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Bhagaloo, K, Ali, R, Baboolal, A et al. (1 more author) (2022) Powering the sustainable transition with geothermal energy: A case study on Dominica. Sustainable Energy Technologies and Assessments, 51. 101910. ISSN 2213-1388

https://doi.org/10.1016/j.seta.2021.101910

Powering the Sustainable Transition with Geothermal Energy: A Case Study on Dominica.

Keeara Bhagaloo[a], Rehannah Ali[a], Anastasia Baboolal[a] and Keeran Ward*[a, b]

[a]Department of Chemical Engineering, The University of the West Indies, St. Augustine, Trinidad and Tobago.
[b]School of Chemical and Process Engineering (SCAPE), University of Leeds, Leeds, LS2 9JT, United Kingdom. Telephone: 1-868-730-1980; keeran.ward@sta.uwi.edu*;

Abstract

Climate change impacts continue to threaten the islands within the Caribbean where guidance on achieving a sustainable energy transition is relatively absent. Thus, we present for the first time, multiple decision criteria utilizing techno-economic and environmental assessments to inform on the hidden benefits of the geothermal rich nation of Dominica. In determining the most sustainable option for Dominica to deploy its geothermal energy capacity, several cases were explored using current and future levelized electricity (LCOE) costs, product annualized costs (TAC) and life cycle assessments (LCA). Our results highlight a 99.5% reduction in national life cycle GHG emissions, coupled with 70% cheaper power by 2030 exploiting 100% geothermal energy. Furthermore, excess energy storage platforms through methanol and ammonia production showed increased financial and environmental benefits in 2030, with a 38% reduction in TAC and avoided burdens as high as 149,000 CO_2-eq/year observed. Nevertheless, the most sustainable outcome for Dominica was revealed through energy exportation to neighbouring islands-avoiding up to 2.5 million tonnes CO_2-eq/year while producing 20% cheaper dispatchable power. Although this energy transition accompanies high capital investment, our results confirm sustainable operations and illustrate the potential for geothermal activity in supporting clean and affordable energy production across the Eastern Caribbean Region.

Keywords: Geothermal Energy, Small Island Developing States, Sustainable Energy, Techno-economics, Life Cycle Assessment.

Nomenclature

AFC- Annualised Fixed Cost

bbl- Barrel of oil

BAU- Business as Usual

CAPEX- Capital Costs

CARICOM- Caribbean Community and Common Market

CEPCI- Chemical Engineering Cost Indices

DAC- Direct Air Capture

FC- Fixed Costs

FU- Functional unit

GDP- Gross Domestic Product

GHG - Greenhouse gases

INDC- Intended Nationally Determined Contribution

LCA- Life Cycle Assessment

LCI- Life Cycle Inventories

LCIA- Life Cycle Impact Assessment

LCOE- Levelized Cost of Electricity

LCOE2019 – Levelized Cost of Electricity (2019)

LCOE2030- Levelized Cost of Electricity (2030)

LCOEDom – Levelized Cost of Electricity for Dominica

LCOEMar – Levelized Cost of Electricity for Martinique

MeOH- Methanol

META- Model for Electricity Technology Assessment

MW- Megawatt

MWh- Megawatt hour

OECS - Organisation of the Eastern Caribbean States

OPEX: Operating expenditure

ORC- Organic Rankine cycle

PEM- Polymer Electrolyte Membrane

RE – Renewable Energy

SDG- Sustainable Development Goals

SIDS- Small Island Developing States
TAC- Total Annualised Cost
UN - United Nations
UNESCO- United Nations Educational, Scientific and Cultural Organization
USD- US dollar
VC- Variable Costs

1. Introduction

The global demand for energy to satisfy social and economic development has significantly increased in the last decade- cumulatively affecting earth's climate and fossil fuel reserves. This has sparked interest in cleaner alternative fuel sources. Access to sustainable energy plays a fundamental role in the development of Small Island Developing States (SIDS)- allowing economic growth, social progress, and increased standard of living for billions [1].The United Nations (UN) Sustainable Energy for All initiative aims to ensure universal access to affordable, reliable and sustainable electricity by 2030[2]; with an estimated 60% of energy growth occurring within developing nations possessing abundant, untapped renewable energy (RE) resources [3,4]. The Eastern Caribbean region provides one such example, where substantial untapped renewable potential can be realised owing to its geography and geology [5]; however, all of the islands are electrically isolated with high fossil fuel dependence and little local resources aligned to energy production [6,7].

The Organisation of the Eastern Caribbean States (OECS) is an intergovernmental association comprising nine SIDS of the eastern Caribbean region with objectives including, but not limited to, accelerating regional trade and promoting economic, environmental, and social resilience [8]. Thus, reinforcement of long-term use of renewable energy is of utmost importance for the OECS in achieving these objectives. This is especially important given the islands' vulnerability to the effects of climate change such as rising sea levels and intense weather systems [9-11] coupled with the longstanding issue of high and volatile oil prices on the global market leading to expensive power generation at low production capacities [12-14]. Furthermore, these islands lack significant energy security dominated by isolated grids with a sole electricity provider, constrained by aging infrastructure [6,9]. In the face of natural disasters, the vulnerability of the aging energy sector is most evident, as countries often experience power outages for long periods of time, putting a strain on its reliant sectors such as healthcare and transport [13].

While the current growing global energy demand is indicative of increased economic growth in developed parts of the world, the current pattern of energy use is unsustainable -highly dependent on finite, diminishing fossil fuels and unprecedented levels of greenhouse gases (GHGs) [8,15]. These anthropogenic emissions are responsible for global warming with its negative effects being most threatening to SIDS [11]. To initiate transformation of the global energy production and infrastructure, the international community ratified the Paris Agreement with the goal of limiting global warming to 1.5 degrees Celsius, compared to pre-industrial levels [15]. Therein lies the challenge of emerging economies and SIDS- to fulfil a growing energy demand for an expanding population while simultaneously transitioning to low-carbon energy systems [16]. The deployment of RE is a global trend that responds to the emerging paradigm of sustainable energy development [17]. However, the selection of viable technologies for harnessing RE are dependent upon several factors, with the most critical being geographical and geological factors [8,10].

Geographically located in the Caribbean, the OECS region is endowed with many forms of renewable energy (RE) such as wind, solar and hydroelectric power. These systems are however, largely intermittent in supply and are affected by seasonal and daily fluctuations, and thus need to be fully consolidated with other dispatchable power systems to maintain reliability [18]. Geologically, the region is situated in an active region around the Caribbean plate, creating ideal geological situations where geothermal energy can be harboured [5]. Geothermal energy is independent of weather and climatic situations and most suitable for scale-up, proving to be the most reliable RE resource for the region [19]. Also, they offer the added advantages of higher capacity factors and lower environmental impact potential, having underground storage [20,21]. Islands such as Guadeloupe with (15 MW installed capacity) [22] and Dominica (up to 1390 MW potential) [5] have begun exploring geothermal energy with ambitions to reduce annual avoided GHG emissions to 0.30 million tonne CO_2/yr by 2027 [5]. Additionally, its abundance in Dominica, which surpasses the national demand, allows for an interconnected grid via subsea transmission- wherein power can be traded with nearby islands encouraging economically viable large scale deployment of geothermal energy since neighbouring islands have much higher power needs [23]. Furthermore, with increased geothermal energy potential, energy storage platforms can be considered from excess power generation-promoting energy security among the region [24].

Six of the nine OECS/SID nations involved in the Paris Agreement have opted to aim for 100% RE grid power by 2050 [22]. However, the region lacks guidance in understanding the various pathways in achieving full sustainable energy transformation. Thus, our study examines the use of multiple decision criteria using techno-economic and environmental assessments, to inform and guarantee sustainable operations of the OECS power sector through a case study approach. Herein, we propose case-specific options for the nation of Dominica in fulfilling its GHG commitments while supporting reliable RE integration across the eastern Caribbean region. By disseminating evidence-based results, solutions can be provided to aid OECS nations in achieving their RE targets and promoting sustainable development through the deployment of clean, modern and affordable energy according to Sustainable Development Goal 7 (SDG 7) [24].

2. Literature Review

2.1. Background

The OECS makes up an 11-member group of islands that form a continuous archipelago consisting of the Lesser Antilles within the easternmost region of the Caribbean Sea (**Figure 1**). The majority of the Lesser Antilles extend in the north as the Leeward islands and in the south as the Windward islands. Within the Leeward and Windward islands, these sections comprise approximately 26 islands, of which 21 are volcanic in nature- many of which are permanently inhabited and within close proximity to one another [25]. These islands are located in the southeast Caribbean, with a tropical climate containing diverse plants and animals. Most of the expanse of the Leeward and Windward islands is located over the Lesser Antilles volcanic arc that stretches over a subduction zone formed due to the collision of the North and South American plate margins and minor parts of the Caribbean Plate as shown in **Figure 1** [26].

This presents a geothermal themed opportunity as several volcanic islands on the oceanic crust of the Caribbean Plate are active. The majority of the islands are primarily composed of igneous rocks and weathered igneous products, and the geological age of the islands are Miocene to Holocene (5 million years ago – present) and considered to be geologically young. Along the Lesser Antilles volcanic arc, tectonic plates are continuously shifting slowly, which triggers volcanic activity, earthquakes and other potential geo-hazards [27].

Among the 11 OECS member states (**Figure 1**), the six islands of Dominica, St. Vincent and the Grenadines, Montserrat, Grenada, St. Kitts and St. Lucia have initiated geothermal development through governments and international agencies since their thermal gradients have been suggested to be higher than average compared to other islands, thus demonstrating a great source of geothermal energy potential [28,29].

