Optimal Decarbonisation Software Framework User Manual

In colloboration with:

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Purpose of Document

This document serves as a user guide for the optimal decarbonisation software framework developed in this research project. The decision-making software framework is based on rigorous mathematical optimisation models, for planning the decarbonisation of ASEAN countries, in line with commitments made while signing the Paris Agreement. The planning framework relies on a combination of proven, mature technologies such as the Carbon Emission Pinch Analysis (CEPA), developed by members of the project team over the past 10 years, and novel mathematical optimisation-based tools that provide rigorous guarantees on the qualities of the solution, subject to planning constraints such as budget, social resistance to uptake, efficiencies of interventions, and implementation time.

The open-source software and planned impact activities ensure that the results and tools' impact is maximised to help both governmental and industrial policymakers in ASEAN countries to identify achievable emissions targets and the optimal paths to achieve them through a range of technologies, interventions, and budgetary and time constraints. The team will deliver significant outreach and engagement activities through multi-day workshops with project partners in emissions-intensive industries in Malaysia, as well as with government agencies to ensure that the software and solutions are data-driven, implementable and align with national strategies.

Further information regarding this research project may be obtained from the project website and GitHub. Further questions about this research project may be directed to Dr Michael Short from the University of Surrey (m.short@surrey.ac.uk).

Acknowledgement

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1. Introduction

Climate change is the gravest threat to humanity's long-term prosperity and the global cooperation to mitigate this threat is unprecedented. The **COP26 summit** taking place in November 2021 aims to accelerate the achievement of the Paris Agreement's goals. To achieve these ambitious emissions targets and keep global warming below 2°C, strategic planning methods for policymaking are essential. These should span entire nations' emissions contributions, across sectors, and should be able to plan for achievable implementation of emissions reduction technologies, negative emissions technologies (NETs), within budgetary, time, and social uptake constraints. Association of South-East Asian Nations (ASEAN) countries, as developing economies, have seen dramatic rises in CO_2 emissions over the past 20 years e.g., CO_2 per capita of Malaysia has risen from 5 t y^{-1} in year 2000 to 8 t y^{-1} in year 2018. Therefore, it is important to develop an energy planning tool that incorporates region-specific conditions.

This research project seeks to develop a decision-making software framework, based on rigorous mathematical optimisation models, for planning the decarbonisation of ASEAN countries, in line with commitments made while signing the Paris Agreement. The novel mathematical optimisation-based tool is expected to provide rigorous guarantees on the qualities of the solution, subject to planning constraints such as budget, social resistance to uptake, efficiencies of interventions and policies, uncertainty, technology readiness levels, and implementation time. The open-source software and planned impact activities ensure that the results and tools' impact is maximised to help both governmental and industrial policymakers in ASEAN countries to identify achievable emissions targets and the optimal paths to achieve them through a range of technologies, interventions, and budgetary and time constraints.

This **research project** brings together academic, industrial and government agencies for the development of the decision-making software framework. The research project team is as follows:

Principal Investigator

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Dr Matteo Cossutta (Aria Sustainability Ltd)

Professor Raymond Tan (De La Salle University, Manila)

Dr Jully Tan (Monash University Malaysia)

2. Optimal Decarbonisation Software Framework

The optimal decarbonisation software developed in this research project is based on a multiperiod energy planning framework. Energy sources i.e., renewable energy, natural gas, oil, and coal each with different output ranges are utilised to satisfy the demand of a geographical region. The satisfaction of the CO_2 emission limit is achievable with the use of energy-producing NETs (EP-NETs), energy-consuming NETs (EC-NETs) and CO_2 capture and storage (CCS). The optimal decarbonisation software framework is built based on the potential deployment of various EP-NETs, EC-NETs and CCS technologies.

2.1. Energy Planning Parameters

The parameters of the optimal decarbonisation software framework are presented in Table 1.

Table 1: Energy Planning Parameters

Parameters	Definition
$\boldsymbol{CS_i}$	CO_2 intensity of power plant *i*
$\boldsymbol{F_{i,LB}}$	Lower bound of energy output by power plant *i*
$\boldsymbol{F_{i,UB}}$	Upper bound of energy output by power plant *i*
$\boldsymbol{D_k}$	Demand for an energy planning system in period *k*
$\boldsymbol{L_k}$	CO_2 emission limit of an energy planning system in period *k*
$\boldsymbol{CM_i}$	Commissioning period
$\boldsymbol{DCM_i}$	Decommissioning period
$\boldsymbol{RR_{k,n}}$	Removal ratio of CCS technology *n* in period *k*
$\boldsymbol{X_{k,n}}$	Parasitic power loss of CCS technology *n* in period *k*
$\boldsymbol{AC_{k,r}}$	Availability of renewable energy source *r* in period *k*
$\boldsymbol{AEP_{k,p}}$	Availability of EP-NETs technology *p* in period *k*
$\boldsymbol{AEC_{k,q}}$	Availability of EC-NETs technology *q* in period *k*
$\boldsymbol{CIAS_{k,s}}$	CO_2 intensity of alternative solid-based fuel *s* in period *k*
$\boldsymbol{CIAG_{k,g}}$	CO_2 intensity of alternative gas-based fuel *g* in period *k*

$\boldsymbol{CIC_{k,r}}$	CO_2 intensity of renewable energy source *r* in period *k*
$\boldsymbol{CIEP_{k,p}}$	CO_2 intensity of EP-NETs technology *p* in period *k*
$\boldsymbol{CIEC_{k,q}}$	CO_2 intensity of EC-NETs technology *q* in period *k*
$\boldsymbol{AFF}$	Annualized cost factor
$\boldsymbol{OF_{i,k}}$	Operational cost of power plant *i* in period *k*
$\boldsymbol{FC1_{i,k}}$	Fixed capital cost of power plant *i* in period *k*
$\boldsymbol{FC2_{i,k}}$	Capacity-dependent capital cost of power plant *i* in period *k*
$\boldsymbol{OC_{k,r}}$	Operational cost of renewable energy source *r* in period *k*
$\boldsymbol{OEP_{k,p}}$	Operational cost of EP-NETs technology *p* in period *k*
$\boldsymbol{OEC_{k,q}}$	Operational cost of EC-NETs technology *q* in period *k*
$\boldsymbol{CC1_{k,r}}$	Fixed capital cost of renewable energy source *r* in period *k*
$\boldsymbol{EPC1_{k,p}}$	Fixed capital cost of EP-NETs technology *p* in period *k*
$\boldsymbol{ECC1_{k,q}}$	Fixed capital cost of EC-NETs technology *q* in period *k*
$\boldsymbol{CC2_{k,r}}$	Capacity-dependent capital cost of renewable energy source *r* in period *k*
$\boldsymbol{EPC2_{k,p}}$	Capacity-dependent capital cost of EP-NETs technology *p* in period *k*
$\boldsymbol{ECC2_{k,q}}$	Capacity-dependent capital cost of EC-NETs technology *q* in period *k*
$\boldsymbol{CTR_{k,n}}$	Power generation cost with the deployment of CCS technology *n* in period *k*
$\boldsymbol{CFR_{k,n}}$	Fixed cost associated with the deployment of CCS technology *n* in period *k*
$\boldsymbol{CTAS_{k,s}}$	Cost of alternative solid-based fuel *s* in period *k*
$\boldsymbol{CTAG_{k,g}}$	Cost of alternative gas-based fuels *g* in period *k*
$\boldsymbol{BD_k}$	Budget allocation in period *k*

The values of each parameter should be declared in the Microsoft Excel-based user-interface file titled '**Optimal_Decarbonisation_User_Interface**'. The Microsoft Excel file consists of 15 tabs. The data to be included in each worksheet tab is explained in Table 2.

Table 2: Data Inclusion for each Worksheet Tab in the User Interface

MICROSOFT EXCEL TAB	ENERGY PLANNING INFORMATION
PLANT_DATA	Type of fuels, lower and upper bounds of power generation, CO_2 intensities, commissioning, and decommissioning timeline of existing and upcoming power plants
ENERGY_PLANNING_DATA	Power demand, CO_2 emissions limit and budget availability in each energy planning period
FUEL_COST_DATA	Costs of fuels utilised in power plants in each energy planning period
RENEWABLE_CI_DATA	CO_2 intensities of available renewable energies in each energy planning period
RENEWABLE_COST_DATA	Costs of available renewable energies in each energy planning period
CAPEX_DATA_1	Fixed capital costs of mitigation technologies in each energy planning period
CAPEX_DATA_2	Capacity-dependent capital costs of mitigation technologies in each energy planning period
ALT_SOLID_CI	CO_2 intensities of alternative solid-based fuels in each energy planning period
ALT_SOLID_COST	Costs of alternative solid-based fuels in each energy planning period
ALT_GAS_CI	CO_2 intensities of alternative gas-based fuels in each energy planning period
ALT_GAS_COST	Costs of alternative gas-based fuels in each energy planning period

CCS_DATA	Removal ratios, parasitic power loss, power generation costs and fixed costs of CCS technologies in each energy planning period
NET_CI_DATA	CO_2 intensities of available NETs in each energy planning period
NET_COST_DATA	Costs of available NETs in each energy planning period
TECH_IMPLEMENTATION_TIME	The availabilities of mitigation technologies in each energy planning period

2.2. Energy Planning Variables

The variables in the optimal decarbonisation software framework are presented in Table 3. These variables had been defined in the Python file titled '**Optimal_Decarbonisation_Model_Python**'.

