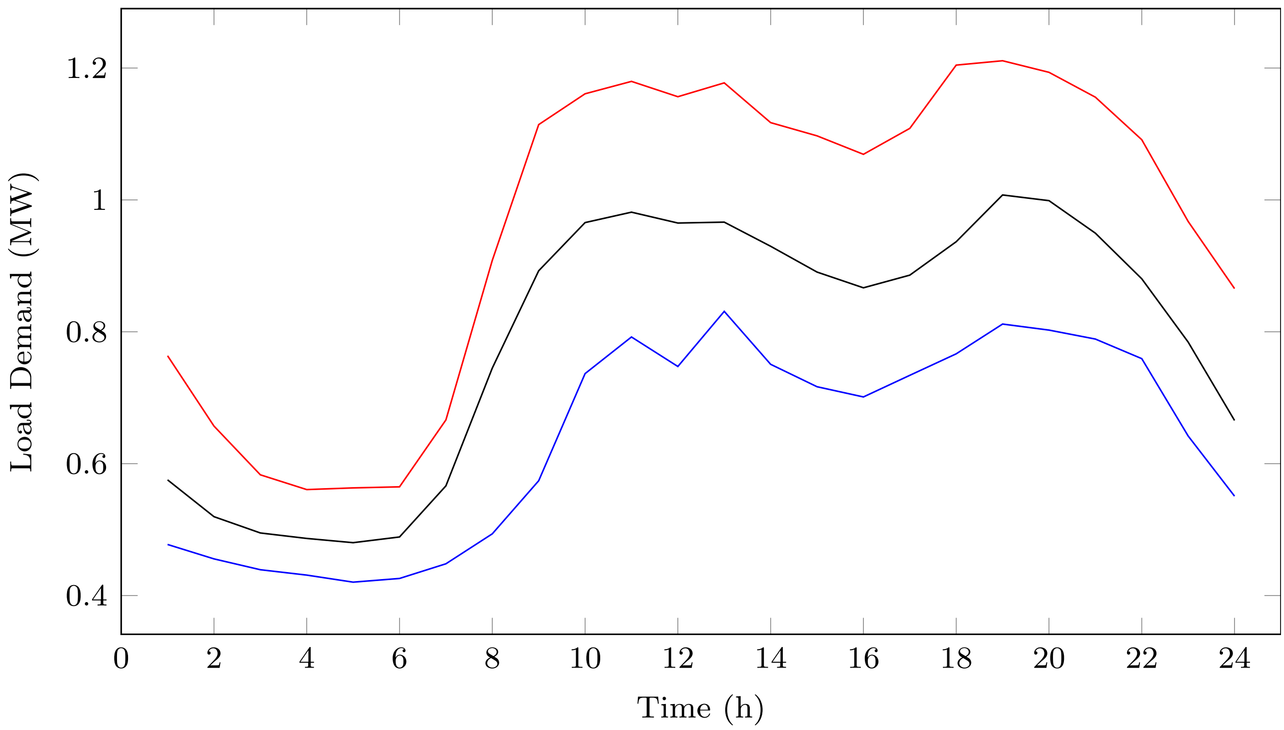


Figure 3.6: The best (blue), nominal (black), and worst (red) representative days for load demands on Alderney island in 2013.