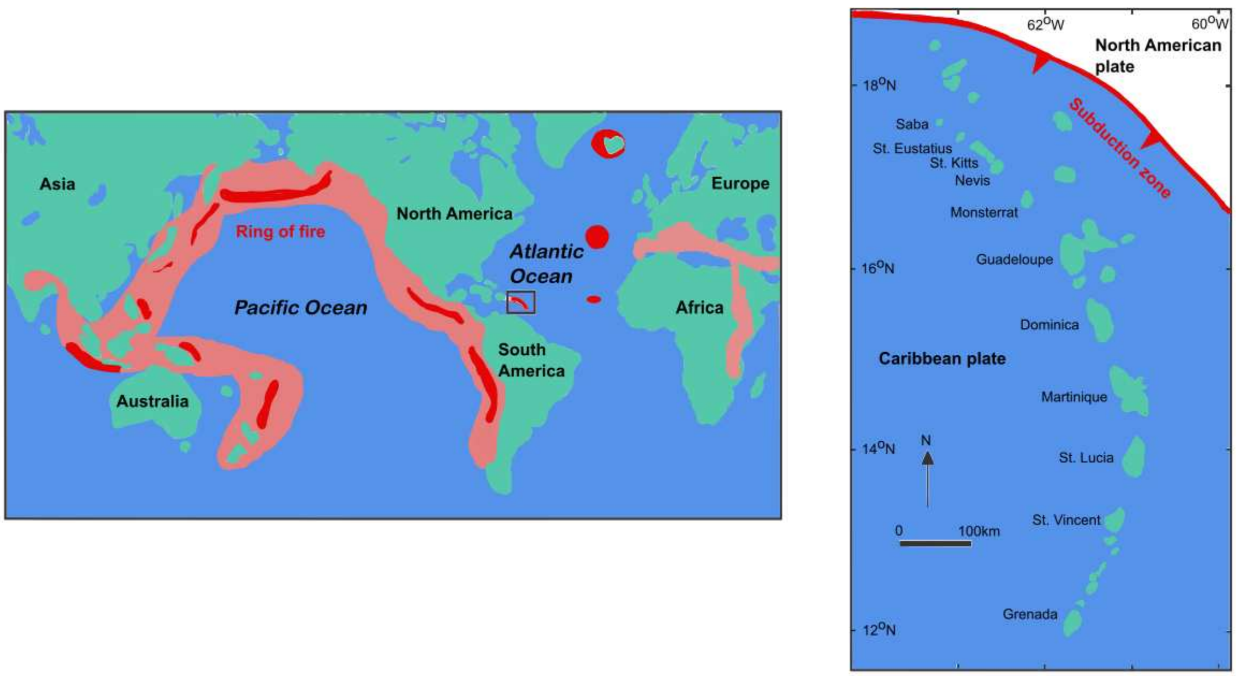

Figure 1: Global geothermal activity map with snapshot of the OECS region of the Caribbean community.

2.2. Types of Geothermal plants

Geothermal energy is the thermal energy stored within the Earth's body, facilitated by the Earth's layered structure. The lithosphere promotes the eventual mobility of tectonic plates due to the forces exerted by the convecting mantle which promotes different thermal responses at the Earth's surface [30,31]. Such responses include the creation of mountain belts, mid oceanic ridges, and sites of volcanic activity which are all associated forms of hydrothermal activity worldwide (**Figure 1**). Focusing on the formation of volcanoes, deep below the earth's surface the magma is a source of heat to trapped fluids. In some instances, heated water comes to the surface in hot springs or geysers. This heat which continually rises from the magma to water trapped under the surface as geofluid is the origin of what is called geothermal energy [32].

Three common types of geothermal power plants used for electricity production include flash steam, dry steam and binary cycle [33]. Globally most geothermal energy is produced in high-enthalpy fields that reach high temperatures at shallow depths. The electricity is generated in dry steam and flash steam power plants [31]. These power plants of high enthalpy fields function as open system geothermal installations. The systems use steam produced by decompressing the thermal heat transfer fluid to drive turbines for electrical production. The minimum operation temperature in flash-steam plants is 175 °C. The turbine converts geothermal energy into mechanical energy that is converted to electrical energy by a generator [34-35]. Apart from this, electrical energy is consumed by pumps and other machinery of the power plant; the net power is fed onto the grid. One major disadvantage of high enthalpy fields is their limited occurrence in volcanic and tectonically active areas along plate boundaries [36]. Dry steam and flash steam systems are currently installed in the following countries: USA, Philippines, Mexico, Indonesia, Italy, Iceland, Russia, Kamchatka Islands, Azores Islands and Guadeloupe [18,31,37].

Electrical energy production from binary cycle power plants are associated with low enthalpy systems and has been installed in few locations worldwide, although suitable locations are far more frequent than high-enthalpy fields. Conversion of heat to electrical energy within binary cycle power plants based on the Organic Rankine Cycle (ORC), is possible if the produced water is above 80°C. ORC plants work with an organic heat transfer fluid with a relatively low boiling temperature [33]. There is an enormous potential for future development and expansion of deep low-enthalpy systems [36]. Countries generating geothermal power using binary cycle power plants include USA, Philippines, Indonesia, Mexico, Italy, New Zealand, Iceland, Japan, El Salvador, Kenya, Azores Islands, Cook Islands and Guadeloupe [18,38]. Recently, geothermal energy supported multi generation systems have been explored and designed for a cleaner and sustainable future [39-41]

2.3. Study sites- Dominica and Martinique

All of the islands highlighted within the Lesser Antilles encompass a territory within the Caribbean identified by the United Nation (2019) as SIDS. The relevance of advancing the potential for geothermal integration throughout suggested Caribbean islands presents the primary advantage of energy security through the reduction of dependence on fossil fuels to generate security [42].

Sea-level rise aligned to climate change is considered a significant threat to SIDS. Although greenhouse gas emissions from SIDS are considered negligible on a global scale, these islands will be among the first affected by changing climatic conditions [43-45]. Therefore, SIDS are a primary focus group due to their high vulnerability and on-going global commitment to climate change mitigation [46,47]. Policy and regulatory framework for RE deployment in Caribbean islands have been well documented during the past twenty years [48]. Though Caribbean islands contribute less than 1% of total GHG emissions, these islands can position themselves to be leaders in energy transition by providing successful examples of RE penetration [47,49]. Acknowledging this, Dominica is among several islands that have pledged to meet 100% of energy needs with renewables by 2030 [50].

Currently geothermal development in Dominica is small compared to the potential resources. Dominica's geothermal plant is being constructed within the Rosseau Valley, historically referred to as Grande Soufriere. This region of the island is the most thermally active and is characterized by multiple hot springs and fumaroles with temperatures ranging 40-96°C [25]. Dominica has nine active volcanoes with the Morne Diablotins found in the northern area of the island having the highest elevation at 1447 m. The island of Dominica is located near Martinique to the south-southwest [26]. While 60% of Dominica's land is classified by the United Nations Educational, Scientific and Cultural Organization (UNESCO) as a World Heritage site, the island has significant potential to change its current power generation mix and eventually reduce the cost of electricity prices. Dominica's geothermal resource has been extensively investigated by the government and international agencies during the past 15 years [51].

Martinique's energy outlook of being self-sufficient by relying on RE by 2030 was partially achieved in 2019 with the 14MW Grand Rivere wind park in the northern mountainous part of the island. Future wind projects are being planned for several communities to produce an installed capacity of 36MW [52-54]. While the northern area of the island is dominated by mountains, volcanoes both active and extinct are covered with rainforest. The south features a more easily traversed geographic region [26].

As shown in **Table 1**, the gross domestic product (GDP), population density, average power consumption and carbon dioxide emission [55] is presented to give a current outlook in each country.

Table 1: Current country level outlook for Dominica and Martinique.

Country	GDP ($US)	Population Density (number per square km)	Average Power Consumption (MW)	Carbon Dioxide emission (metric tons per capita)
Dominica	1.02 billion	97.8	16.8	2.52
Martinique	9.8 billion	332.8	235	6.17

Despite considerable renewable resources and progress of the OECS region, islands have been slow to RE deployment. There are many economic, political and social barriers that can be identified as challenges for RE implementation. These challenges have been linked directly to the need for new policies and regulatory regimes to each island's specific context. While the region has untapped geothermal potential to enable a large energy supply across the wider Caribbean, further collaboration and support is needed to reduce the challenges aforementioned. Thus, in this study, we seek to propose the relevance of aligning the geothermal potential of Dominica and the promotion of sustainable energy deployment among neighbouring OECS nations.

3. System Description

Our modelling framework for this study was guided by the renewable potential of OEC states. In particular, the small island nation of Dominica was studied due to its potential for geothermal energy deployment and exportation. Thus, our evaluation considers environmental and techno-economic assessments aligned to conceptual process design, life cycle impacts and economic viability across several case studies. The basis of our calculations stem from mass and energy balances aligned to input-output inventory flows, which were used to guide decision-making in transitioning towards greater sustainable power generation.

3.1. Country Level Overview: Business as Usual (BAU)

The power sector of Dominica has been heavily dependent on conventional fossil resources- with 2019 available data indicating a 63% share for fossil fuels (diesel) and 37% for hydropower [50] (**Figure 2**). Dominica's initial commitment to RE projects include small-scale wind (0.23 MW installed out of a 30 MW potential) and solar (6.6MW installed out of a 45MW potential) [56] which currently accounts for < 1% towards the RE input [50]. Martinique's electricity generation mix includes (75.1%) fossil fuel (diesel), (16.4%) biomass, (5.5%) solar and (3.0%) wind [54]. The installed RE capacity accounts for 24% of the current energy mix.

Despite considerable abundant renewable resources, like many Caribbean islands both Dominica and Martinique have been slow to adopt RE even though there are existing policies and regulatory frameworks in place [50]. Dominica, a formal member of the Caribbean Community CARICOM and Martinique which falls within the Government of the French Republic, has ratified the Paris Agreement to reduce 45% of GHG emissions by 2030 [57].