Table 3: Energy Planning Variables

Variables	Definition
$\boldsymbol{FS_{i,k}}$	Energy generation by power plant *i* in period *k*
$\boldsymbol{A_{i,k}}$	Binary variable for the energy generation by power plant *i* in period *k*
$\boldsymbol{CR_{i,k,n}}$	CO_2 intensity of power plant *i* with the deployment of CCS technology *n* in period *k*
$\boldsymbol{FR_{i,k,n}}$	Deployment of CCS technology *n* in power plant *i* in period *k*
$\boldsymbol{B_{i,k,n}}$	Binary variable for the deployment of CCS technology *n* in power plant *i* in period *k*
$\boldsymbol{FNR_{i,k,n}}$	Net energy of power plant *i* after the deployment of CCS technology *n* in period *k*
$\boldsymbol{FNS_{i,k}}$	Net energy of power plant *i* without the deployment of mitigation technologies in period *k*
$\boldsymbol{FAS_{i,k,s}}$	Deployment of alternative solid-based fuel *s* in power plant *i* in period *k*
$\boldsymbol{FAG_{i,k,g}}$	Deployment of alternative gas-based fuel *g* in power plant *i* in period *k*

$\boldsymbol{FC_{k,r}}$	Deployment of renewable energy source *r* in period *k*
$\boldsymbol{FEP_{k,p}}$	Deployment of EP-NETs technology *p* in period *k*
$\boldsymbol{FEC_{k,q}}$	Deployment of EC-NETs technology *q* in period *k*
$\boldsymbol{C_{k,r}}$	Binary variable for the deployment renewable energy source *r* in period *k*
$\boldsymbol{D_{k,p}}$	Binary variable for the deployment EP-NETs technology *p* in period *k*
$\boldsymbol{E_{k,q}}$	Binary variable for the deployment EC-NETs technology *q* in period *k*
$\boldsymbol{CTF_{k}}$	Total costs of power plant *i* in period *k*
$\boldsymbol{CTC_{k}}$	Total cost associated with the deployment of renewable energy source *r* in period *k*
$\boldsymbol{CTEP_{k}}$	Total cost associated with the deployment of EP-NETs technology *p* in period *k*
$\boldsymbol{CTEQ_{k}}$	Total cost associated with the deployment of EC-NETs technology *q* in period *k*
$\boldsymbol{TE_{k}}$	Total CO_2 load contribution from all power plants and mitigation technologies of energy planning period *k*
$\boldsymbol{TC_{k}}$	Total cost of the energy planning period *k*

2.3. Mathematical Formulation

The energy planning software framework in this work is based on a superstructural model, consisting of existing and upcoming power plants available for power generation, as well as a pool of mitigation technologies. The superstructural model initially determines the energy generation from power plant *i* that satisfies the power demand of period *k*. Following this, the optimal deployment of mitigation technologies i.e., CCS, NETs, and alternative fuels for power plant *i* in period *k* is determined based on the demand and CO_2 emissions constraints. The superstructural model developed in this work would act as a guide to policymakers in terms of power plants' commissioning and decommissioning timeline and total costs involved in meeting the energy demand and CO_2 emissions limit of a geographical region.

Firstly, the cumulative deployment of energy source from power plant $i \in I$ should satisfy the energy demand of period *k*; shown in Equation 1. Note that energy generation by power plant *i* in period *k* ($FS_{i,k}$) is constrained by its lower ($F_{i,LB}$) and upper bound of energy generation ($F_{i,UB}$) as demonstrated in Equation 2 and Equation 3 respectively.

$$\sum_{i} FS_{i,k} = D_k \qquad \forall k$$ Equation 1

$$FS_{i,k} \geq F_{i,LB} \times A_{i,k} \qquad \forall i\ \forall k$$ Equation 2

$$FS_{i,k} \leq F_{i,UB} \times A_{i,k} \qquad \forall i\ \forall k$$ Equation 3

Next, the energy generation from power plant *i* in period *k* is subject to either its commissioning or decommissioning timeline as demonstrated in Equation 4. Energy generation from power plant *i* would only take place from the commissioning period, CM_i onwards. Before the commissioning period, there should not be any energy generation from power plant *i*. By contrast, energy generation from power plant *i* would only take place until the period before the decommissioning period, DCM_i.

$$FS_{i,k} = \begin{cases} 0, & k < CM_i \\ 0, & k \geq DCM_i \end{cases} \qquad \forall i\ \forall k$$ Equation 4

Also, the energy generated from power plant *i* in period *k* should at least match its generation in the previous period, as shown in Equation 5. The constraint ensures a continuous operation for power plant *i* if it is selected for power generation. A temporary shut-down for power plant *i* would be impractical.

$$FS_{i,k+1} \geq FS_{i,k} \qquad \forall i\ ;\ k = 1,2,\dots,n-1$$ Equation 5

CCS is one of the mitigation technologies that may be employed in power plant *i* for the satisfaction of the CO_2 emissions limit. CDR via CCS decreases the CO_2 intensity of power plant *i*. Therefore, the CO_2 intensity of power plant *i* with the deployment of CCS technology *n* in period *k* is calculated from Equation 6.

$$CR_{i,k,n} = \frac{CS_i \times \left(1 - RR_{k,n}\right)}{1 - X_{k,n}} \qquad \forall i\ \forall k\ \forall n$$ Equation 6

The deployment of CCS technology *n* is constrained by the upper bound of energy generation by power plant *i*; shown in Equation 7. Also, the cumulative deployment of all CCS technologies should not exceed the energy generation by power plant *i* in period *k* as demonstrated in Equation 8.

$$FR_{i,k,n} \leq F_{i,UB} \times B_{i,k,n} \qquad \forall i\ \forall k\ \forall n$$ Equation 7

$$\sum_{n} FR_{i,k,n} \leq FS_{i,k} \qquad \forall i\ \forall k$$ Equation 8

Like the energy generation from power plant *i*, the deployment of CCS technology *n* in power plant *i* in period *k* should at least match its deployment in the previous period as shown in Equation 9. CCS technology is capital intensive. Therefore, it is not practical for CCS technology *n* to be deployed in period *k* and not used in the subsequent period.

$$FR_{i,k+1,n} \geq FR_{i,k,n} \qquad \forall i\ \forall n\ ;\ k = 1,2,\ldots,n-1 \qquad \text{Equation 9}$$

CCS deployment incurs parasitic power loss of energy sources. Therefore, the net energy of power plant *i* after the deployment of CCS technology *n* in period *k*, $FNR_{i,k,n}$ is calculated from Equation 10.

$$FR_{i,k,n} \times \left(1 - X_{k,n}\right) = FNR_{i,k,n} \qquad \forall i\ \forall k\ \forall n \qquad \text{Equation 10}$$

Aside from CCS, mitigation technologies that are available for power plant *i* in this work are alternative solid-based fuel *s* and alternative gas-based fuel *g*. Note that alternative solid and gas-based fuels may be used to replace fuels in power plant *i* which are in solid and gas phases respectively. The deployment of these alternative fuels in power plant *i* in period *k* should at least match its deployment in the previous period as shown in Equation 11 and Equation 12. The reasoning for this is like CCS deployment.

$$FAS_{i,k+1,s} \geq FAS_{i,k,s} \qquad \forall i\ \forall s\ ;\ k = 1,2,\ldots,n-1 \qquad \text{Equation 11}$$

$$FAG_{i,k+1,g} \geq FAG_{i,k,g} \qquad \forall i\ \forall g\ ;\ k = 1,2,\ldots,n-1 \qquad \text{Equation 12}$$

The cumulative deployment of all mitigation technologies available in this work should equate to the energy generated by power plant *i* in period *k* as demonstrated in Equation 13. The latter is initially determined from Equation 1.

$$FNS_{i,k} + \sum_{n} FR_{i,k,n} + \sum_{s} FAS_{i,k,s} + \sum_{g} FAG_{i,k,g} = FS_{i,k} \qquad \forall i\ \forall k \qquad \text{Equation 13}$$

Other mitigation technologies that are available in this work are renewable energy source *r*, EP-NETs technology *p* and EC-NETs technology *q*. Note that these technologies are not plant-specific. Instead, the cumulative deployment of these mitigation technologies is determined for period *k*. The deployment of renewable energy source *r* ($FC_{k,r}$), EP-NETs technology *p* ($FEP_{k,p}$) and EC-NETs technology *q* ($FEC_{k,q}$) in period *k* are constrained by the availability of each technology, as demonstrated in Equation 14, Equation 15 and Equation 16 respectively.

$$FC_{k,r} \leq AC_{k,r} \times C_{k,r} \qquad \forall k\ \forall r \qquad \text{Equation 14}$$

$$FEP_{k,p} \leq AEP_{k,p} \times D_{k,p} \qquad \forall k\ \forall p \qquad \text{Equation 15}$$

$$FEC_{k,q} \leq AEC_{k,q} \times E_{k,q} \qquad \forall k\ \forall q \qquad \text{Equation 16}$$

The cumulative deployment of all mitigation technologies (CCS, alternative fuel, renewable energy sources and NETs) should satisfy the total demand of the energy system of period *k*; the latter includes the total power requirement (D_k) and that required by EC-NETs ($FEC_{k,q}$), as demonstrated in Equation 17.

$$\sum_i FNS_{i,k} + \sum_i \sum_n FNR_{i,k,n} + \sum_i \sum_s FAS_{i,k,s} + \sum_i \sum_g FAG_{i,k,g} + \sum_r FC_{k,r} + \sum_p FEP_{k,p} = \sum_q FEC_{k,q} + D_k \quad \forall k \qquad \text{Equation 17}$$

Following this, the total CO_2 load contribution from all power plants and mitigation technologies of energy planning period *k* (TE_k) is determined from Equation 18.

$$\sum_i FNS_{i,k}\, CS_i + \sum_i \sum_n FNR_{i,k,n}\, CR_{i,k,n} + \sum_i \sum_s FAS_{i,k,s}\, CIAS_{k,s} + \sum_i \sum_g FAG_{i,k,g}\, CIAG_{k,g} + \sum_r FC_{k,r}\, CIC_{k,r} + \sum_p FEP_{k,p}\, CIEP_{k,p} + \sum_q FEC_{k,q}\, CIEC_{k,q} = TE_k \quad \forall k \qquad \text{Equation 18}$$

Next, the total costs of power plant *i* in period *k* (CTF_k) are calculated from Equation 19. While the first term of those equations represents the operating costs, the remaining two terms constitute the capital expenditure of the mitigation technologies. For the capital expenditure, the second term relates to the fixed cost associated with the development of a new plant e.g., land and machinery. Meanwhile, the third term is the fixed cost associated with the plant capacity. A larger plant capacity would have a higher fixed cost and vice versa.

$$\sum_i \Big(\big(FNS_{i,k}\, OF_{i,k}\big) + \big(AFF \times A_{i,k} \times FC1_{i,k}\big) + \big(AFF \times FNS_{i,k} \times FC2_{i,k}\big) \Big) = CTF_k \quad \forall k \qquad \text{Equation 19}$$

Following this, the total costs associated with the deployment of renewable energy source *r* (CTC_k), EP-NETs technology *p* ($CTEP_k$) and EC-NETs technology *q* ($CTEQ_k$) in period *k* are determined from Equation 20, Equation 21 and Equation 22 respectively.

$$\sum_r \Big(\big(FC_{k,r}\, OC_{k,r}\big) + \big(AFF \times C_{k,r} \times CC1_{k,r}\big) + \big(AFF \times FC_{k,r} \times CC2_{k,r}\big) \Big) = CTC_k \quad \forall k \qquad \text{Equation 20}$$

$$\sum_p \Big(\big(FEP_{k,p}\, OEP_{k,p}\big) + \big(AFF \times D_{k,p} \times EPC1_{k,p}\big) + \big(AFF \times FEP_{k,p} \times EPC2_{k,p}\big) \Big) = CTEP_k \quad \forall k \qquad \text{Equation 21}$$

$$\sum_{q}\left(\left(FEC_{k,q}\, OEC_{k,q}\right)+\left(AFF\times E_{k,q}\times ECC1_{k,q}\right)\right.$$
$$\left.+\left(AFF\times FEC_{k,q}\times ECC2_{k,q}\right)\right)=CTEQ_{k}\qquad\forall k \qquad \text{Equation 22}$$

The total cost of the energy planning period k, TC_k is calculated from Equation 23. Note that this calculation procedure considers all power plants and mitigation technologies, including those calculated from Equation 20, Equation 21 and Equation 22.

$$CTF_{k}+\sum_{i}\sum_{n}\left(FNR_{i,k,n}\, CTR_{k,n}+\, CFR_{k,n}B_{i,k,n}\right)+\sum_{i}\sum_{s}FAS_{i,k,s}\, CTAS_{k,s}$$
$$+\sum_{i}\sum_{g}FAG_{i,k,g}\, CTAG_{k,g}+\ CTC_{k}+CTEP_{k}+CTEC_{k}$$
$$=TC_{k}\qquad\forall k \qquad \text{Equation 23}$$

Subsequently, Equation 24 and Equation 25 present the constraints related to the total CO_2 emissions and total energy planning cost respectively.

$$TE_{k}\ \leq L_{k}\qquad\forall k \qquad \text{Equation 24}$$

$$TC_{k}\leq BD_{k}\qquad\forall k \qquad \text{Equation 25}$$

where BD_k is the budget allocation of energy planning period k.