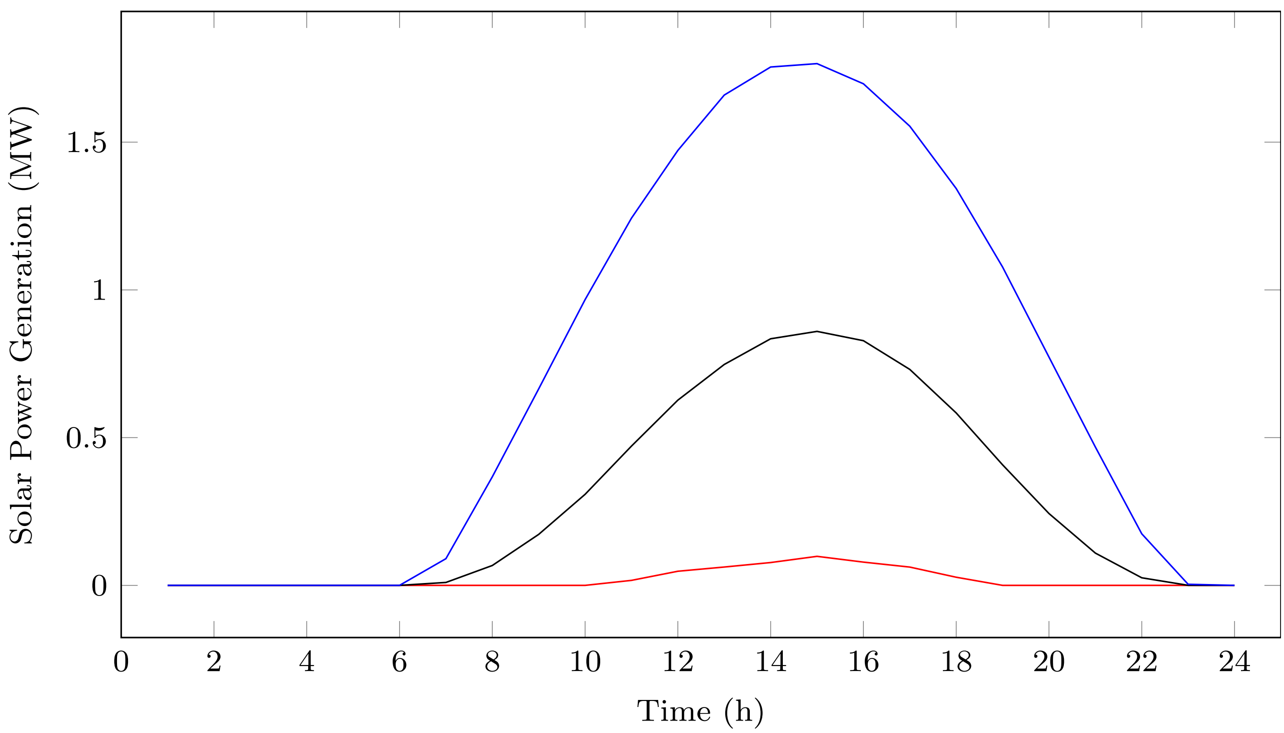


Figure 3.7: The best (blue), nominal (black), and worst (red) representative days for solar power generations on Alderney island in 2013.

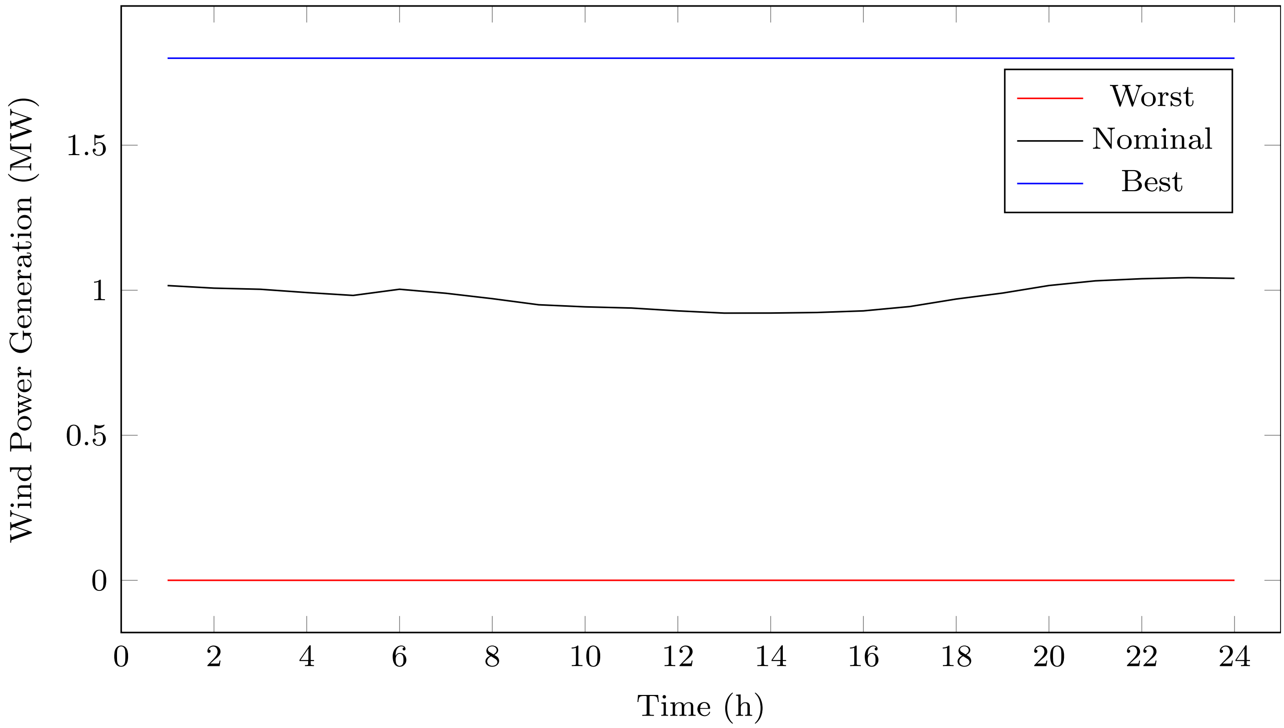


Figure 3.8: The best (blue), nominal (black), and worst (red) representative days for wind power generations on Alderney island in 2013.