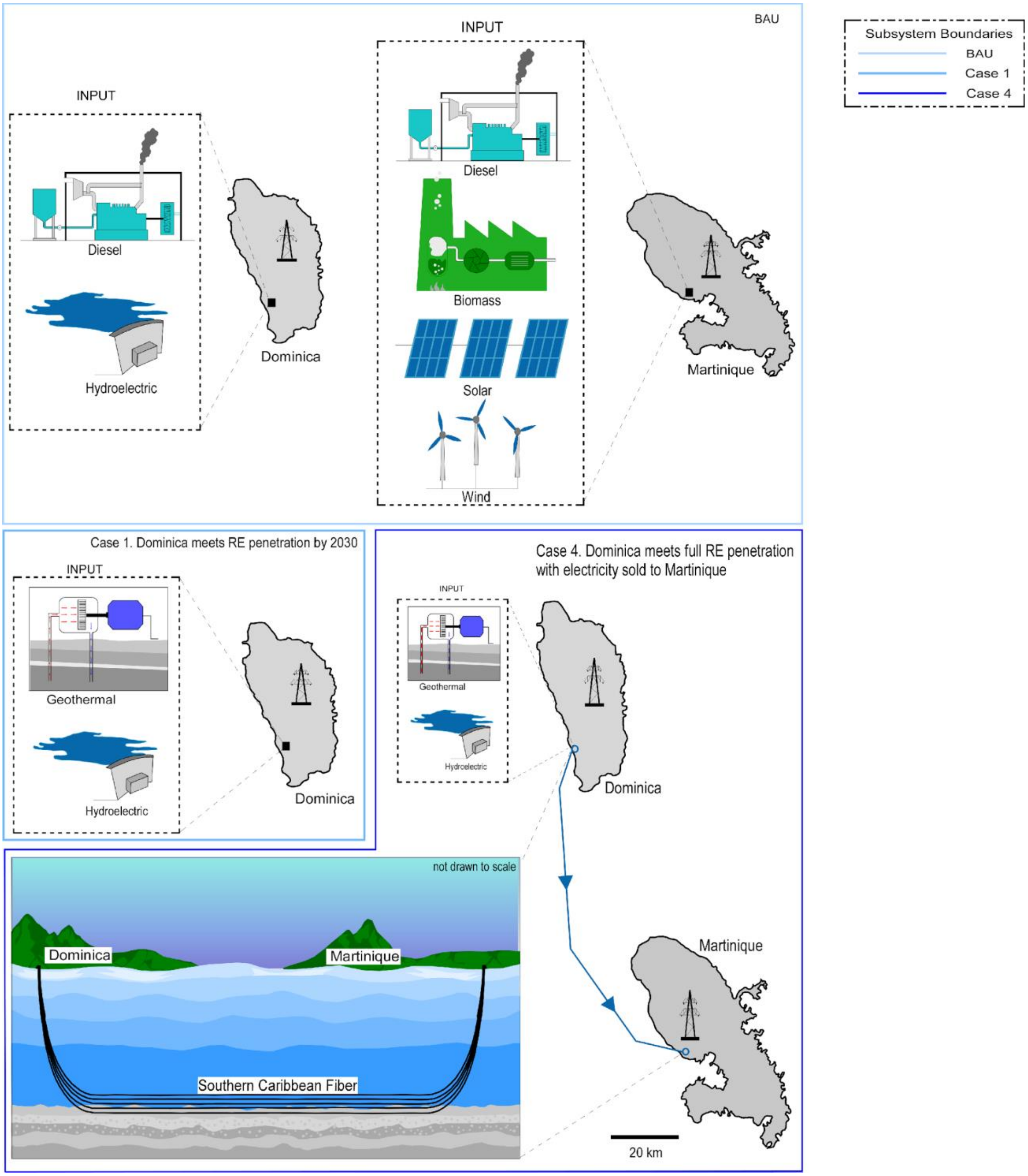

Figure 2: Case-specific system boundary definitions for country level overview (BAU), Dominica 2030 outlook (Case 1) and geothermal energy exportation (Case 4).

3.2. Dominica 2030 Outlook: 100% RE Deployment (Case 1)

Owing to the island's geographic position in the volcanic arc of the Caribbean region [28], Dominica can realise more than 20 times its projected power demand by utilising its untapped geothermal resource solely. The island boasts the highest geothermal potential among OECS nations in the eastern Caribbean [5]. Geothermal energy is considered dispatchable since it meets the following requirements: controllable, firm, flexible [58], and capable of reliably replacing power from fossil fuels. Furthermore, the World Bank's Model for Electricity Technology Assessment (META) reinforces the benefits of low operating and management costs associated with geothermal energy in the long term as well as the economic stability it offers in comparison to the nation's present-day diesel-powered power plants [58]. Thus, in Case 1 (**Figure 2**) we explore the feasibility of utilising a fraction of Dominica's geothermal potential to fulfil 67% of local demand (27MW) while power from existing hydroelectric plants constitutes 37% of the grid.

3.3. Energy Storage Platforms: MeOH and NH_3 Production (Case 2 and 3)

In examining the potential for energy exportation, we consider the sustainable production of methanol (MeOH) and ammonia (NH_3) through electrochemical H_2 production from excess geothermal energy. Hydrogen supply chains for each power-to-fuel process are considered polymer electrolyte membrane (PEM) electrolysis, mainly due to its maturity and utilization at industrial scale [59, 60]. A 100MW electrolysis system was proposed, producing an average of 1,721 kg/hr of H_2, with an assumed current stack lifetime of 85,000 hours **(Eq 1).** Furthermore, the influence of electrolyser system efficiency (%) on productivity and economic viability was also investigated over the range of 63%-78% [61].

3.3.1 MeOH Production (Case 2)

Renewable MeOH production through CO_2 hydrogenation was designed using Aspen Plus V10 in accordance with past studies by some of us [62-64] (**Figure 3**). Given the lack of major industrial activity in Dominica, CO_2 was supplied DAC [65]. The DAC sub-system consisted of a closed loop KOH-CaO scrubbing and stripping process, producing 12,521 kg/hr of CO_2 for MeOH operations. The mixed synthesis gas (H_2: CO_2 molar ratio- 3:1) was compressed to 50 bars, preheated to 240°C and reacted over a non-isothermal plug flow reactor, using Cu-ZnO-Al_2O_3 **(Eq**

2-3) catalyst and kinetics derived by Vanden Busshe and Froment [64]. The exit crude MeOH (3.17% mol) was cooled to 40°C using cooling water, depressurized to 2 bar and distilled to 99.99% (mol) MeOH using two distillation columns. Purge gas (purge gas/recycle gas split ratio = 3%) combustion and the exothermic heat from MeOH synthesis was integrated into the production of saturated steam (48 bar) which added some support to distillation heat duties. The refining distillation column bottoms, with a composition of >99.99%(mol) water, was recycled to the electrolysis sub-system as a resource circular feedstock.

$$CO_2 + 3H_2 \leftrightarrow CH_3OH + H_2O \qquad \Delta H^\circ = -41.2\frac{kJ}{mol} \tag{1}$$

$$CO_2 + H_2 \leftrightarrow CO + H_2O \qquad \Delta H^\circ = 41\frac{kJ}{mol} \tag{2}$$

3.3.2 NH_3 Production (Case 3)

The NH_3 process model (**Figure 4**) considered the traditional Haber process flowsheet designed using Aspen Plus V10 [66-67], whereby NH_3 is produced from reacting N_2 and H_2 over an iron catalyst **(Eq 4)**. Here, 7,920 kg/hr of N_2- manufactured from cryogenic air separation, is mixed with H_2 in a 1:3 ratio, compressed to 141 bar and preheated to 450°C for NH_3 synthesis. The synthesis sub-unit consisted of a 4-bed adiabatic cascade unit-with heat integration and medium pressure steam generation, effectively removing the exothermic heat of reaction. Reactivity data in accordance with Temkin and Pyzhev [68,69] was imported into Aspen Plus and used to simulate NH_3 synthesis. Finally, the NH_3 effluent (20.1% mol) was chilled to -33°C through refrigeration and flash separated at 1 bar to yield 100% NH_3 product. The steam generated from heat integration coupled with energy recovered from boil-off NH_3 vapor combustion, was utilized for power generation within the process system.

$$N_2 + 3H_2 \rightarrow 2NH_3 \qquad \Delta H^\circ = -91.4\frac{kJ}{mol}. \tag{3}$$

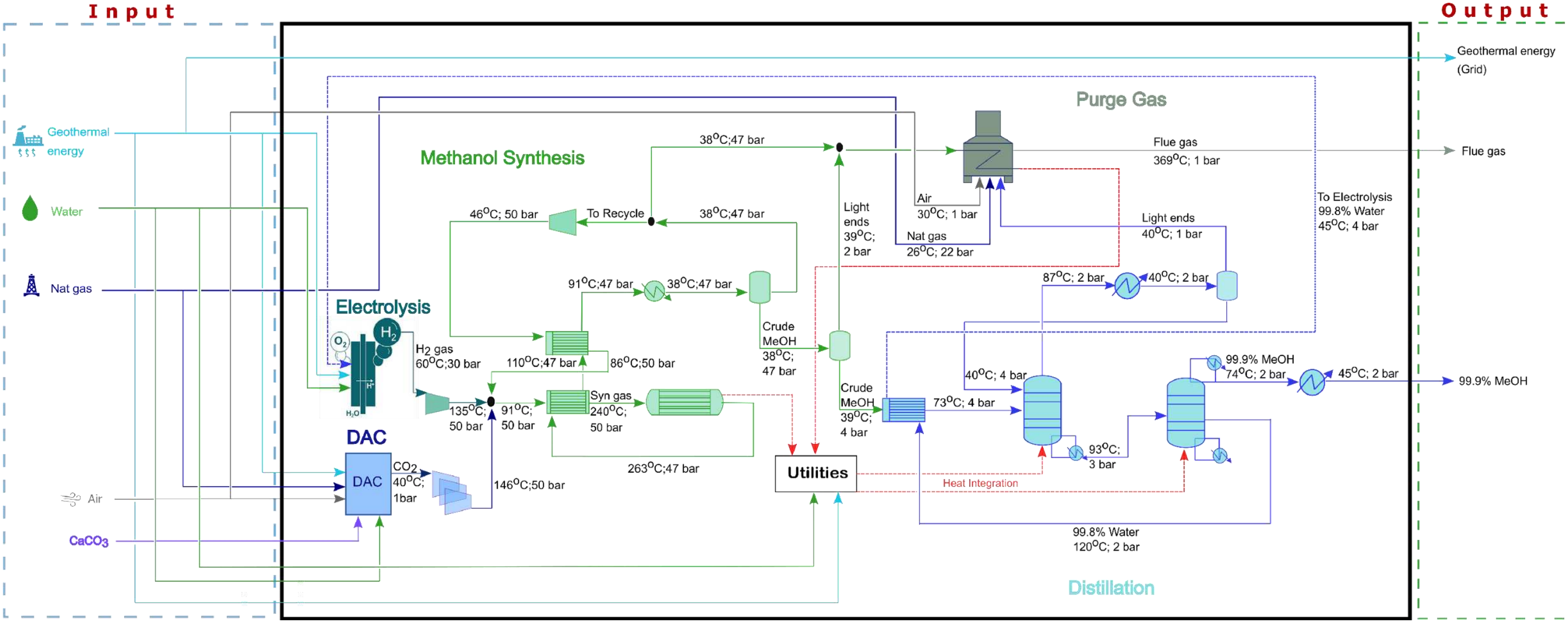

Figure 3: Process flow diagram and system boundary definition for MeOH production (Case 2).