The next section discusses the objective function of the optimal decarbonisation software framework.

2.4. Objective Function

The objective function of this work is set to minimise either the total energy planning cost (Equation 26) or total CO_2 emissions (Equation 27). If the former is selected as the objective function, the constraints from Equation 1 till Equation 24 ensures that the CO_2 emissions limit of a geographical region in period k is satisfied. Meanwhile, for the latter objective function, the constraints from Equation 1 till Equation 23 and Equation 25 limit the deployment of mitigation technologies subject to the budget availability of energy planning period k. Therefore, the CO_2 emissions limit may or may not be satisfied.

$$\min TC_{k} \qquad \text{Equation 26}$$

$$\min TE_{k} \qquad \text{Equation 27}$$

The resulting mathematical formulation is a mixed-integer linear programming (MILP) model. The model is implemented in Pyomo, with an easy-to-use input spreadsheet to formulate one's problems. The next section describes the step-by-step procedure to download the relevant files for optimal decarbonisation from GitHub.

2.5. GitHub Files Download

All files relevant to the optimal decarbonisation framework should be downloaded from GitHub to a user's operating machine before performing any optimisation task. The step-by-step procedure for the download of the relevant files from GitHub is as follows:

i. A user should access the BCCOP26 Trilateral Project in GitHub from https://github.com/mchlshort/BCCOP26TrilateralProject.

ii. A user had arrived at the right landing page if the top right of the GitHub page is labelled as '**mchlshort/BCCOP26TrilateralProject**'

iii. A user should click the green icon '**Code**', followed by '**Download ZIP**' to download all files relevant to the optimal decarbonisation framework, as shown in Figure 1.

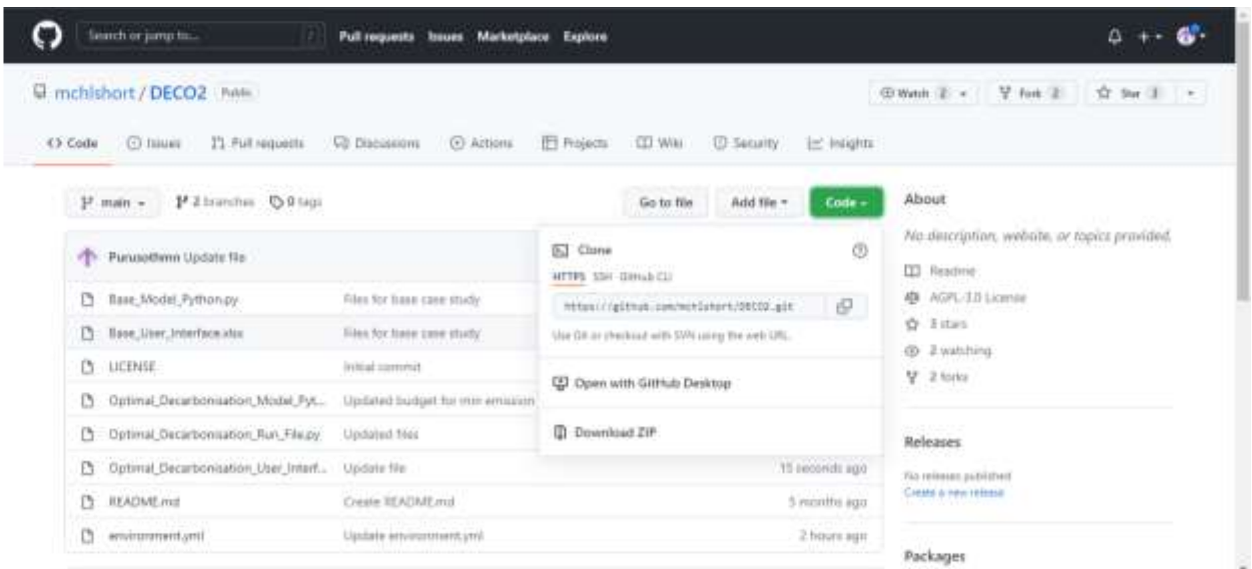

Figure 1: GitHub Landing Page

iv. The ZIP folder downloaded from GitHub would contain files, described as follows:

- **Optimal_Decarbonisation_User_Interface** – This file contains the user interface for the optimal decarbonisation software framework. A user should input the plant and energy planning data in this file before performing the optimisation in Python.

- **Optimal_Decarbonisation_Model_Python** – This file contains the complete mathematical formulation for the optimal decarbonisation software framework.

- **Optimal_Decarbonisation_Run_File** – This file contains the run code for the optimal decarbonisation framework in Python

- **environment.yml** – This file contains the environment to be imported to Anaconda

v. A user should ensure that the files are saved in the same directory that would be used later for the Octeract Engine solver files.

The MILP model is solved using **Pyomo, a Python-based open-source optimisation modelling language**. To perform the optimisation task in Pyomo, there are two parts of installation necessary beforehand i.e., **Anaconda and Octeract Engine Solver**. The following section describes the installation procedure of Anaconda on a user's operating machine. Note that some users might experience issues during the installation of both programmes. If any issue occurs, a user should choose to 'run as admin' before installation.

2.6. Anaconda Installation

Anaconda is a free and open-source distribution for Python programming language to be used for scientific computing. Anaconda contains multiple data-science packages that may be used in Windows, Linus and macOS. Therefore, the first step would be for a user to install Anaconda on one's operating machine. The step-by-step procedure for Anaconda installation is as follows:

i. A user should install Anaconda from https://www.anaconda.com/distribution/

ii. During installation, a user should uncheck the 'Add Anaconda3 to my PATH environment variable' box and check the 'Register Anaconda3 as my default Python 3.8' box, as shown in Figure 2.

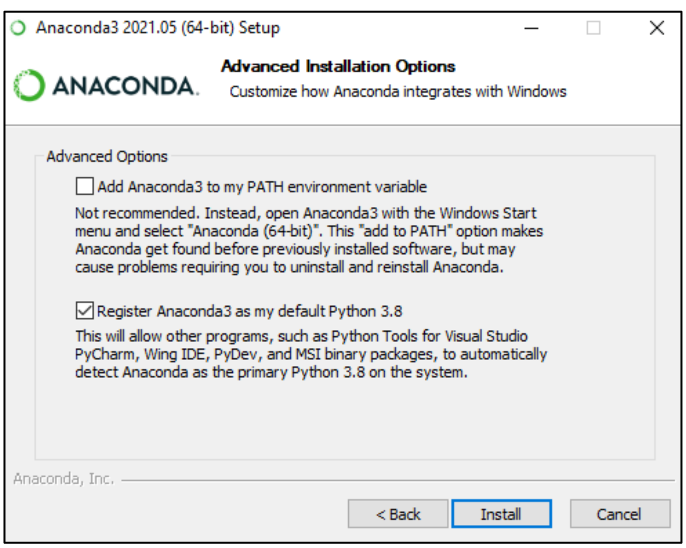

Figure 2: Anaconda Installation Options

iii. Once download, a user should launch the Anaconda application and view the home page as shown in Figure 3.

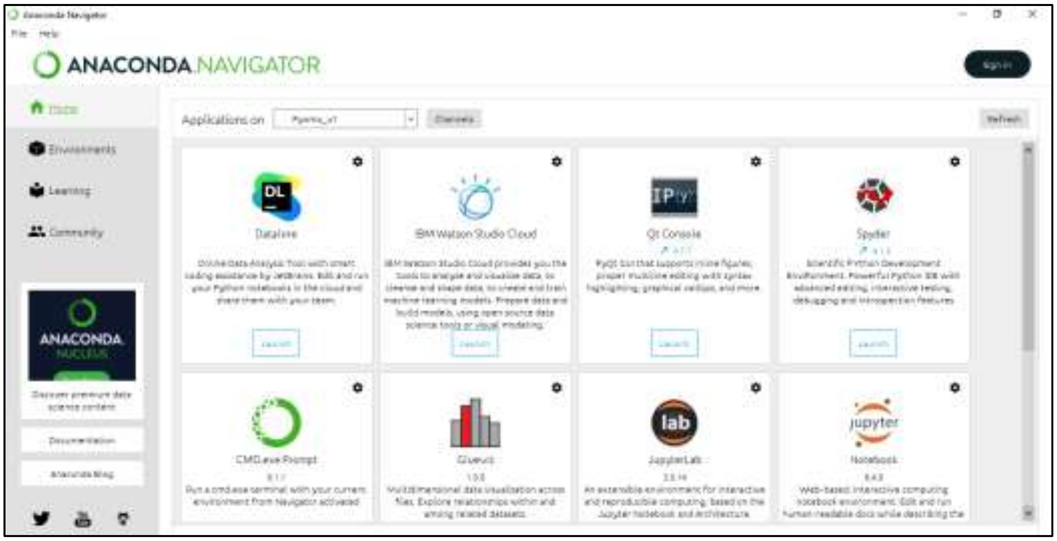

Figure 3: Anaconda Home Page

iv. Under the top-left of the home page, a user should click the '**Environment**' tab.

v. At the bottom of the '**Environment**' tab, a user would see four options provided to create a new environment in Anaconda. (see Figure 4)

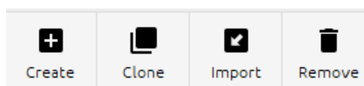

Figure 4: Options for new Anaconda Environment

vi. A user should click on '**Import**' and arrive at the '**Import new environment**' pop-up window visualised in Figure 5.