daily profiles of load demand, solar power generation, and wind power generation for one representative day are depicted in Figures 3.6, 3.7, and 3.8, respectively. Also, to enhance the accuracy of the proposed planning tool, a larger number of representative operating days are obtained by using the k-means clustering technique.

3.4 Investment and Operation Costs of Different Production Technologies

In this study, battery, solar, and wind units are considered as investment candidates. Investment costs of different technologies are taken from `https://atb.nrel.gov/` and depicted in Table 3.4. Also, it is assumed that the interest rate (i.e., i) is equal to 0.053, while the life time (i.e., y) of battery, solar, and wind units is equal 15, 30, and 30, respectively. The capital recovery factor (i.e., CRF) for each investment candidate can be calculated as follows:

$$CRF = \frac{i \cdot (1+i)^y}{(1+i)^y - 1} \tag{3.1}$$

Accordingly, CRF for battery, solar, and wind units is equal to 0.098, 0.067, and 0.067, respectively, and consequently, the annualised investment costs can be calculated as depicted in Table 3.4. According to Table 3.4, battery units have the highest annualised investment costs while solar units have the lowest annualised investment costs. However, the capacity factor of solar farms is less than the capacity factor of wind farms on Alderney island, as mentioned in Section 3.3. Therefore, it is necessary to use the proposed planning tool to obtain the optimal

Table 3.4: Investment Cost of Different Technologies

Technology	Battery Unit	Solar Unit	Wind Unit
Investment Cost (M£/MW)	0.98	0.84	1.21
Annualised Investment Cost (£/MW)	96040	56280	81070

technologies creating a sustainable electricity network on Alderney island.

In this project, it is assumed that operation costs of battery, solar, and wind units are equal to zero while the operation cost of diesel units (i.e., the wholesale price of diesel oil on Alderney island [19]) is equal to 196.2 £/MWh based on the costs at the time of the project. Additionally, the charging and discharing rates of candidate battery units are equal to 100% during every hour of each representative day.

3.5 Analysis of Potential Solutions

In this section, the proposed planning tool is tested on Alderney microgrid under different conditions. It is assumed that power factor at different nodes is equal to 0.98. In practice, the power factor at different nodes is between [0.98,1.0] on Alderney island. Accordingly, the *worst-case* power factor is considered in all case studies.

First, in subsection 3.5.1, the results only considering one (1) representative day are shown. This approach is the least computational intensive, but forces the use of very distinct inputs. This analysis is given for comparison and to introduce the benchmark.

Second, in subsection 3.5.2, the results of considering multiple representative days are shown. This approach is more computationally intensive, but provides more balanced and accurate results.

3.5.1 Investment Plan Under Best, Nominal, and Worst Scenarios for One Representative Day

In this study, one best, nominal, and worst representative day are constructed using the yearly profiles of load demands and solar/wind power generations on Alderney island in 2013, as illustrated in Figures. 3.3, 3.4, and 3.5, respectively. Also, different investment alternatives are considered at the current location of the AEL power plant, including:

Case 1 (C1): Only 10×1.8-MW wind units are considered as investment candidates, without any diesel units installed.

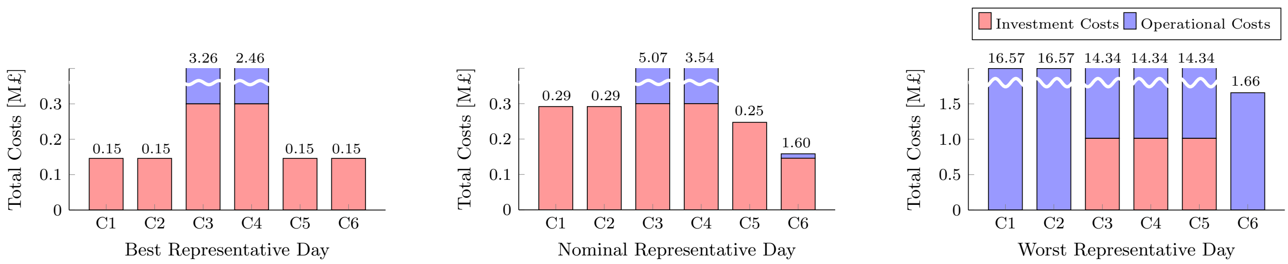
Case 2 (C2): Both 10×1.8-MW battery units and 10×1.8-MW wind units are considered as investment candidates, without any diesel units installed.