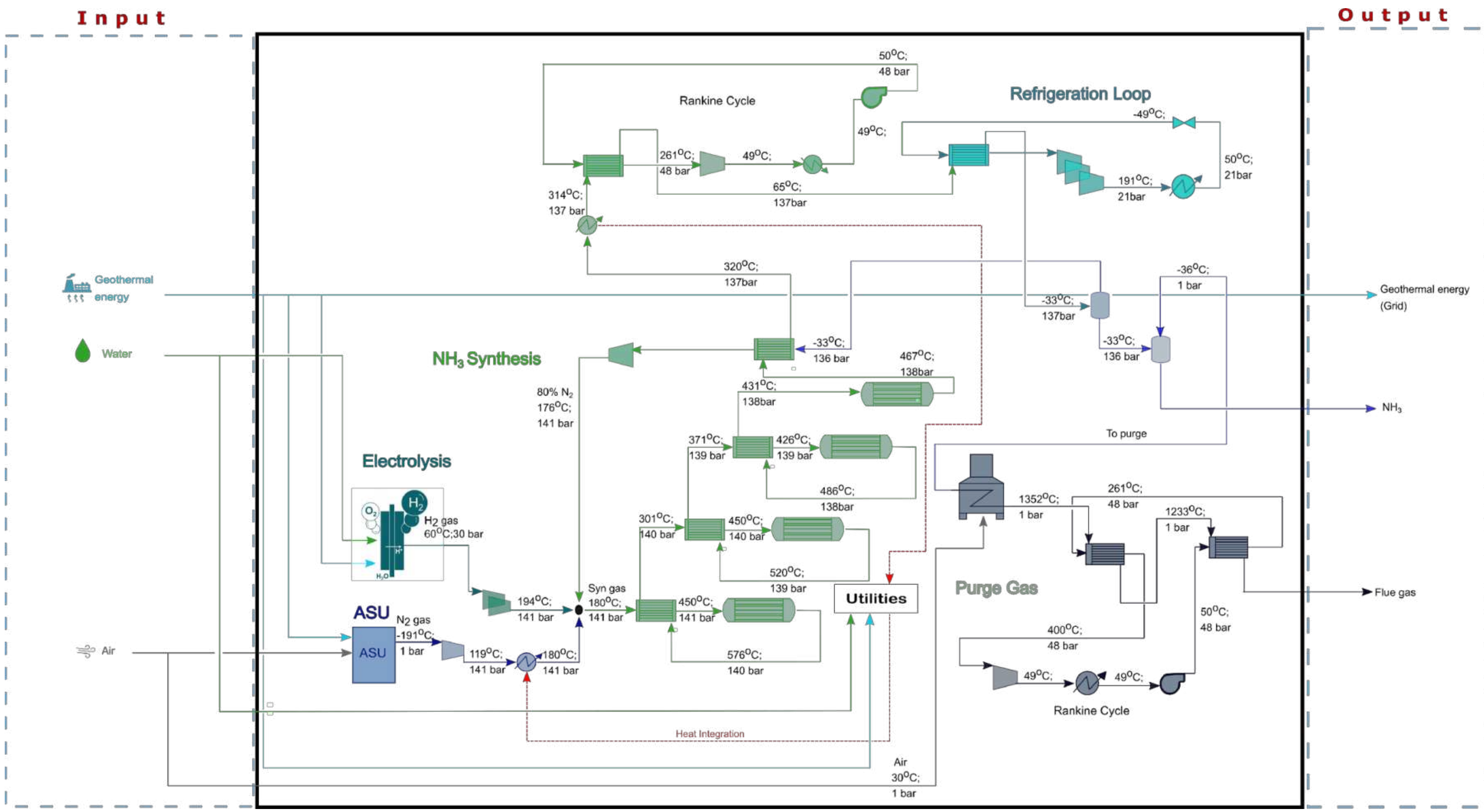

Figure 4: Process flow diagram and system boundary definition for NH_3 production (Case 3).

3.4. Geothermal Energy Exportation: Martinique 2030 Outlook (Case 4)

Dominica's abundance of geothermal energy gives the nation an opportunity, not only to provide clean, reliable energy domestically, but also to neighbouring islands [58]. Dominica has a relatively small projected demand (27MW) in 2030. This small demand affects the economic feasibility of domestic projects [28] as realising profits may be difficult at small-scale production. Martinique, a neighbouring island, having a projected demand of 407MW is a candidate for partnership, interconnection and trade for the benefit of both parties. Thus, Case 4 (**Figure 2**) explores the practicability of Dominica fulfilling their projected power demand by employing geothermal energy, while simultaneously exporting the full demand of Martinique through sub-sea cable transmission.

4. Analysis

4.1. Economic Assessment

The economic feasibility was assessed by computing the levelized cost of electricity (LCOE) for all four cases as well as the Total Annualized Cost (TAC) (on a kilogram basis) for NH_3 and MeOH produced from excess energy storage (Cases 2 and 3).

4.1.1. Levelized Cost of Electricity (LCOE)

The LCOE for each case was determined by using **Eq (4)** where P_{ij} represents the energy (MWh) derived from technology j, and $LCOE_j$ is the fixed LCOE (USD/MWh) associated with technology j.

$$LCOE = \frac{\sum_j^n (P_{ij} x\ LCOE_j)}{\sum_j^n P_{ij}} \tag{4}$$

4.1.2. Total Annualised Cost (TAC)

Total Annualized Cost (TAC) was computed by firstly estimating the capital costs (CAPEX) and operating costs (OPEX) associated with MeOH and NH_3 operations. CAPEX was calculated using bare module costing parameters based on equipment attributes [70], with purchased equipment costs extrapolated for the cost year 2020 using Chemical Engineering Plant Cost Index (CEPCI) [71]. For packaged units such as air separation and electrolyzer sub-systems, scaling factors were incorporated using current literature [72]. OPEX was estimated from fixed costs (FC) using cost allocations [73] and variable costs (VC) such as raw material prices based on current and future market analysis. TAC scores were subsequently compiled using **Eq 6,** whereby the annualized fixed costs (AFC) were calculated using the annual capital cost ratio (**Eq 5)** [74] and a 330 day yearly on-stream factor. To account for the sensitivities in raw material price, geothermal energy as well as electrolyzer efficiency and CAPEX, variable cost factors were included in estimating future TAC scores in 2030 for both technologies. A detailed overview of costs factors and allocations used in estimating CAPEX and OPEX are given below**.**

$$AFC = FCI \times \frac{(1+i)^n \times i}{(1+i)^n - 1} \tag{5}$$

Where, FCI -Fixed Capital Investment (CAPEX), interest rate i = 7% [75] and the designated plant lifetime, n = 20 years

$$TAC = \frac{AFC + OPEX}{Yearly\ production\ rate} \tag{6}$$

A detailed overview of costs factors and allocations used in estimating CAPEX and OPEX are given below**.**

4.1.2.1. Bare Module Cost

Bare module costing [70] was used for specific NH_3 and MeOH unit operations (**Eq 7**). The CEPCI for the year 2020 [71] were utilised in the extrapolation of the purchased equipment costs (**Eq 8**). All major equipment (reactor, heat exchanger, pump, compressor, heater and cooler) were cost utilizing equations and design parameters from **Tables 7 and 8** along with cost factors from R.K. Sinnott [73].

$$C_{BM_i} = C_{p_i}^0 \times (B_1 + B_2 \times F_M \times F_P) \times CEPCI\ ratio \tag{7}$$

Where: C_{BM} is the bare module cost, C_p^0 is the cost to purchase the equipment under the base conditions, B_x is the bare module factors, F_M is the material factor, F_P is the pressure factor and CEPCI ratio [72] is:

$$CEPCI\ ratio = \frac{CEPCI\ 2020}{CEPCI\ 2002} = \frac{600.6}{397} = 1.51 \quad (8)$$

4.1.2.2. Capital Costs (CAPEX)

The fixed capital investment (FCI) for the entire plant comprises direct plant costs (PPC), indirect plant costs (IPC) as well as the capital costs of package units: electrolyser (Cases 2 and 3), air separation unit (ASU, Case 3) and the steam turbines (Case 3). The variability in the CAPEX of the electrolyser unit was taken from literature sources [76,77] (**Table 6**), with an assumed stack lifetime of 85000 h (approximately 10 years). In addition to the capital cost for the electrolyser, a replacement stack cost of 40% of the capital cost was taken into consideration for a plant life of 20 years.