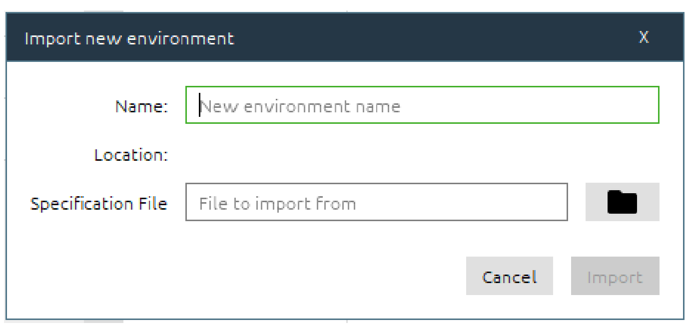

Figure 5: Import New Environment

vi. The name of the new environment may be customised according to a user's preference e.g., *Energy Planning*, *Modelling* etc.

vii. Under the '**Specification File**' box, a user should import the environment file titled '**environment.yml**'.

viii. Once the environment file is loaded, a user should click import. The import process should take several minutes to be completed.

ix. Once the import process is completed, a user should be able to see the name of the new environment below the default (base) Anaconda environment.

x. A user should select the new environment. If this new environment was not previously selected, this process of activating the new environment should take approximately 30 seconds.

xi. Next, a user should left click on the arrow and select '**Open Terminal**', as shown in Figure 6.

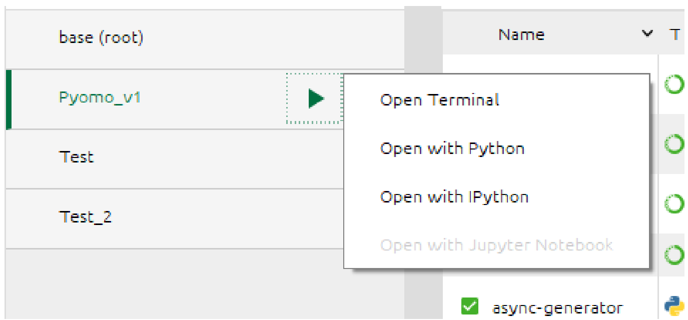

Figure 6: Accessing Environment Terminal

xii. A pop-up window would appear as shown in Figure 7. A user should ensure that the terminal is loaded for the correct environment. The name of the new environment should appear in a bracket before the directory specification (see Figure 7).

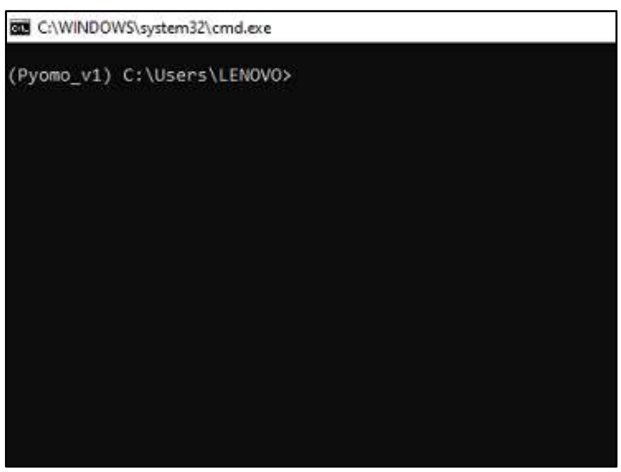

Figure 7: Environment Terminal Command Prompt

xiii. Under the terminal, a user should type '**Spyder**' and click enter, as shown in Figure 8.

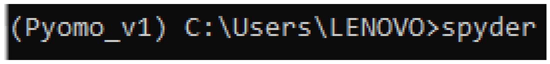

Figure 8: Launching Spyder from Environment Terminal

xiv. The Spyder application would be launched, and a user would be able to view the Spyder console, as shown in Figure 9.

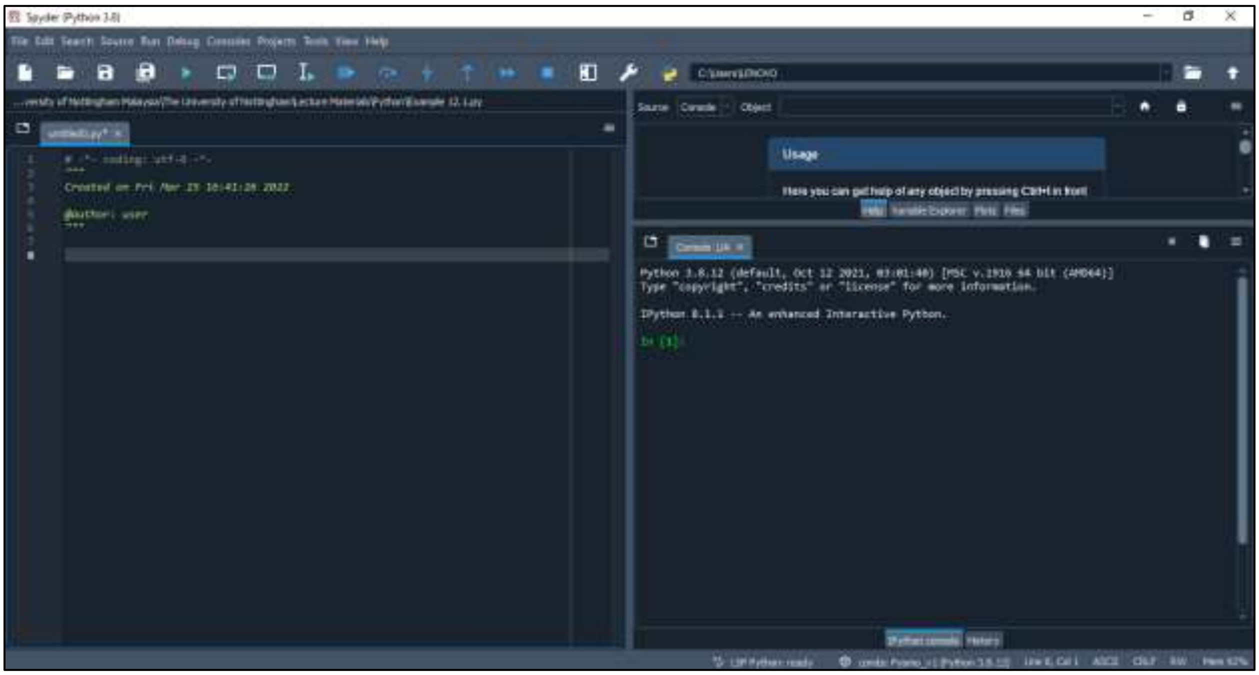

Figure 9: Spyder Console

At this step, a user should be able to use Spyder to solve an optimisation problem. Since the mathematical formulation for this research project is a MILP model, a user should install an appropriate optimisation solver i.e., Octeract Engine. The following section describes the installation procedure of Octeract Engine for the Windows operating system.

2.7. Octeract Engine Installation for Windows Operating System

Octeract Engine is the optimisation solver for the MILP mathematical formulation in this research project. Since Octeract Engine is not readily available in Python, a user should install the Octeract Engine solver beforehand. The step-by-step procedure for the Octeract Engine installation for the Windows operating system is as follows:

i. A user should install the Octeract Engine solver from https://octeract.com/#download
ii. A user should also complete the registration process at https://octeract.com/register to obtain the authentication token to be used during the engine setup.
iii. During installation, the user would be prompted to choose an authentication token, as shown in Figure 10.

iv. The user should choose the second option '**Use an existing authentication token**' (see Figure 10).

v. The user would then be prompted to select a file containing the authentication token downloaded from the website upon completion of registration.

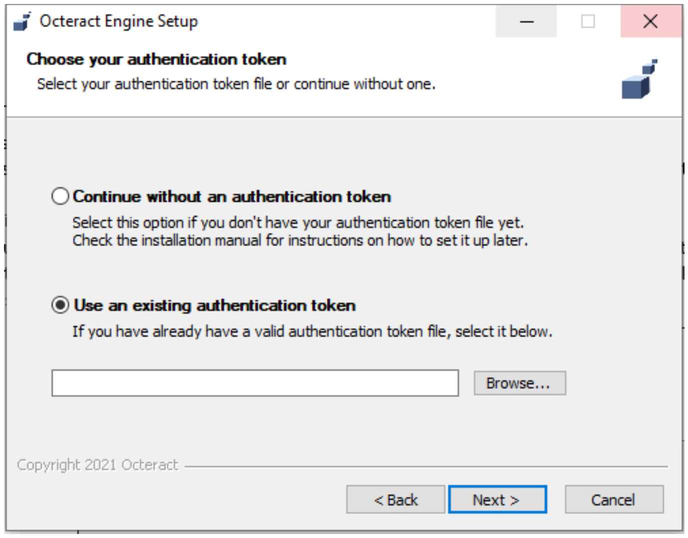

Figure 10: Octeract Engine Authentication Token

vi. Note, the Octeract Engine solver should be installed in the same directory (folder) that was used to save the optimisation files downloaded from GitHub (see Figure 11).

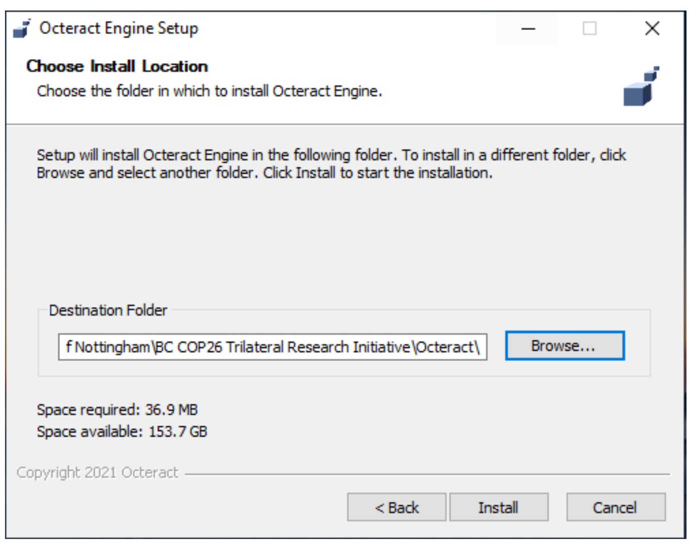

Figure 11: Octeract Engine Solver Directory Change

vii. Upon installation, a user should re-check that the Octeract Engine solver is installed within the same directory as the optimisation files (see Figure 12).