Case 3 (C3): Only 10×1.8-MW solar units are considered as investment candidates, without any diesel units installed.

Case 4 (C4): Both 10×1.8-MW battery units and 10×1.8-MW solar units are considered

Table 3.5: Optimal investment plans for different cases under best, nominal, and worst representative days

Case Number	C1	C2	C3	C4	C5	C6
Best Representative Day	$1\times$ W	$1\times$ W	$5\times$ S	$1\times$ B,$2\times$ S	$1\times$ W	$1\times$ W
Nominal Representative Day	$2\times$ W	$2\times$ W	$9\times$ S	$1\times$ B,$5\times$ S	$1\times$ S,$1\times$ W	$1\times$ W
Worst Representative Day	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible	AEL MG



(a) Risk-Seeker (b) Risk-Neutral (c) Risk-Averse

Figure 3.9: Total investment and operational costs for different cases under best, nominal, and worst representative days.

as investment candidates, without any diesel units installed.

Case 5 (C5): All 10×1.8-MW battery units, 10×1.8-MW solar units, and 10×1.8-MW wind units are considered as investment candidates, without any diesel units installed.

Case 6 (C6): All of the current AEL diesel units are considered installed and all options in C5 are considered as investment candidates.

The best, nominal, and worst representative days are illustrated in Figures. 3.6, 3.7, and 3.8 wherein solar/wind power generations are provided for each unit. The optimal investment plans for all cases under the best, nominal, and worst representative days are presented in Table 3.5. Moreover, the total investment and operational costs are depicted in Fig. 3.9.

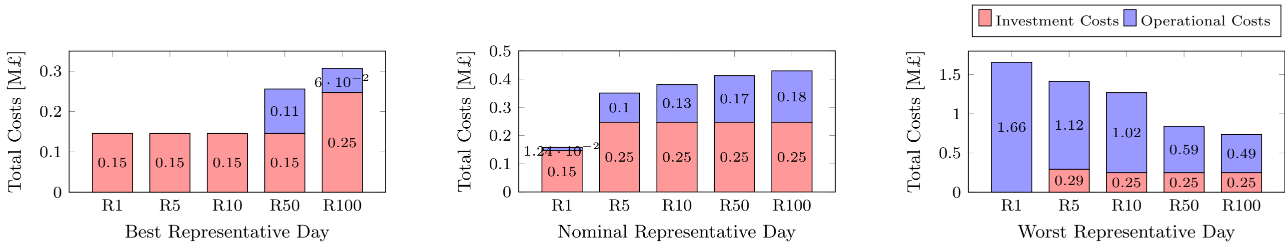
As expected, for all cases (C1-C6), the total costs under the best representative day have the lowest value while the total costs under the worst representative day have the highest value. For instance, the total costs for the best, nominal, and worst representative days of C1 are equal to 0.15 M£ in Fig. 3.9a, 0.29 M£ in Fig. 3.9b, and 16.57 M£ in Fig. 3.9c, respectively.

It is noteworthy to mention that the best representative day for wind power generation corresponds to the maximum capacity of each candidate wind unit while the worst representative day for wind power generation corresponds to no power generation (see Figure 3.8). Accordingly, cases C1-C5, under the worst representative day result in *infeasible* solutions, as illustrated in Table 3.5. Their total costs in Fig. 3.9c (i.e., 16.57 M£ or 14.34 M£) correspond to the penalty cost of load demand curtailment during the entire planning horizon. However, C1, C2, C5, and C6 under the best representative day result in identical optimal investment plans, only constructing a 1.8 MW wind unit and obviating the need to operate the current diesel units.