The PPC and IPC were estimated by the Lang factor approach considering the PEC shown in **Eqs 9-11**:

$$PPC = (1 + f_1 + f_2 + f_3 + f_4) \times PEC \quad (9)$$

Where $f_1 = 0.1, f_2 = 0.5, f_3 = 0.05, f_4 = 0.15$ which represent the Lang factors of Electrical, Utilities [70], Site developments and Ancillary Buildings respectively.

$$PEC = \sum_{i=1}^{n} C_{BM_i} \quad (10)$$

Where PEC is the total purchased equipment cost, n is the total amount of equipment.

$$IPC = (f_5 + f_6) \times PPC \quad (11)$$

Where $f_5 = 0.2, f_6 = 0.05$ which represent the Lang factors of design and engineering and contingency respectively

Package units (**Table 2**) are specific unit operations that fall outside the specific process operations such as utilities, and are cost based on scale factors as shown in **Eqs 12 and 13** below:

$$Capex\ (MM) = C_0 \times \left(\frac{S}{S_o}\right)^{sf} \quad (12)$$

where C_0 is the base case capital cost, S is the cost flow basis and S_0 is the base case flow.

$$Final\ Capex\ (2020) = Capex\ (MM) \times CEPCI\ ratio \quad (13)$$

where the $CEPCI\ ratio\ = \frac{CEPCI\ 2020}{CEPCI\ 2016} = \frac{600.6}{536.4} = 1.12$

Table 2: Scale Factors for Package Units.

	C_o	sf	S_0	S	Capex (MM)	Final Capex (MM)
Air Separation Unit (ASU) [72]	230.77	0.50	145	0.28 (kg/s O_2)	10.01	11.21
Steam Turbine [72]	61.47	0.67	136	1.78 MW	3.37	3.76

FCI was calculated by summing the PPC, IPC and packaged unit costs, while the total capital investment (TCI) was estimated by assuming a working capital (WC) of 15% FCI; given in **Eqs 14 and 15** below:

$$FCI = PPC + IPC \quad (14)$$

$$TCI = WC + FCI \quad (15)$$

4.1.2.3. Operating Costs (OPEX)

OPEX was estimated from variable (VC) and fixed costs (FC) shown in **Tables 3 and 4** below [73]. Electricity costs derived from geothermal energy was taken from Lazard's latest annual Levelized Cost of Energy Analysis (LCOE 14.0.) [78]. The variability of raw material costs (**Table 5**) was considered based on market analysis and current cost projection. The operating labour cost (**Eqs 16 and 17**) was estimated by quantifying the number of operators required for a single process and the hourly rate-which is paid at USD 8.44/hr [70].

$$Operators/shift = (6.29 + 31.7P^2 + 0.23N_{np})^{0.5} \quad (16)$$

Where P is the quantity of particulate processing steps, N_{np} is the quantity of non-particulate processing steps.

$$Cost\ of\ Labour\ = 31\ operators\ \times\ \$8.44\ \times\ 7920\ hours\ per\ year = \$2{,}072{,}188.80 \quad (17)$$

Table 3: Fixed Costs Allocation obtained from R.K. Sinnott [73].

Fixed Costs	
Maintenance	5% of FCI
Operating Labour	-
Laboratory Costs	21.5% of Operating Labour
Supervision	20% of Operating Labour
Plant Overheads	50% of Operating Labour
Capital Charges	10% of Operating Labour
Insurance	1% of TCI
Royalties	1% of TCI

Table 4: Fixed Utilities Cost [79].

Utilities	Cost	Unit
Process Water	1.52	$/MT
Cooling Water	0.378	$/GJ

For Case 4, the transmission cost of power to Martinique was found as a function of the sub-sea distance between the substation in Dominica to the electricity substation in Martinique (approx: 104.24 km) according to **Eq 18**.

$$\boldsymbol{Cost\ (million\ USD/year)\ =\ 1.21 \times (1.36\,D\ +\ 366.78)} \tag{18}$$

where D is the subsea distance between the two substations.

4.1.2.4. Projections for 2030

All cases were analysed using 2019 LCOE prices as the benchmark. Cases 1-4 were further analysed using a forecasted LCOE for geothermal energy in 2030. Projected electrolyser costs and increased stack lifetime for 2030 were also considered based on expected technological advancements. These projections are shown in **Table 6.**

Table 5: Variable Costs.

Unit Cost				
	Low	**Average**	**High**	**Unit**
Electricity (Geothermal) 2019 [77]	59	80	101	$/MWh
Electricity (Geothermal) 2030 [77]	38	57	76	$/MWh
Diesel Power [77]	197	239	281	$/MWh
Hydropower [77]	20	45	70	$/MWh
CO_2 (From DAC) [80]	94	163	232	$/tonne
Natural Gas [77]	2.12	2.66	3.38	$/MMBTU

Table 6: Capital cost of electrolyser based on 1kW.

	Unit Cost (USD/kW)			Stack Lifetime(h)
	Low	**Average**	**High**	
2019 [76]	682	777	886	85000
2030 [77]	200			10000-20000

Table 7: Equipment Design Parameters for MeOH

Equipment	Design Parameter	Characteristic Range	Unit
Methanol Reactor[a]	Volume	7.47	m^3
	Heat Transfer Area	671.04	m^2
Purge Boiler	Duty	5.06	MW
HEX	Heat Transfer Area	2-782	m^2
Topping Column	Volume	247-300	m^3
	Dimensions	Diameter: 0.73, Height: 29.26	m
Refining Column	Volume	77.10	m^3
	Dimensions	Diameter:1.25, Height: 62.2	m
Flash Drums	Volume	0.01-16.79	m^3
Pump	Power	0.45-80.05	kW
Compressor	Power	356-728	kW
Storage Tank	Volume	2534.49	m^3

[a]Reactor cost is based on both volume for methanol synthesis and heat exchanger (HEX) surface area for MP steam production.

Table 8: Equipment Design Parameters for NH_3

Equipment	Design Parameter	Characteristic Range	Unit
Ammonia Reactor	Volume	40	m³
Purge Boiler	Duty	1.04	MW
HEX	Heat Transfer Area	0.65-269.36	m²
Flash Drums	Volume	203.81	m³
Pump	Power	2-16	kW
Turbines	Power	1860-1999	kW
Compressor	Power	126-1755	kW

4.2. LCA Framework

An LCA was carried out considering a cradle-to-power generation gate as outlined in **Figures 2-4**, in accordance with the ISO 14040:2006 methodology [81]. Our study considers several cases for which the total national power consumption for the island of Dominica was considered the main product; thus, the FU used for each case was the production of 1 MWh of energy. Subsequently, case specific LCI were established based on mass and energy balances for each individual case, normalized to the FU (**Table 9**). Major inputs and outputs include electrical production from deep geothermal wells, hydroelectric run-of-river, petrol/oil, biomass, solar and wind supply chains, deionized water, natural gas (heating purposes) and flue gas emissions (MeOH/NH_3 process). For the purposes of this study, impacts associated with commissioning/construction phases were neglected [66,67]- mainly since these impacts are negligible when compared to the operating phase of the process [82-84].

Inventories linked to raw materials and other inputs as well as embedded fugitive emissions were retrieved from Ecoinvent v3.4 databases attached to the SimaPro software platform. Case-specific environmental burdens were characterized in the life cycle impact assessment (LCIA) stage at the midpoint level, using the ReCiPe 2016 hierarchist method [62-64, 66, 67], comprising 18 impact categories as detailed in the **Results and Discussion Section**. For Cases 2-4 where multiple products were generated (MeOH/NH_3 production and energy export to Martinique), a substitution allocation approach was used to distribute environmental burdens among co-products. In accordance with ISO 14040:2006 methodology, the substitution allocation approach allows for burdens associated with marketable products to be displaced by the production of cleaner, greener co-products [82,85,86]. Here, the burdens linked to traditional "business-as-usual" processes are subtracted from the overall burdens of the multifunctional systems (Cases 2-4). Ecoinvent databases linked to traditional products were used to assess the avoided burden. Finally, in the interpretation stage of the LCA framework, environmental benefits were evaluated, providing evidence supporting the transition towards greater sustainable power generation.

Table 9: Case-specific life cycle inventories for each sub-system boundary normalized to 1MWh energy produced on Dominica/Martinique power grid.

	Process System										
Inputs	**Dominica (BAU-2019)**	**Dominica (BAU-2021)**	**Dominica (BAU-2023)**	**Dominica (BAU-2025)**	**Dominica (BAU-2027)**	**Dominica (BAU-2030)**	**Martinique (BAU-2030)**	**Case 1**	**Case 2**	**Case 3**	**Case 4**
Electricity (Diesel)/ MWh	0.558	0.579	0.579	0.615	0.632	0.673	0.857	-	-	-	-
Electricity (hydroelectric)/MWh	0.442	0.421	0.421	0.384	0.368	0.327	-	0.327	0.327	0.327	0.327
Electricity (wind-onshore)/MWh	-	-	-	-	-	-	0.010	-	-	-	-
Electricity (photovoltaic-mounted)/MWh	-	-	-	-	-	-	0.048	-	-	-	-
Electricity (biomass)/MWh	-	-	-	-	-	-	0.085	-	-	-	-
Electricity (geothermal)/ MWh	-	-	-	-	-	-	-	0.673	4.459	3.918	15.746
$CaCO_3$/kg	-	-	-	-	-	-	-	-	8.890	-	-

Water/kg	-	-	-	-	-	-	-	-	1522.084	1037.315	-
Natural gas/ m^3	-	-	-	-	-	-	-	-	4.395	-	-
Outputs											
MeOH/kg	-	-	-	-	-	-	-	-	294.438	-	-
NH_3/kg	-	-	-	-	-	-	-	-	-	316.877	-
Electricity (Dominica)/ MWh	1.000	1.000	1.000	1.000	1.000	1.000	-	1.000	1.000	1.000	1.000
Electricity (Martinique)/ MWh	-	-	-	-	-	-	1.000	-	-	-	15.074
Flue gas (CO_2)/kg	-	-	-	-	-	-	-	-	75.493	-	-

5. Results and Discussion

Here, we present our findings linked to both environmental and economic performance of each case proposed. For each scenario investigated, a system boundary was proposed and evaluated using mass and energy balances. These calculations were further utilized to size and cost unit operations, utilities and raw materials as well as identify environmental burdens and benefits that exist within case-specific process operations. Through the understanding of both performance indicators- aligned to multiple decision criteria, our analysis identifies favourable options for both Dominica and Martinique to symbiotically achieve their 2030 sustainability goals.