Octeract	24/09/2021 11:51	File folder	
environment.yml	14/08/2021 14:56	YML File	6 KB
LICENSE	02/06/2021 19:01	File	35 KB
Optimal Decarbonisation User Manual	24/09/2021 12:14	Microsoft Word Docume...	872 KB
Optimal Decarbonisation User Manual	16/08/2021 14:03	Adobe Acrobat Document	579 KB
Optimal_Decarbonisation_Model_Python	17/09/2021 11:22	PY File	20 KB
Optimal_Decarbonisation_Model_Python_Malaysia	21/09/2021 17:45	PY File	20 KB
Optimal_Decarbonisation_Run_File	23/09/2021 18:55	PY File	2 KB
Optimal_Decarbonisation_Run_File_Malaysia	21/09/2021 16:59	PY File	2 KB
Optimal_Decarbonisation_User_Interface	17/09/2021 12:13	Microsoft Excel Worksheet	26 KB
Optimal_Decarbonisation_User_Interface_Malaysia	21/09/2021 18:02	Microsoft Excel Worksheet	39 KB

Figure 12: Octeract Engine Solver Directory

viii. For a smoother user experience, a user should set the path directory of the environment variables. A user should search for ‘**environment variables**’ (see Figure 13) and arrive at the page shown in Figure 14.

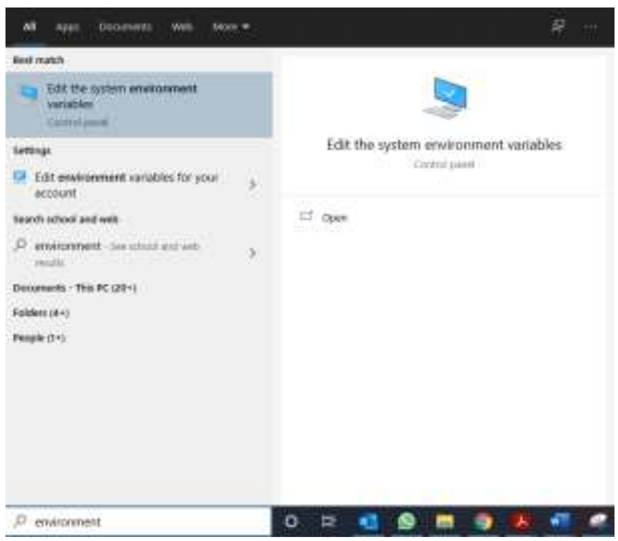

Figure 13: Environment Variable Search from Start-up Menu

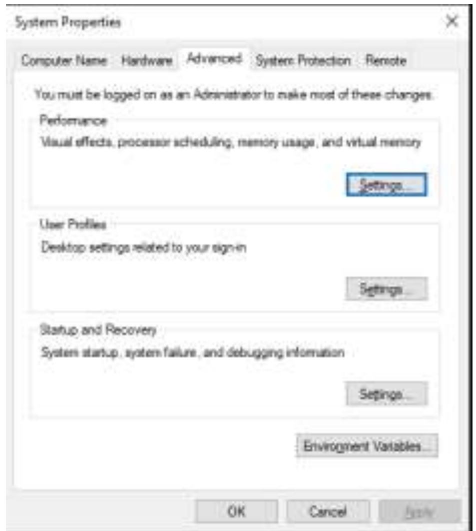

Figure 14: System Properties

ix. Next, the user should click the '**Environment Variables**'.

x. Under the 'user variables for user' box, a user should select '**Path**' and click '**Edit**', as shown in Figure 15.

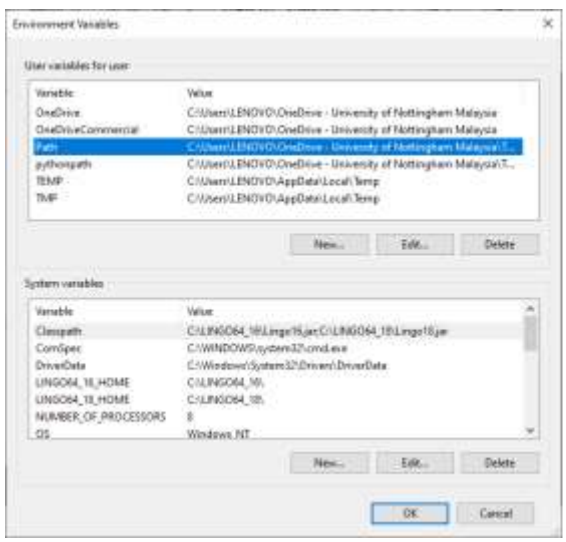

Figure 15: Environment Variables

xi. Then, a user should click '**New**' to add the directory that the necessary files for the optimal decarbonisation software framework (see Figure 16). The directory should be similar to the pathname for the optimisation files (see Figure 17). Note that a user only needs to add one directory.

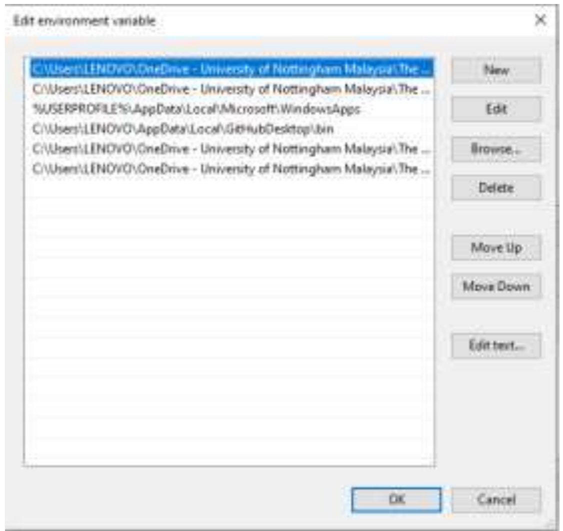

Figure 16: Edit Environment Variables

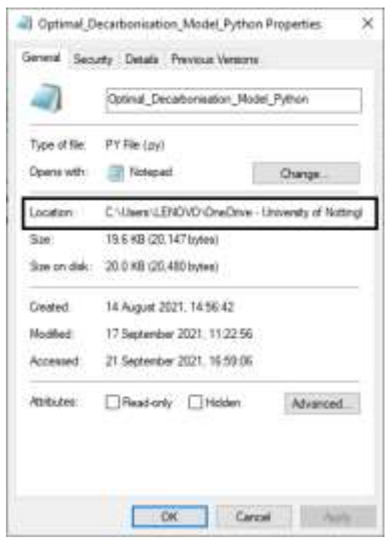

Figure 17: Pathname of Optimisation Files

xii. For more information regarding environment variables and Octeract Engine installation, kindly refer to the explanatory video and installation guide respectively.

The following section describes the installation procedure of Octeract Engine for the Mac operating system.

2.8. Octeract Engine Installation for Mac Operating System

Presently, the Octeract Engine is not supported for the Mac operating system. A Mac user could use a Windows or Linus virtual machine to install the Octeract Engine solver (refer to Section 2.7 for the installation procedure). The next section describes the step-by-step procedure of optimising the mathematical formulation in Section 2.3, based on the objective function in Section 2.4.

2.9. Mathematical Optimisation

The optimisation of the decarbonisation framework would be conducted via Spyder. The step-by-step procedure for the mathematical optimisation is as follows:

i. In Spyder, a user should open the file titled '**Optimal_Decarbonisation_Run_File**' by selecting '**Open**' under the '**File**' tab.
ii. Once the '**Optimal_Decarbonisation_Run_File**' file is opened, the pathname in line 14 must be changed.
iii. To obtain the pathname, a user would right-click the folder that contains the optimisation files and click '**Properties**'. Under the '**General**' tab, the pathname could be found at the '**Location**' (see Figure 18).
iv. Once the pathname had been copied, a user should paste and replace the text *"COPY_PATHNAME_ AND_REPLACE_THIS_TEXT"* in line 14 of the '**Optimal_Decarbonisation_Run_File**' file. Note that the pathname must be placed within **single quotation marks**.

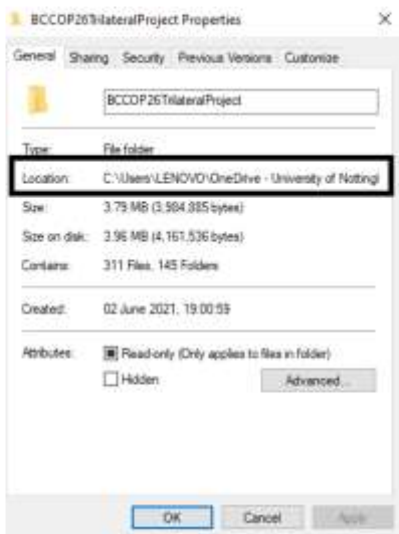

Figure 18: File Directory

v. Before optimising the decarbonisation framework, a user should input the plant and energy planning data in the Microsoft Excel file titled '**Optimal_Decarbonisation_User_Interface**'. The user should also specify the objective function. Kindly refer to Section 2.4 for more details regarding the objective function.
vi. Once the user had inputted the plant and energy planning data, a user should save and close the Microsoft Excel file titled '**Optimal_Decarbonisation_User_Interface**'.
vii. A user should then click F5 to run the file in Spyder. The optimisation procedure is complete once the solver status is displayed, as shown in Figure 19.

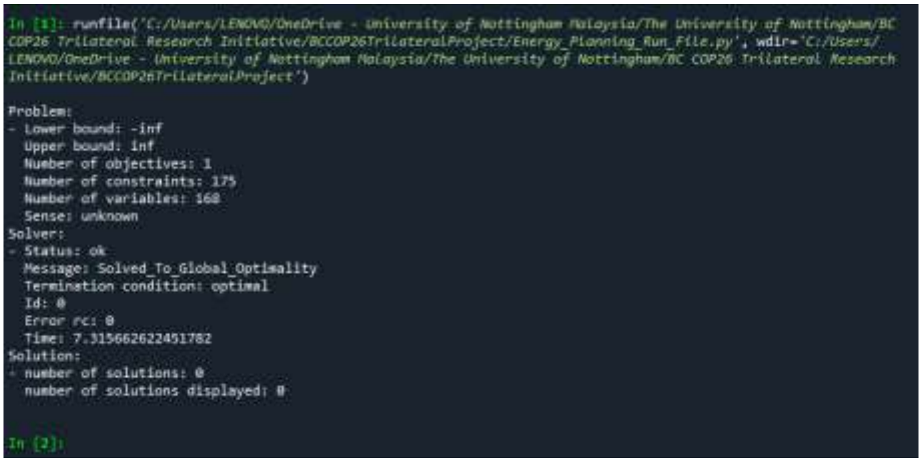

Figure 19: Solver Status

viii. A user should then re-open the Microsoft Excel file titled '**Optimal_Decarbonisation_User_Interface**' to view the detailed results.

ix. A user would observe additional worksheet tabs beyond the '**TECH_IMPLEMENTATION TIME**' tab consisting of the optimisation results for each period.

x. Note that a user should consider deleting the results sheet or moving the results to a separate Microsoft Excel file before optimising a different case study. Else, the results would be duplicated, thus messy.