Furthermore, C6 provides not only the lowest total costs, similar to C1, C2, C5, and C5, under the best representative day, but also the lowest total costs under the nominal and worst representative days. However, C6 under the worst representative day only rely on the current

Table 3.6: Investment plans for different number of best, nominal, and worst representative days for Case C6

Case Number	R1	R5	R10	R50	R100
Best Representative Day	$1 \times$ W	$1 \times$ W	$1 \times$ W	$1 \times$ W	$1 \times$ S,$1 \times$ W
Nominal Representative Day	$1 \times$ W	$1 \times$ S,$1 \times$ W	$1 \times$ S,$1 \times$ W	$1 \times$ S,$1 \times$ W	$1 \times$ S,$1 \times$ W
Worst Representative Day	AEL MG	$2 \times$ W	$1 \times$ S,$1 \times$ W	$1 \times$ S,$1 \times$ W	$1 \times$ S,$1 \times$ W



(a) Risk-Seeker (b) Risk-Neutral (c) Risk-Averse

Figure 3.10: Total investment and operational costs for different number of best, nominal, and worst representative days.

AEL MG without constructing any battery, solar, or wind units. The main reason is that creating a sustainable MG on Alderney based on only one worst representative day results in an over-conservative investment plan.

3.5.2 Investment Plan for Different Number of Representative Days

To enhance the accuracy of the proposed solution, different number of best, nominal, and worst representative days can be considered for C6, including 1 (R1), 5 (R5), 10 (R10), 50 (R50), and 100 (R100). The optimal investment plan for C6 for each choice are presented in Table 3.6 and their total investment and operational costs are depicted in Fig. 3.10. Increasing the number of representative days increases the total costs under the best representative day (Fig. 3.10a) and the nominal representative day (Fig. 3.10b), while decreases the total cost under the worst representative day (Fig. 3.10c). Additionally, the investment plans are identical under the best, nominal, and worst representative days in R100 (constructing one 1.8 MW solar and one 1.8 MW wind unit in addition to the current AEL MG). It is worthwhile to mention that the optimal investment plan remains unchanged after 5 representative days under the nominal condition, while it remains unchanged after 100 (resp. 10) representative days under the best (resp. worst) conditions, as shown in Fig. 3.10. Finally, it can be concluded that 5 nominal representative days can appropriately characterise the uncertain profiles of load demand and RES generation on Alderney island with reasonable computational complexity.

Chapter 4

Conclusions and Recommendations

4.1 Concluding Remarks

In this project, PyEPLAN as an open-source energy planning tool developed at UoL is utilised to desing a sustainable MG on Alderney island under the uncertainty of load demands and RES power generations. The investment planning module in PyEPLAN is modelled as a two-stage stochastic optimisation problem where investment variables are considered as here-and-now decisions and not a function of uncertain parameters while operation variables are considered as wait-and-see decisions and a function of uncertain parameters. The proposed optimisation problem is coded using Pyomo in PyEPLAN, which can be solved by different optimisation packages. Furthermore, all electrical network parameters as well as yearly patterns of load demands and RES power generations are provided for the Alderney microgrid. Moreover, the k-means clustering technique is used to characterise the yearly profiles of load demands and RES power generations through a sufficient number of best, nominal, and worst representative days. According to case studies on Alderney island, it can be concluded that:

- The Alderney microgrid is presented as a practical test system for future investment and operation planning studies on sustainable microgrids.
- The accuracy of the optimal investment plan can be enhanced by increasing the number of representative days.
- The optimal investment plan can be obtained by using either best, nominal, or worst representative days. Since it is probable to face cases with no RES power generation at several hours of a specific day, utilising worst representative days is more reliable than utilising best/nominal representative days.
- The best low-carbon investment plan on Alderney island pertains to a hybrid MG including both solar and wind power in addition to current AEL diesel units.

4.2 Academic-Industrial Links

In this project, the team at UoL has closely collaborated with the team at AEL to evaluate the possibility and feasibility of moving towards a sustainable microgrid on Alderney island. The UoL team had on-site meetings with the AEL team to extend and utilise PyEPLAN and create a sustainable electricity network on Alderney island. For the first time, all electrical parameters of the Alderney microgrid have been calculated in this research project, enabling AEL to undertake further investment and operation studies on the Alderney microgrid.

4.3 Follow-on Projects

This project has presented practical guidelines for creating a sustainable microgrid on Alderney island. The UoL and AEL teams intend to extend this research project by:

- Enhance the accuracy and practicality of the proposed planning tool based on socioeconomic metrics,
- Evaluate the impact of investment in roof-top PVs as a strategic plan on both the utility and consumers,
- Analyse the practicality and feasibility of a hybrid solution based on tidal, solar, and wind energy,
- Investigate the impact of peer-to-peer energy trading between neighbours with roof-top PVs on reducing fixed electricity tariffs on Alderney island.

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