5.1. Environmental Performance.

In considering the country level analysis for Dominica as it pertains to its current energy consumption, the island nation requires a peak demand output of 20MW; for which diesel constitutes 63% [50] of its grid capacity while hydroelectric power maintains the other 37%. The energy sector is dependent on imported fossil fuels at an annual cost of 27 million USD (5% of Dominica's GDP [5]. The BAU case assumes that while power generation from existing hydroelectric power plants remains at capacity [87] due to hindrances such as seasonal fluctuations and changing precipitation patterns associated with climate change, diesel generation increases to satisfy the growing energy demand in subsequent years-up to 2030. Ultimately, fuel imports are forecasted to increase accompanied by an increase in GHG emissions. Our LCA results indicate (**Figure 5**) that currently (2019), national life cycle GHG emission quotas stood at 90,366 tonnes CO_2 eq/year- with diesel emissions dominating the total GHG contributions at >99%. Furthermore, GHG emissions are expected to increase to 146,831 tonnes CO_2 eq/year in 2030 to fulfil the projected demand of 27MW. This shows a 62% increase in life cycle GHG emissions if the transition to more sustainable, climate smart energy integration does not take precedence. Additionally, this transition is essential for Dominica to honour its INDC to global climate change mitigation under the Paris Agreement [15] and Climate Action aligned to UN SDG 13 [88], wherein the nation aims to reduce GHG emission quotas by 44.7% by 2030 [89].

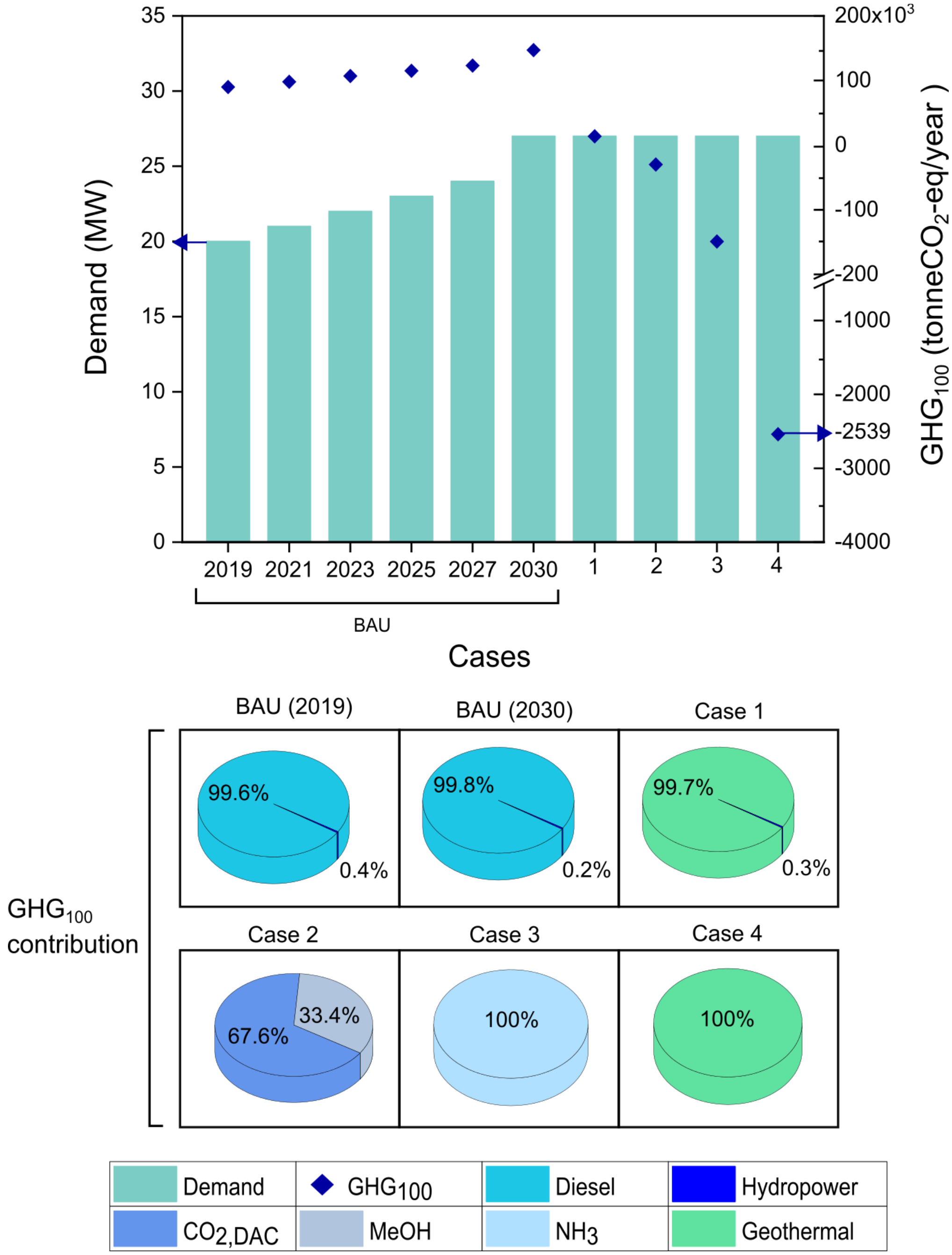

Figure 5: Case-specific life cycle GHG emission quotas (tonne CO_2-eq/year) for Dominica as a function of net energy demand over the period 2019-2030. GHG contributions are given with respect to technology grid share (BAU 2019-2030; Case 1) as well as avoided burdens (Cases 2-4).

In promoting options towards sustainable power generation, Case 1 explores the deployment of geothermal energy to completely substitute diesel generation by 2030. Although geothermal energy dominates the total GHG emissions arising (>99%) from Case 2, the technology provides cleaner energy, supporting a decline in total emission quotas to 734 tonnes CO_2 eq/year- allowing Dominica to achieve its intended GHG mitigation commitments. Furthermore, Cases 2 and 3 explore opportunities for excess energy storage in the form of MeOH and NH_3. As shown in **Figure 5,** both cases were found to achieve negative carbon emissions through avoided burdens- with MeOH and NH_3 production avoiding 36,871 and 149,013 tonnes CO_2-eq/year respectively. Ultimately, high levels of avoided emissions are attainable when traditionally used fossil fuels are replaced partially or completely by more sustainable energy sources. Hence, avoided burdens were mainly attributed to lower fossil fuel utilization- through the absence of conventional energy intensive steam methane reforming for hydrogen production (33.4% and 100% avoided emission contributions for MeOH and NH_3 respectively), as well as CO_2 utilization through direct air capture (DAC) operations (67.6% avoided emissions). Furthermore, synthesis of these fuels is energy intensive, with the electrolysis process accounting for the largest energy share. Our life cycle GHG emission data indicates that an appreciable higher GHG avoidance is realized in Case 3 owing mainly to: higher energy efficiency of NH_3 synthesis (56%) over MeOH production (42%) and complete avoidance of fossil fuels relying solely on renewable grid power. This subsequently leads to an overall decrease of 304% in life cycle GHG emissions compared to Case 2.

Lastly, Case 4 investigates the option of a RE export supply chain from Dominica to Martinique- wherein excess geothermal energy is harnessed to fulfil both countries' peak demand in 2030. Our results indicate, for Case 4, a consolidated avoided life cycle GHG emission quota of 2.5 million tonnes CO_2-eq- the highest amongst all scenarios investigated. Thus, Case 4 can significantly contribute to GHG emission reduction efforts for both countries under the Paris Agreement [15]. Currently in 2019, fossil fuels accounted for 82% of Martinique's energy share. Through geothermal energy integration onto the national grid, emissions can be curtailed to guarantee 40% reduction in GHG emission quota by 2030. Furthermore, by promoting full geothermal penetration accounting for 100% energy share, Martinique can accomplish and surpass France's mandate to increase renewable electricity potential by 32% in 2030 [89].

5.2. LCA Comparison

The midpoint approach (ReCiPe 2016 Midpoint (H) V1.01) [64-66,68,69] based on a cradle to gate LCA with a functional unit of 1 MWh of energy was utilized to assess the case-specific environmental burdens across the following impact categories: global warming; stratospheric ozone depletion; ionizing radiation; ozone formation human health; particulate matter formation; ozone formation terrestrial ecotoxicity; terrestrial acidification; freshwater eutrophication; marine eutrophication; freshwater ecotoxicity; marine ecotoxicity; human carcinogenic toxicity; human non-carcinogenic toxicity; land use; mineral resource scarcity, fossil resource scarcity and water consumption.

The cases were compared in terms of their specific environmental impact across all eighteen (18) impact categories, shown in **Figure 6**. Considering all cases investigated, the BAU process produces the largest environmental burdens. This was mainly attributed to emissions consolidated through fossil fuel combustion as well as fossil fuel extraction- which led to toxic elements such as Hg, Pb and Ni as well as GHGs such as CO_2, CH_4 and N_2O emitted from input process operations. These gave high contributions across impact categories, ranging from 79.3%-100% of the total normalized environmental impact. Compared to the BAU process, the transition to renewable power integration within Cases 1-3 showed favourable reduction of up to 67% in environmental burden - with contributions of 33.9% - 99.7% across impact categories. Furthermore, largely negative burdens associated with excess energy export to Martinique contributed the least (0% - 46%) to the normalized environmental impact- mainly due to the avoided burdens associated with reduced fossil fuel resource utilization across both countries. Thus, among all cases considered, Case 4 proves to be the most environmentally sustainable option.