2.10 Results Visualisation

Upon optimising the energy planning superstructural model, the console displays the solver status and parameters associated with an optimisation problem e.g., number of objectives, variables, user time etc. If the termination condition is mentioned as 'optimal', it indicates that the superstructural model is solved to global optimality. An energy planner may now re-open the Microsoft Excel file for results viewing. Figure 20 presents the snapshot of the results in the Microsoft Excel-based user-interface file.

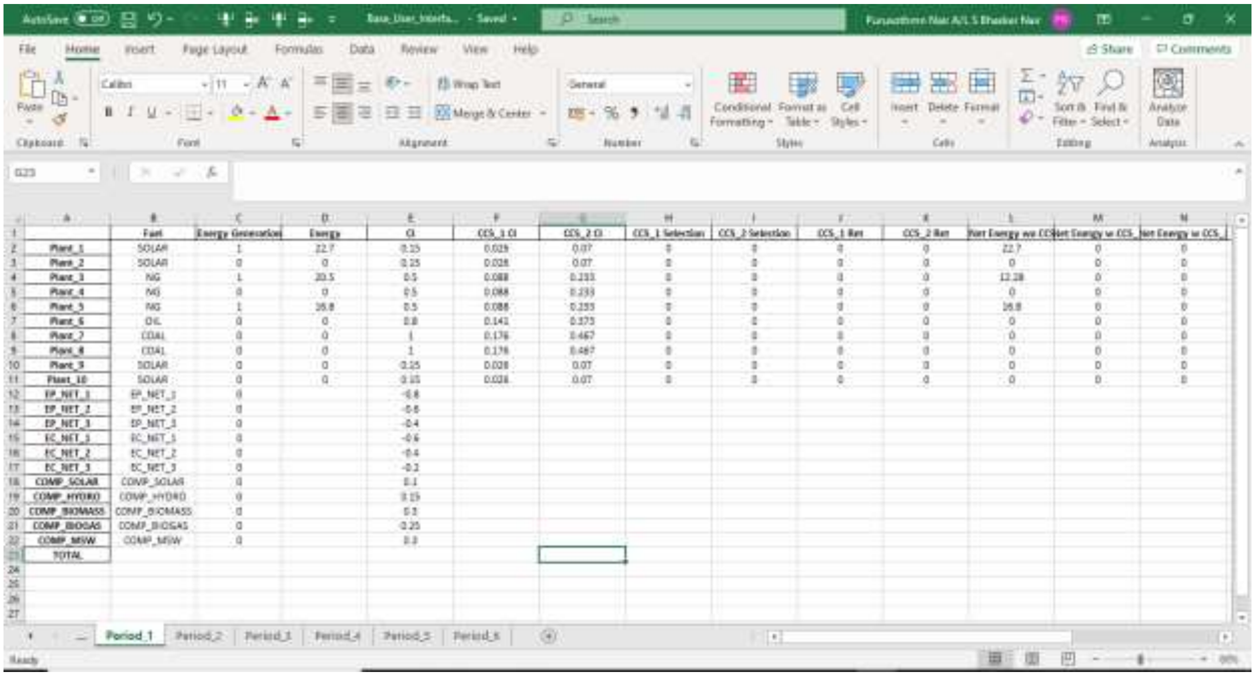

Figure 20: Results snapshot of the optimised energy planning superstructural model

The results in Figure 20 consists of all power plants specified in the ***'PLANT_DATA'*** tab, as well as available mitigation technologies. Table 4 describes the definition of the column heading in Figure 20.

Table 4: Description of the column heading under the results tab

COLUMN HEADING	DESCRIPTION
Fuel	Type of fuel used in the power plant
Energy Generation	Binary variable for the energy generation by each power plant
Energy	Gross energy generated by each power plant
CI	CO_2 intensity of each power plant
CCS_1 CI	CO_2 intensity of each power plant with the deployment of CCS technology 1
CCS_2 CI	CO_2 intensity of each power plant with the deployment of CCS technology 2
CCS_1 Selection	Binary variable for the deployment of CCS technology 1 in each power plant

CCS_2 Selection	Binary variable for the deployment of CCS technology 2 in each power plant
CCS_1 Ret	Energy from each power plant subjected to the deployment of CCS technology 1
CCS_2 Ret	Energy from each power plant subjected to the deployment of CCS technology 2
Net Energy wo CCS	Net energy from each power plant without CCS deployment
Net Energy w CCS_1	Net energy from each power plant with the deployment of CCS technology 1
Net Energy w CCS_2	Net energy from each power plant with the deployment of CCS technology 2
SOLID_1	Energy generation by alternative solid-based fuel type 1 in each power plant
SOLID_2	Energy generation by alternative solid-based fuel type 2 in each power plant
GAS_1	Energy generation by alternative gas-based fuel type 1 in each power plant
GAS_2	Energy generation by alternative gas-based fuel type 2 in each power plant
Net Energy	The net energy of each power plant and mitigation technology (NETs & renewable energy)
Carbon Load	The total CO_2 load of each power plant and mitigation technology (NETs & renewable energy)
Cost	The total cost of the energy planning system

The next section presents the base case study to demonstrate the optimisation of the decarbonisation framework via Python.

3. Base Case Study

A case study is used to demonstrate the application of the optimal decarbonisation software framework. The energy planning superstructural model in this work is demonstrated with six periods, each spanning a time interval of five years.

3.1 Energy Planning Data

Table 5 presents the energy planning data that is specified in the user interface file titled ***'Base_User_Interface'***.

Table 5: Case study energy planning data: (a) 'PLANT_DATA', (b) 'ENERGY_PLANNING_DATA', (c) 'FUEL_COST_DATA', (d) 'COMPENSATORY_CI_DATA', (e) 'COMPENSATORY_COST_DATA', (f) 'CAPEX_DATA_1', (g) 'CAPEX_DATA_2', (h) 'ALT_SOLID_CI', (i) 'ALT_SOLID_COST', (j) 'ALT_GAS_CI', (k) 'ALT_GAS_COST', (l) 'CCS_DATA', (m) 'NET_CI_DATA', (n) 'NET_COST_DATA' and (o) 'TECH_IMPLEMENTATION_TIME'

(a)

Plant	Category	Fuel	Lower Bound / TWh y^{-1}	Upper Bound / TWh y^{-1}	CO_2 Intensity / Mt TWh^{-1}	CM_i	DCM_i
Plant 1	Renewable	Solar	20.03	26.70	0.15	1	7
Plant 2			15.98	21.30	0.15	1	7
Plant 3	Fossil Fuel	Natural Gas	5.13	20.50	0.50	1	7
Plant 4			3.48	13.90	0.50	1	7
Plant 5			4.20	16.80	0.50	1	7
Plant 6		Oil	4.00	16.00	0.80	1	3
Plant 7		Coal	6.68	26.70	1.00	1	5
Plant 8			4.53	18.10	1.00	1	7
Plant 9	Renewable	Solar	15.00	20.00	0.15	2	7
Plant 10			18.75	25.00	0.15	4	7

(b)

Energy planning parameters	1	2	3	4	5	6
Demand / TWh y^{-1}	60	75	90	105	120	135
CO_2 Emissions Limit / Mt	20	18	15	11	6	0
Budget / mil USD y^{-1}	3,000	3,500	4,000	4,500	5,000	5,500

(c)

Fuel cost / mil USD TWh^{-1}	1	2	3	4	5	6
Natural Gas	25					
Oil	49					
Coal	12					
Solar	40	35	25	13	8	3

(d)

CO_2 intensity of renewable energy / Mt TWh^{-1}	1	2	3	4	5	6
Solar	0.10	0.09	0.08	0.07	0.06	0.05
Hydropower	0.15	0.14	0.13	0.12	0.11	0.10
Biomass	0.30	0.28	0.26	0.24	0.22	0.20
Biogas	0.25	0.23	0.21	0.19	0.17	0.15
Municipal Solid Waste	0.30	0.29	0.28	0.27	0.26	0.25

(e)

Cost of renewable energy / mil USD TWh^{-1}	1	2	3	4	5	6
Solar	40	35	25	13	8	3
Hydropower	30	29	28	27	26	25
Biomass	20	18	16	14	12	10
Biogas	25	23	21	19	17	15
Municipal Solid Waste	20	19	18	17	16	15

(f)

<table>
<tr><th>Fixed capital costs / mil USD TWh⁻¹</th><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th></tr>
<tr><td>Natural Gas</td><td colspan="6" rowspan="3">400</td></tr>
<tr><td>Oil</td></tr>
<tr><td>Coal</td></tr>
<tr><td>Solar</td><td>400</td><td>350</td><td>300</td><td>250</td><td>200</td><td>150</td></tr>
<tr><td>Hydropower</td><td>400</td><td>380</td><td>360</td><td>340</td><td>320</td><td>300</td></tr>
<tr><td>Biogas</td><td rowspan="3">400</td><td rowspan="3">390</td><td rowspan="3">380</td><td rowspan="3">370</td><td rowspan="3">360</td><td rowspan="3">350</td></tr>
<tr><td>Biomass</td></tr>
<tr><td>Municipal Solid Waste</td></tr>
<tr><td>EP-NETs technology 1</td><td rowspan="3">600</td><td rowspan="3">550</td><td rowspan="3">500</td><td rowspan="3">450</td><td rowspan="3">400</td><td rowspan="3">350</td></tr>
<tr><td>EP-NETs technology 2</td></tr>
<tr><td>EP-NETs technology 3</td></tr>
</table>

EC-NETs technology 1						
EC-NETs technology 2	800	750	700	650	600	550
EC-NETs technology 3						

(g)

Fixed capital costs / mil USD TWh^{-1}	1	2	3	4	5	6
Natural Gas						
Oil			100			
Coal						
Solar	100	85	70	55	40	25
Hydropower	100	90	80	70	60	50
Biogas						
70Biomass	100	95	90	85	80	75
Municipal Solid Waste						
EP-NETs technology 1						
EP-NETs technology 2	150	140	130	120	110	100
EP-NETs technology 3						
EC-NETs technology 1						
EC-NETs technology 2	200	190	180	170	160	150
EC-NETs technology 3						

(h)

CO_2 intensity of alternative solid-based fuel / Mt TWh^{-1}	1	2	3	4	5	6
Technology 1	0.20	0.19	0.18	0.17	0.16	0.15
Technology 2	0.40	0.38	0.36	0.34	0.32	0.30

(i)

Cost of alternative solid-based fuel / Mt TWh^{-1}	1	2	3	4	5	6
Technology 1	20	19	18	17	16	15
Technology 2	15	14	13	12	11	10

(j)

CO_2 intensity of alternative gas-based fuel / Mt TWh^{-1}	1	2	3	4	5	6
Technology 1	0.15	0.14	0.13	0.12	0.11	0.10
Technology 2	0.25	0.23	0.21	0.19	0.17	0.15

(k)

Cost of alternative gas-based fuel / Mt TWh^{-1}	1	2	3	4	5	6
Technology 1	35	34	33	32	31	30
Technology 2	30	29	28	27	26	25

(l)

CCS data	1	2	3	4	5	6
Removal ratio of CCS technology 1	0.85	0.86	0.87	0.88	0.89	0.90
Parasitic power loss of CCS technology 1	0.15	0.14	0.13	0.12	0.11	0.10
Power generation cost of CCS technology 1 / mil USD TWh^{-1}	34	33	32	31	30	29
Fixed cost of CCS technology 1 / mil USD TWh^{-1}	600	590	580	570	560	550
Removal ratio of CCS technology 1	0.65	0.66	0.67	0.68	0.69	0.70
Parasitic power loss of CCS technology 1	0.25	0.24	0.23	0.22	0.21	0.20
Power generation cost of CCS technology 2 / mil USD TWh^{-1}	29	28	27	26	25	24
Fixed cost of CCS technology 2 / mil USD TWh^{-1}	550	540	530	520	510	500

(m)

CO_2 intensity of NETs / Mt TWh^{-1}	1	2	3	4	5	6
EP-NETs technology 1	-0.80	-0.81	-0.82	-0.83	-0.84	-0.85
EP-NETs technology 2	-0.60	-0.61	-0.62	-0.63	-0.64	-0.65
EP-NETs technology 3	-0.40	-0.41	-0.42	-0.43	-0.44	-0.45
EC-NETs technology 1	-0.60	-0.61	-0.62	-0.63	-0.64	-0.65
EC-NETs technology 2	-0.40	-0.41	-0.42	-0.43	-0.44	-0.45
EC-NETs technology 3	-0.20	-0.21	-0.22	-0.23	-0.24	-0.25

(n)

Cost of NETs / mil USD TWh^{-1}	1	2	3	4	5	6
EP-NETs technology 1	43	41	39	37	35	33
EP-NETs technology 2	40	38	36	34	32	30
EP-NETs technology 3	37	35	33	31	29	27
EC-NETs technology 1	49	47	45	43	41	39
EC-NETs technology 2	37	35	33	31	29	27
EC-NETs technology 3	24	22	20	18	16	14

(o)

Technology Availability	1	2	3	4	5	6
Solar	✓	✓	✓	✓	✓	✓
Hydropower	✓	✓	✓	✓	✓	✓
Biomass	✓	✓	✓	✓	✓	✓
Biogas	✓	✓	✓	✓	✓	✓
MSW	✗	✓	✓	✓	✓	✓
Alternative solid-based fuel technology 1	✗	✗	✓	✓	✓	✓
Alternative solid-based fuel technology 2	✗	✓	✓	✓	✓	✓
Alternative gas-based fuel technology 1	✗	✗	✓	✓	✓	✓
Alternative gas-based fuel technology 2	✗	✓	✓	✓	✓	✓
CCS technology 1	✗	✗	✗	✓	✓	✓
CCS technology 2	✗	✗	✓	✓	✓	✓
EP-NETs technology 1	✗	✗	✗	✗	✓	✓
EP-NETs technology 2	✗	✗	✗	✓	✓	✓
EP-NETs technology 3	✗	✗	✓	✓	✓	✓
EC-NETs technology 1	✗	✗	✗	✗	✓	✓
EC-NETs technology 2	✗	✗	✗	✓	✓	✓
EC-NETs technology 3	✗	✗	✓	✓	✓	✓

Based on Table 5a, there are 10 power plants available for power generation. While the first eight plants are existing power plants (commissioned from Period 1 onwards), Plants 9 and 10 are upcoming power plants to be commissioned from Periods 2 and 4 respectively. In other words, Plants 9 and 10 would not be available for power generation before Periods 2 and 4 respectively. On the other hand, Plants 6 and 7 utilising oil and coal respectively would be decommissioned in later periods. Meanwhile, the lower bound of power generation by plants utilising renewable energy sources (Plants 1, 2, 9 and 10) is set to 75% of their upper bounds. In other words, the power generation from operational renewable-based power plants should at least be 75% of its maximum capacity since these plants cannot be ramped up easily to meet a sudden demand surge. By contrast, power generation from plants utilising fossil-based sources may be ramped up quickly. Therefore, the lower bound for these plants (Plants 3 till 8) is set to 25% of their maximum generation capacity.

Moving on to Table 5b, the energy planning is conducted based on an incremental demand and stricter CO_2 emissions limits between successive periods. This scenario is often observed in developing countries where an increasing population leads to higher demand requirements. At the same time, lower CO_2 emissions limits are required for countries to meet their climate change targets. The rate of decline of CO_2 emissions limit increases from 2 Mt y^{-1} between Period 1 and 2 to 6 Mt y^{-1} between Period 5 and 6. It is projected that the greater availability of mitigation technologies in later periods would make it relatively easier to drive CO_2 emissions reduction. Note that this work targets to achieve net-zero emissions by the final period, consistent with the pledges made at the COP26. Also, economic growth contributes to a greater budget available for energy planning across periods. Since the power plants in Table 5a make use of solar, natural gas, oil and coal, the associated fuel costs are presented in Table 5c. Since fossil-based sources are technologically matured, their costs are projected to remain constant for all periods. By contrast, recent technological advancement has resulted in a significant decline in the cost of solar energy. This information is captured in this work with the declining cost of solar energy in Table 5c. Note that the cost decline in earlier periods is gradual before increasing drastically towards later periods.

Aside from the existing plants, this work also considers the potential deployment of renewable energies as separate plants for mitigating CO_2 emissions. The five renewable energies that are considered in this work are solar, hydropower, biomass, biogas, and municipal solid waste (MSW). Each renewable energy differs in terms of CO_2 intensities (Table 5d) and costs (Table 5e). Like solar energy, the CO_2 intensities and costs of renewable energies are expected to decrease across periods. In the final period, solar energy would be the cheapest and has the lowest CO_2 intensity. The energy planning superstructural model in this work would determine the optimal deployment of renewable energy sources if necessary to meet the demand and CO_2 emissions limits.

Next, Table 5f and Table 5g present the capital costs associated with all plants (fossil fuel, renewable and NETs). Note that this work assumes the capital expenditure for NETs plants to be higher than fossil-based plants. Given that NETs are still in an early development phase with the lack of technological maturity, it is assumed that greater initial investment is required for NETs plants. However, the capital costs of all plants except fossil-based plants are expected to decrease across periods, with solar witnessing the largest decline. In this work, alternative solid and gas-based fuels are meant to replace coal and natural gas respectively. For each fuel replacement, there are two types available for use. Note that cheaper alternative fuel has a higher CO_2 intensity and vice versa. The CO_2 intensities and cost of the alternative fuels are presented in Table 5h - Table 5k. Once again, the improved energy efficiencies are projected to decrease the CO_2 intensities and costs of alternative fuels across periods.

Following this, the CCS data is presented in Table 5l. Note that there are two CCS technologies available for deployment. CCS technology 1 has a higher removal ratio and lower parasitic power loss in comparison to CCS technology 2. Therefore, the former has a higher cost of power generation and fixed cost in comparison to the latter technology. Due to the projected improved technological maturities, the removal ratios of the CCS technologies are expected to increase. Meanwhile, the remaining CCS parameters (parasitic power loss and costs) are projected to decline across periods. Finally, the CO_2 intensities and costs of NETs are presented in Table 5m and Table 5n respectively. Note that both EP-NETs and EC-NETs are considered in this work, where each NETs type is made up of three technologies. Note that NETs with the lowest CO_2 intensity is the most expensive technology and vice versa. Once again, like CCS technologies and renewable energy, all NETs are projected to get matured across periods resulting in declining CO_2 intensities and costs.

3.2 Optimisation Results

Figure 21 presents the results for the minimised cost objective function.

	Fuel	Energy Generation	Energy	CI	Net Energy	Carbon Load	Cost
Plant_1	SOLAR	1	26.7	0.15	26.7	4	
Plant_2	SOLAR	1	21.16	0.15	21.16	3.17	
Plant_3	NG	0	0	0.5	0	0	
Plant_4	NG	0	0	0.5	0	0	
Plant_5	NG	0	0	0.5	0	0	
Plant_6	OIL	0	0	0.8	0	0	
Plant_7	COAL	0	0	1	0	0	
Plant_8	COAL	1	12.14	1	12.14	12.14	
Plant_9	SOLAR	0	0	0.15	0	0	
Plant_10	SOLAR	0	0	0.15	0	0	
COMP_SOLAR	COMP_SOLAR	0		0.1	0	0	
COMP_HYDRO	COMP_HYDRO	0		0.15	0	0	
COMP_BIOMASS	COMP_BIOMASS	0		0.3	0	0	
COMP_BIOGAS	COMP_BIOGAS	0		0.25	0	0	
TOTAL					**60**	**19**	**3500**

(a)

	Fuel	Energy Generation	Energy	CI	SOLID_2	GAS_2	Net Energy	Carbon Load	Cost
Plant_1	SOLAR	1	26.7	0.15	0	0	26.7	4	
Plant_2	SOLAR	1	21.16	0.15	0	0	21.16	3.17	
Plant_3	NG	0	0	0.5	0	0	0	0	
Plant_4	NG	0	0	0.5	0	0	0	0	
Plant_5	NG	0	0	0.5	0	0	0	0	
Plant_6	OIL	0	0	0.8	0	0	0	0	
Plant_7	COAL	0	0	1	0	0	0	0	
Plant_8	COAL	1	12.14	1	5.75	0	12.14	8.57	
Plant_9	SOLAR	1	15	0.15	0	0	15	2.25	
Plant_10	SOLAR	0	0	0.15	0	0	0	0	
COMP_SOLAR	COMP_SOLAR	0		0.09			0	0	
COMP_HYDRO	COMP_HYDRO	0		0.14			0	0	
COMP_BIOMASS	COMP_BIOMASS	0		0.28			0	0	
COMP_BIOGAS	COMP_BIOGAS	0		0.23			0	0	
COMP_MSW	COMP_MSW	0		0.29			0	0	
TOTAL							75	18	3959

(b)