In promoting the transition towards greater GHG mitigation, it should be noted that burden shifting was observed- that is collateral damage that arises from geothermal energy deployment. From **Figure 6**, burden shifting exists mainly within ionizing rad, freshwater eutroph, marine eutroph, freshwater ecotox, marine ecotox, human carcino and non-carcino toxicities and mineral scarcity. Among cases, MeOH production was the worst performing within ionizing rad, marine and freshwater ecotox and human non-carcino toxicity-mainly. Furthermore, geothermal power exportation proved to be particularly damaging within freshwater and marine eutroph, human carcino toxicity and mineral scarcity. These damaging impacts were mainly associated with active geothermal extraction operations which released toxic chemicals such as Co-60, C-14, Fe, benzene, and Ba from deep within the earth's surface. Although these impacts should not be overlooked in understanding the overall environmental sustainability of each case, our results indicate for Case 4 in particular, that the incurred benefits outweigh the risks in achieving set emission reduction targets by 2030.

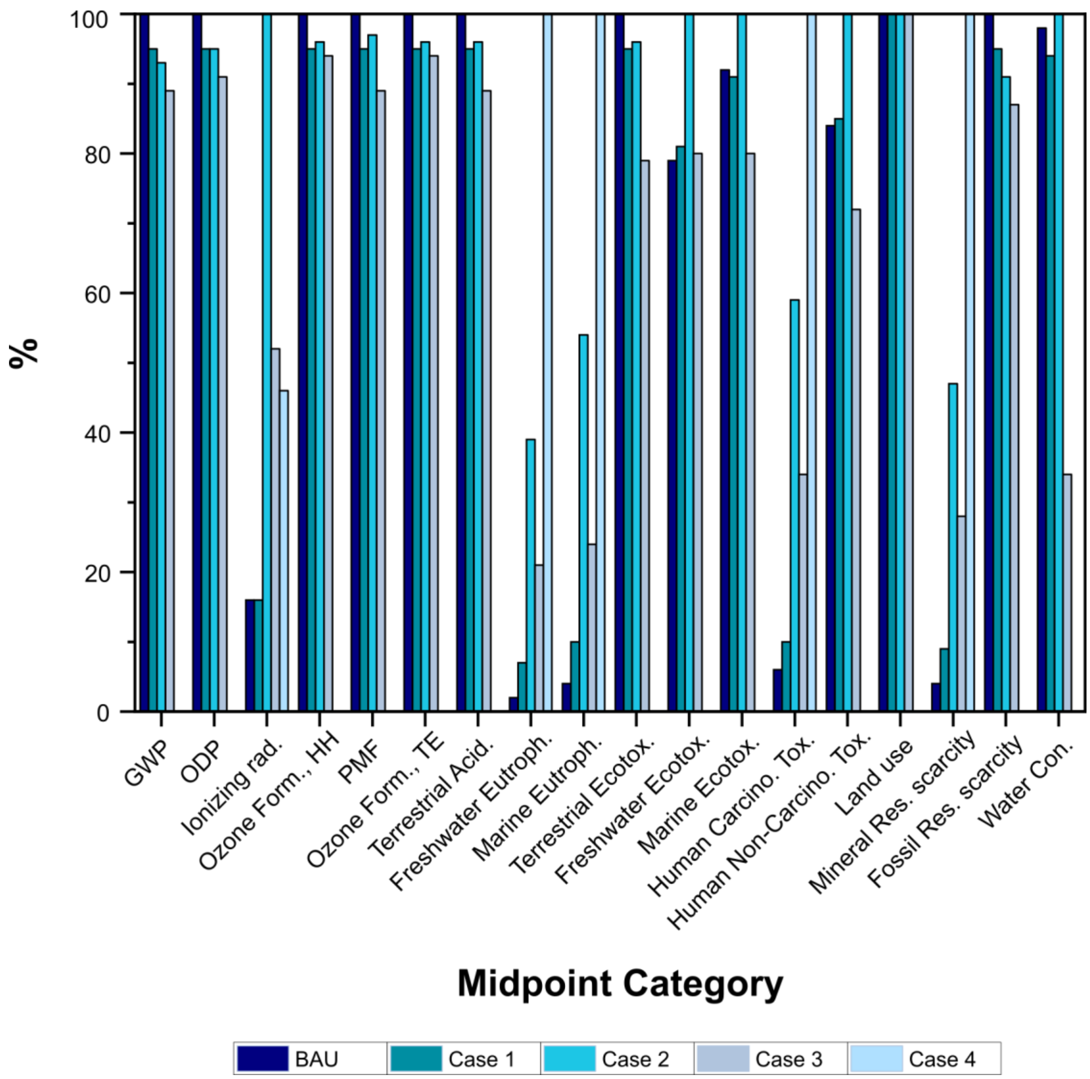

Figure 6: LCA comparison illustrating normalized % contributions for model cases across impact categories (Method-ReCiPe 2016 Midpoint (H); FU- 1MWh of energy produced)

5.3. Economic Performance

Here in this section, we examine the economic feasibility of all cases considered by utilizing current and future LCOE data for each technology as well as energy storage potential in the form of MeOH and NH_3 grassroots operations. For the BAU case, the LCOE for Dominica increases from 153 USD in 2019 to 175 USD/MWh in 2030 due to a 35% increase in power demand (from 20MW to 27MW) as shown in **Figure 7**. This is mainly attributed to the increase in diesel share contribution from 87% in 2019 to 92% in 2030. Diesel generation is further conditioned by the volatile market price of diesel oil to be imported into the country which stood at 61.4 USD/bbl with an expected increase to 70 USD/bbl in 2030 [90]. Although hydropower maintains less than 50% of the grid (44% in 2019), it accounts for 13% of the LCOE- 431% cheaper than diesel generation. In spite of being a less expensive and cleaner alternative for power generation, the technology is constrained by high reliance on the natural water cycle which is being intensified in the face of global warming and extreme climate events [91]. This impedes on its potential for dispatchable power generation- leading to a likely decrease in energy share to 33% in 2030.

Now, examining the potential for geothermal deployment across Cases 1-3, our results show a drastic decrease in LCOE for Dominica. For Case 1, a 62% decrease in LCOE to 69 USD/MWh is attributed to the complete substitution of diesel power generation by geothermal energy. This case represents a 100% renewable grid; with 67% of the demand fulfilled by geothermal integration, contributing to 72% of the LCOE. The high contribution of geothermal power to the consolidated LCOE is owing to its individual average $LCOE_{2019}$ (80 USD/MWh) being 77% higher than that of hydropower (45 USD/MWh). However, advancements in geothermal technology coupled with high learning rates [92,93] are expected to decrease LCOE in 2030 to an average 53 USD/MWh- leading to an overall decrease of 70% compared to the BAU case.

Upon considering the economics of energy storage potential in the form of MeOH and NH_3 production, Cases 2 and 3 were analysed using TAC as a key performance indicator. The TAC score takes into consideration the total CAPEX and OPEX for both technologies. **Figure 8** describes the respective current and future economic feasibility for each power-to-fuel scenario. Results illustrate TAC ranges for MeOH and NH_3 from 1.22 to 2.07 USD/kg_{MeOH} and 1.07 to 1.61 USD/kg_{NH3} respectively. Thus, our data shows MeOH production to be the more expensive of the two scenarios-mainly attributed to energy and capital-intensive operations surrounding electrolysis and DAC. Overall, cost contributions to TAC for each process show major expenses attributed to geothermal electricity utilization (48%-51%) - with fixed and capital costs giving 9%-31% and 21%-22% respectively. Furthermore, DAC operations accrued up to 16% of the total TAC for MeOH production. Comparing current prices for both MeOH and NH_3 markets, associated green production routes utilizing geothermal energy can be regarded as uncompetitive - with 75-80% higher costs compared to fossil-based technologies at 0.2-0.4 USD/kg_{MeOH} and <0.4USD/kg_{NH3} [69,79]. However, taking future electrolyser capital costs, stack lifetime and lower geothermal energy prices into consideration, our results reveal an overall 26% - 38% decrease in TAC- ranging from 0.82-1.21 USD/kg_{MeOH} and 0.79-1.18 USD/kg_{NH3} respectively. Furthermore, it should be noted that TAC scores are particularly sensitive to the efficiency of the electrolyser sub-system. Thus, enhancing the reliability of the electrolysis process can lead to marked improvements in the economic feasibility of both energy storage systems. Future market outlook for the period 2040-2050 for both processes show reduced prices within 0.25 - 0.77 USD/kg [79,94], and thus aligns well with our results at lower $LCOE_{2030}$ and high electrolyser stack lifetime-with optimistically competitive future prices within the range of 0.79-0.85 USD/kg for both MeOH and NH_3 production from geothermal energy.

Lastly, the economic feasibility of Dominica's RE export capacity was assessed through Case 4. Apart from achieving 100% RE penetration for both Dominica and Martinique by exporting 434MW of geothermal power, the projected $LCOE_{Mar}$ (**Figure 7**) was found to be 259 USD/MWh-11% lower than the current consumer price for the island ($292USD/MWh) [89]. Furthermore, with lower geothermal costs expected in the future, a further decrease in $LCOE_{Mar}$ to 236 USD/MWh in 2030 is anticipated- 20% lower than current price projections. Among the case-specific cost contributions, subsea transmission accounts for 75% of the $LCOE_{Mar}$ while geothermal energy generation accounts for the remaining 25%. Notwithstanding high transmission costs, Dominica can expect to earn in excess of 925 million USD/year in revenue from export sales. Even with higher MeOH and NH_3 capacities (>100MW), economic viability would still favour energy exportation as significant energy is currently lost during the electrolysis process compared to direct transmission. Regardless, given that the projected geothermal energy potential of Dominica surpasses the total deployment covered in this study (Proven potential = 1390 MW), the nation can realize increased economic advantages while promoting sustainable operations from coupled exportation and energy storage activities in the future- aligned to geothermal energy deployment for the provision of affordable energy (SDG 7) [24].