	Fuel	Energy Generation	Energy	CI	CCS_2 CI	CCS_2 Selection	CCS_2 Ret	Net Energy wo CCS	Net Energy w CCS_2	SOLID_1	SOLID_2	GAS_1	GAS_2	Net Energy	Carbon Load	Cost
Plant_1	SOLAR	1	26.7	0.15	0.064	0	0	26.7	0	0	0	0	0	26.7	4	
Plant_2	SOLAR	1	21.3	0.15	0.064	0	0	21.3	0	0	0	0	0	21.3	3.19	
Plant_3	NG	0	0	0.5	0.214	0	0	0	0	0	0	0	0	0	0	
Plant_4	NG	1	3.9	0.5	0.214	0	0	0	0	0	0	3.9	0	3.9	0.51	
Plant_5	NG	0	0	0.5	0.214	0	0	0	0	0	0	0	0	0	0	
Plant_6	OIL	0	0	0.8	0.343	0	0	0	0	0	0	0	0	0	0	
Plant_7	COAL	0	0	1	0.429	0	0	0	0	0	0	0	0	0	0	
Plant_8	COAL	1	18.1	1	0.429	0	0	0	0	12.35	5.75	0	0	18.1	4.29	
Plant_9	SOLAR	1	20	0.15	0.064	0	0	20	0	0	0	0	0	20	3	
Plant_10	SOLAR	0	0	0.15	0.064	0	0	0	0	0	0	0	0	0	0	
EP_NET_3	EP_NET_3	0		-0.42										0	0	
EC_NET_3	EC_NET_3	0		-0.22										0	0	
COMP_SOLAR	COMP_SOLAR	0		0.08										0	0	
COMP_HYDRO	COMP_HYDRO	0		0.13										0	0	
COMP_BIOMASS	COMP_BIOMASS	0		0.26										0	0	
COMP_BIOGAS	COMP_BIOGAS	0		0.21										0	0	
COMP_MSW	COMP_MSW	0		0.28										0	0	
TOTAL														90	15	3858

(c)

	Fuel	Energy Generation	Energy	CI	CCS_1 CI	CCS_2 CI	CCS_1 Selection	CCS_2 Selection	CCS_1 Ret	CCS_2 Ret	Net Energy wo CCS	Net Energy w CCS_1	Net Energy w CCS_2	SOLID_1	SOLID_2	GAS_1	GAS_2	Net Energy	Carbon Load	Cost
Plant_1	SOLAR	1	26.7	0.15	0.02	0.062	0	0	0	0	26.7	0	0	0	0	0	0	26.7	4	
Plant_2	SOLAR	1	21.3	0.15	0.02	0.062	0	0	0	0	21.3	0	0	0	0	0	0	21.3	3.19	
Plant_3	NG	0	0	0.5	0.068	0.205	0	0	0	0	0	0	0	0	0	0	0	0	0	
Plant_4	NG	1	12.22	0.5	0.068	0.205	0	0	0	0	0	0	0	0	0	12.22	0	12.22	1.47	
Plant_5	NG	0	0	0.5	0.068	0.205	0	0	0	0	0	0	0	0	0	0	0	0	0	
Plant_6	OIL	0	0	0.8	0.109	0.328	0	0	0	0	0	0	0	0	0	0	0	0	0	
Plant_7	COAL	1	6.67	1	0.136	0.41	0	0	0	0	6.67	0	0	0	0	0	0	6.67	6.67	
Plant_8	COAL	1	18.1	1	0.136	0.41	0	0	0	0	0	0	0	12.35	5.75	0	0	18.1	4.05	
Plant_9	SOLAR	1	20	0.15	0.02	0.062	0	0	0	0	20	0	0	0	0	0	0	20	3	
Plant_10	SOLAR	0	0	0.15	0.02	0.062	0	0	0	0	0	0	0	0	0	0	0	0	0	
EP_NET_2	EP_NET_2	1		-0.63														10.75	-6.77	
EP_NET_3	EP_NET_3	0		-0.43														0	0	
EC_NET_2	EC_NET_2	1		-0.43														10.75	-4.62	
EC_NET_3	EC_NET_3	0		-0.23														0	0	
COMP_SOLAR	COMP_SOLAR	0		0.07														0	0	
COMP_HYDRO	COMP_HYDRO	0		0.12														0	0	
COMP_BIOMASS	COMP_BIOMASS	0		0.24														0	0	
COMP_BIOGAS	COMP_BIOGAS	0		0.19														0	0	
COMP_MSW	COMP_MSW	0		0.27														0	0	
TOTAL																		105	11	5055

(d)

	Fuel	Energy Generation	Energy	CI	CCS_1 CI	CCS_2 CI	CCS_1 Selection	CCS_2 Selection	CCS_1 Ret	CCS_2 Ret	Net Energy wo CCS	Net Energy w CCS_1	Net Energy w CCS_2	SOLID_1	SOLID_2	GAS_1	GAS_2	Net Energy	Carbon Load	Cost
Plant_1	SOLAR	1	26.7	0.15	0.019	0.059	0	0	0	0	26.7	0	0	0	0	0	0	26.7	4	
Plant_2	SOLAR	1	21.3	0.15	0.019	0.059	0	0	0	0	21.3	0	0	0	0	0	0	21.3	3.19	
Plant_3	NG	0	0	0.5	0.062	0.198	0	0	0	0	0	0	0	0	0	0	0	0	0	
Plant_4	NG	1	12.22	0.5	0.062	0.198	0	0	0	0	0	0	0	0	0	12.22	0	12.22	1.34	
Plant_5	NG	0	0	0.5	0.062	0.198	0	0	0	0	0	0	0	0	0	0	0	0	0	
Plant_6	OIL	0	0	0.8	0.099	0.314	0	0	0	0	0	0	0	0	0	0	0	0	0	
Plant_7	COAL	0	0	1	0.124	0.332	0	0	0	0	0	0	0	0	0	0	0	0	0	
Plant_8	COAL	1	18.1	1	0.124	0.332	0	0	0	0	0	0	0	12.35	5.75	0	0	18.1	3.82	
Plant_9	SOLAR	1	20	0.15	0.019	0.059	0	0	0	0	20	0	0	0	0	0	0	20	3	
Plant_10	SOLAR	1	21.68	0.15	0.019	0.059	0	0	0	0	21.68	0	0	0	0	0	0	21.68	3.25	
EP_NET_1	EP_NET_1	1		-0.84														8.52	-7.16	
EP_NET_2	EP_NET_2	0		-0.64														0	0	
EP_NET_3	EP_NET_3	0		-0.44														0	0	
EC_NET_1	EC_NET_1	1		-0.64														8.52	-5.45	
EC_NET_2	EC_NET_2	0		-0.44														0	0	
EC_NET_3	EC_NET_3	0		-0.24														0	0	
COMP_SOLAR	COMP_SOLAR	0		0.06														0	0	
COMP_HYDRO	COMP_HYDRO	0		0.11														0	0	
COMP_BIOMASS	COMP_BIOMASS	0		0.22														0	0	
COMP_BIOGAS	COMP_BIOGAS	0		0.17														0	0	
COMP_MSW	COMP_MSW	0		0.26														0	0	
TOTAL																		128	6	4309

(e)

	Fuel	Energy Generation	Energy	CI	CCS_1 CI	CCS_2 CI	CCS_1 Selection	CCS_2 Selection	CCS_1 Ret	CCS_2 Ret	Net Energy wo CCS	Net Energy w CCS_1	Net Energy w CCS_2	SOLID_1	SOLID_2	GAS_1	GAS_2	Net Energy	Carbon Load	Cost
Plant_1	SOLAR	1	26.7	0.15	0.017	0.058	0	0	0	0	26.7	0	0	0	0	0	0	26.7	4	
Plant_2	SOLAR	1	21.3	0.15	0.017	0.058	0	0	0	0	21.3	0	0	0	0	0	0	21.3	3.19	
Plant_3	NG	0	0	0.5	0.058	0.186	0	0	0	0	0	0	0	0	0	0	0	0	0	
Plant_4	NG	1	12.22	0.5	0.058	0.186	0	0	0	0	0	0	0	0	0	12.22	0	12.22	1.22	
Plant_5	NG	1	11.68	0.5	0.058	0.186	0	0	0	0	0	0	0	0	0	0	11.68	11.68	1.75	
Plant_6	OIL	0	0	0.8	0.089	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	
Plant_7	COAL	0	0	1	0.111	0.375	0	0	0	0	0	0	0	0	0	0	0	0	0	
Plant_8	COAL	1	18.1	1	0.111	0.375	0	0	0	0	0	0	0	12.35	5.75	0	0	18.1	3.58	
Plant_9	SOLAR	1	20	0.15	0.017	0.058	0	0	0	0	20	0	0	0	0	0	0	20	3	
Plant_10	SOLAR	1	25	0.15	0.017	0.058	0	0	0	0	25	0	0	0	0	0	0	25	3.75	
EP_NET_1	EP_NET_1	1		-0.85														13.67	-11.62	
EP_NET_2	EP_NET_2	0		-0.65														0	0	
EP_NET_3	EP_NET_3	0		-0.45														0	0	
EC_NET_1	EC_NET_1	1		-0.65														13.67	-8.88	
EC_NET_2	EC_NET_2	0		-0.45														0	0	
EC_NET_3	EC_NET_3	0		-0.25														0	0	
COMP_SOLAR	COMP_SOLAR	0		0.05														0	0	
COMP_HYDRO	COMP_HYDRO	0		0.1														0	0	
COMP_BIOMASS	COMP_BIOMASS	0		0.2														0	0	
COMP_BIOGAS	COMP_BIOGAS	0		0.15														0	0	
COMP_MSW	COMP_MSW	0		0.25														0	0	
TOTAL																		135	0	4693

(f)

Figure 21: Results for minimised cost objective function: (a) Period 1, (b) Period 2, (c) Period 3, (d) Period 4, (e) Period 5 and (f) Period 6

Based on Figure 21, note that the total CO_2 load and cost for each period may be observed at the bottom right of the optimisation results in Microsoft Excel. A similar format may be observed for the remaining worksheet tabs containing the optimisation results. Note that a user may observe a different set of solutions (degenerate solutions). In this case, a user should check if the objective functions stay the same.

4. Potential Bugs and Solutions

The optimisation of the decarbonisation framework would take place in Pyomo while utilising the Octeract Engine as the choice of the solver. During the optimisation procedure, a user may encounter several potential bugs. Therefore, this section aims to provide solutions for some of the potential bugs that may be encountered by a user.

4.1. Excel Permission Denied

For this error, a user might obtain an error message as shown in Figure 22.

```
PermissionError: [Errno 13] Permission denied:
'Optimal_Decarbonisation_User_Interface.xlsx'
```

Figure 22: Excel Permission Denied Error

To avoid this error, a user should save and close the '**Optimal_Decarbonisation_User_Interface' Excel** file before running the file in Python/Sypder. Upon running the Python file, a user may re-open the Excel file to view the results.

4.2. Absent Pyomo Module

For this error, a user might obtain an error message as shown in.

```
ModuleNotFoundError: No module named 'pyomo'
```

Figure 23: Absent Module Error

To overcome this error, a user should ensure that the Pyomo environment is properly installed within the selected environment in Anaconda. Note that the '**environment.yml**' file contains the Pyomo environment. Therefore, importing the '**environment.yml**' file (see Section 2.6) during Anaconda installation would overcome this issue.