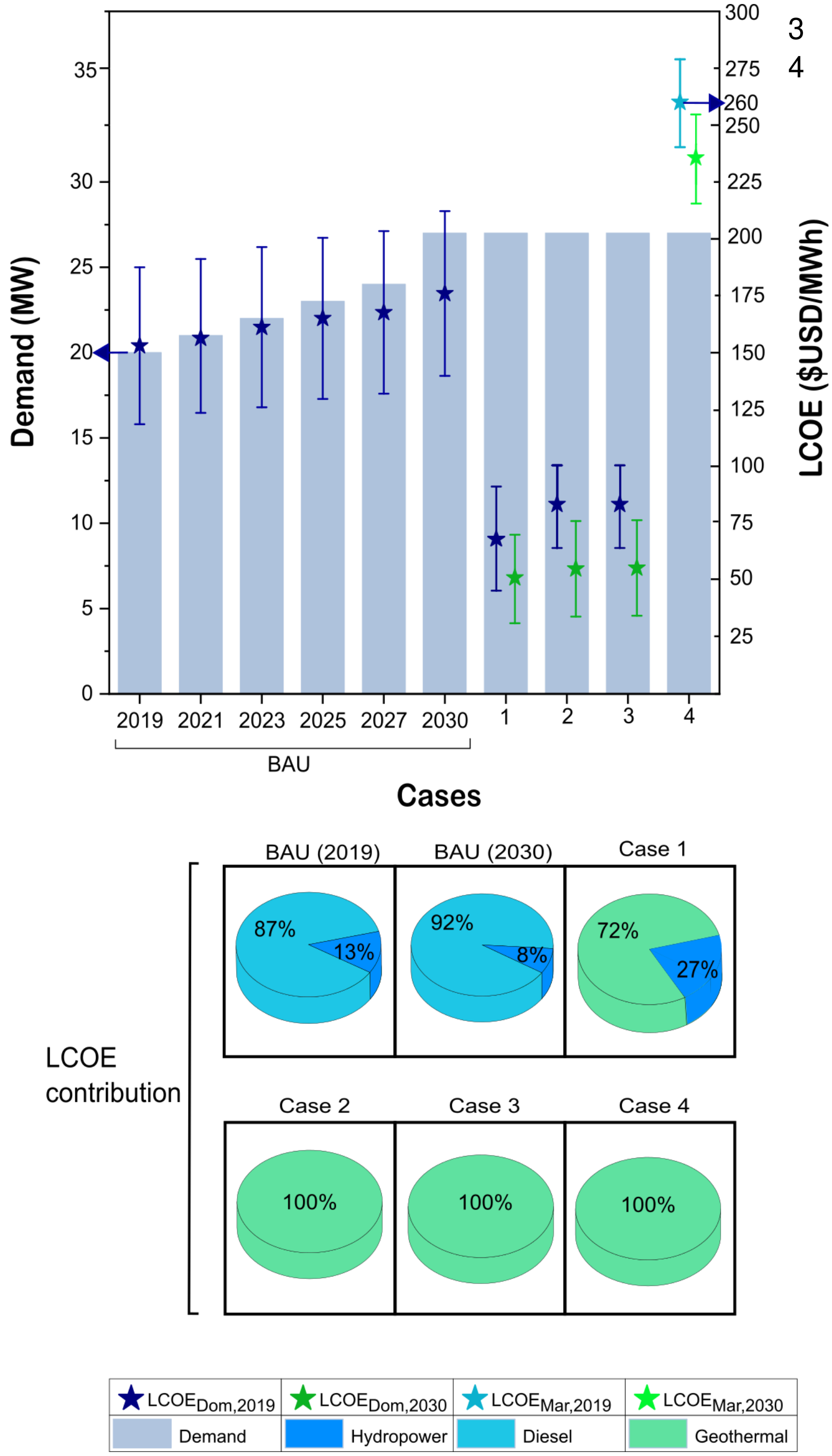

Figure 7: Case-specific LCOE as a function of net energy demand over the period 2019-2030. LCOE contributions are given with respect to technology grid share.

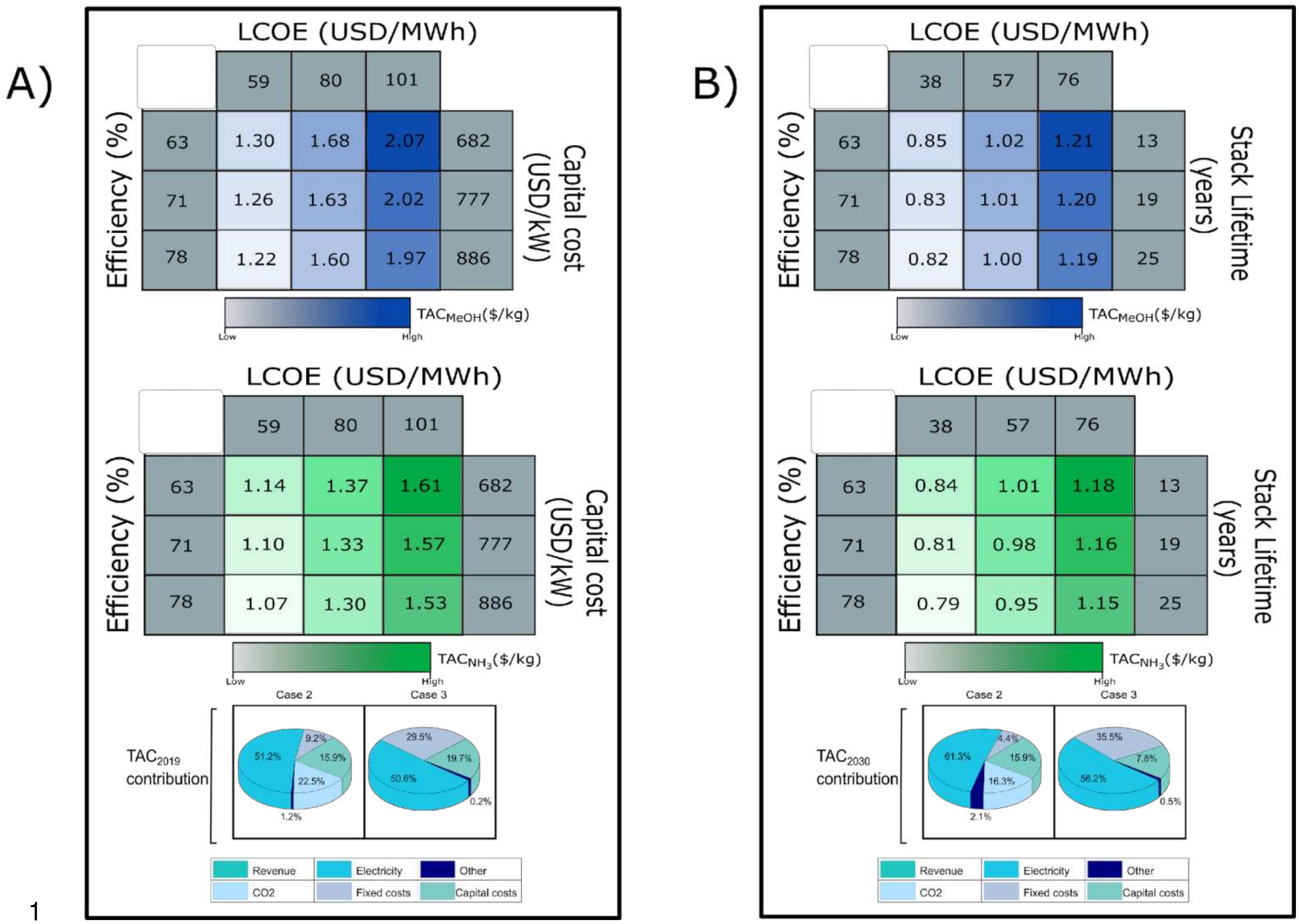

Figure 8: Current-2020 (A) and future-2030 (B) TAC for MeOH (blue) and NH_3 (green) production as a function of LCOE (geothermal power), electrolyser efficiency, capital cost and stack lifetime. Costs associated with the category other are natural gas fuel, process water, wastewater and catalyst charges.

6. Conclusion

The shift to sustainable forms of energy takes precedence as the Caribbean region faces several challenges due to the on-going impact of climate change. Through the utilization of multiple decision criteria, techno-economic and environmental assessments were carried out to guide the island of Dominica. To this end, several cases were explored utilizing current LCOE data, TAC projections and LCA to determine the most sustainable options for Dominica to utilize its geothermal energy potential.

Our results illustrate for the BAU case, a 62% increase in life cycle GHG emission quotas due to increased energy demand from 20MW in 2019 to 27MW in 2030. The impact is further consolidated in an increase in $LCOE_{2030}$ of up to 35% at 175 USD/MWh. However, through 100% geothermal integration, life cycle GHG emissions can be reduced by 99.5% - allowing Dominica to meet its GHG commitments under the Paris Agreement and provide 70% cheaper energy with a $LCOE_{2030}$ of 53 USD/MWh. Additionally, energy storage can promote negative GHG quotas as fossil-based MeOH and NH_3 production are avoided through the utilization of cleaner supply chains- with avoided emissions as high as 149 kilo-tonne CO_2-eq/year observed. Despite this, both processes were found to be 75-80% more expensive compared to current fossil-based technologies- with a TAC range of 1.07-2.07USD/kg, and thus were deemed financially uncompetitive. Nonetheless, with future market growth shifting towards greener processes with higher learning rates, renewable MeOH and NH_3 production costs are expected to reduce by 26-38% to a more competitive price range of 0.79-0.85 USD/kg. While energy storage provides major economic and environmental incentives in the future, Case 4 proved to be the most sustainable- avoiding 2.5 million tonnes CO_2-eq/year and producing 20% cheaper power with a $LCOE_{Mar}$ of 236 USD/MWh in 2030.

Although the cases outlined in this study accompany high capital commitments and project costs coupled with associated burden shifting consolidated in energy extraction activities, the overall financial and environmental benefits are obvious with geothermal energy promoting affordable and clean energy both nationally and internationally among OECS nations.

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