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Decarbonizing the Energy System of Non-Interconnected Islands: The Case of Mayotte

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Abstract: Islands face unique challenges on their journey towards achieving carbon neutrality by the mid-century, due to the lack of energy interconnections, limited domestic energy resources, extensive fossil fuel dependence, and high load variance requiring new technologies to balance demand and supply. At the same time, these challenges can be turned into a great opportunity for economic growth and the creation of jobs with non-interconnected islands having the potential to become transition frontrunners by adopting sustainable technologies and implementing innovative solutions. This paper uses an advanced energy–economy system modeling tool (IntE3-ISL) accompanied by plausible decarbonization scenarios to assess the medium- and long-term impacts of energy transition on the energy system, emissions, economy, and society of the island of Mayotte. The model-based analysis adequately captures the specificities of Mayotte and examines the complexity, challenges, and opportunities to decarbonize the island's non-interconnected energy system. The energy transition necessitates the adoption of ambitious climate policy measures and the extensive deployment of low- and zero-carbon technologies both in the demand and supply sides of the energy system, accounting for the unique characteristics of each individual sector, while sectoral integration is also important. To reduce emissions from hard-to-abate sectors, such as transportation and industry, the measures and technologies can include the installation and use of highly efficient equipment, the electrification of end uses (such as the widespread adoption of electric vehicles), the large roll-out of renewable energy sources, as well as the production and use of green hydrogen and synthetic fuels.

Keywords: decarbonization; energy transition pathways; Mayotte; energy system planning tools; RES penetration; non-interconnected islands

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1. Introduction

The goal of the Paris Agreement to limit global warming to well below 2 °C and pursue efforts to limit it to 1.5 °C [1] requires the transition to carbon-free energy systems by the mid-century through the large-scale uptake of clean energy and innovative technologies, energy efficient equipment, and renewable energy. This requires ambitious decarbonization efforts, principally by major emitting economies, such as the EU, USA, and China [2]. The European Commission announced its objective to steer its economy and society towards a more sustainable and environmentally friendly pathway in 2019 [3], while in 2021, it set out a roadmap to achieve climate neutrality by 2050, including the intermediate target of at least a 55% net reduction of greenhouse gas (GHG) emissions by 2030 [4]. Considering that about 3/4 of European Union's GHG [5] stem from the energy sector, the EU's long-term climate ambition must be guided by sustainable energy system planning and supported by the appropriate decision-making tools.

Recent research has revealed that the decarbonization strategy of each country and the adoption of the appropriate emission reduction options depend on a country's specificities and priorities [6].

Around 4% of the EU's total population live on islands. There are almost 2200 inhabited EU islands, greatly diverse in terms of size, population, geography, and territory. Non-interconnected islands face unique challenges on the pathway to decarbonization that differ from those of the mainland based on their geo-graphical location, lack of energy interconnections, large variation in energy requirements within a year, high reliance on imported fossil fuels, limited infrastructure, and renewable energy potentials, as well as climate change vulnerability.

Island economies frequently rely on seasonal touristic activities, necessitating the over-dimensioning of energy systems to accommodate the seasonal, short-term in-flux of visitor needs and the resulting load variations. Non-interconnected electricity grids face considerable problems in balancing supply and demand, especially in islands with high load volatility (e.g., due to touristic season), causing fluctuations in electricity load voltage and frequency or even interruptions in the electricity supply. Furthermore, the dependency of non-interconnected islands on imported fossil fuels (commonly diesel) for electricity supply and transportation brings in economic, environmental, and energy security problems, such as price volatility, high electricity prices—thus a higher cost of living—and increased CO_2 emissions [7].

In this context, the energy system planning of non-interconnected islands necessitates the use of customized and holistic modeling approaches capable of capturing these specificities, as detailed in [7]. Moreover, the interlinkages between energy and economy dictate the integrated assessment of the transition pathway, including the comprehensive analysis of the available resources, the environmental and socio-economic impacts, and the technology uptake requirements, with the active participation of multiple system agents and stakeholders.

The transition to a competitive, sustainable, and low-carbon economy should be based on comprehensive energy–economy system planning, supported by extensive multi- and inter-sectoral modeling analysis and plausible scenarios to benefit the local society and the environment [8].

To address these needs, the present study aims to design and develop a holistic energy–economy system approach, specifically for non-interconnected islands, and apply it to the EU island of Mayotte. Recently, Ref. [7] proposed a new energy–economy modeling tool (IntE3-ISL model) that goes beyond the approaches, at present, by incorporating the specificities of non-interconnected islands' energy systems for medium- and long-term projections.

The IntE3-ISL energy–economy model has several innovative features that allow an improved and more consistent representation of non-interconnected islands' specificities. IntE3-ISL represents endogenous energy demand by sector and captures in detail its complex interactions with energy supply through market-derived prices based on a market equilibrium approach. It can evaluate the impacts of policies and associated technologies to provide flexibility to small-scale insular systems [7]. IntE3-ISL projects the insular energy demand and supply with high granularity, including: (i) a detailed and complete representation of the key drivers of energy demand by sector; (ii) adequate sectoral disaggregation to represent key dynamics shaping up future energy market developments; (iii) explicit representation of energy- and climate-related policies, as well as their implications on technology uptake, fuel-mix usage, and emissions; (iv) engineering-based simulation of the energy system operation; (v) representation of economic agents' behavior; (vi) capture of inter-linkages between energy demand, supply, and the formation of energy prices, as well as the socio-economic impacts of decarbonization; and (vii) adaption to island-scale specificities, especially related to the decarbonization of islands with great expansion of variable renewables and flexibility services.

To ensure a comprehensive and sustainable energy–economy system plan for non-interconnected islands, this study engages multiple system factors to analyze the available resources, relevant impacts, and technology uptake requirements. This study also explores cross-sectoral solutions for flexibility enhancement that reflect the island's system.

Therefore, this study aims to provide an innovative and comprehensive approach to energy system planning for non-interconnected islands. This approach will enable the transition to competitive, sustainable, and low-carbon island economies, contributing to the development of local skills and jobs for island communities, as well as the global efforts to limit climate change.

The structure of the paper is as follows: Section 2 presents a literature review; Section 3 describes the selected methodological approach, data gathering process, and scenario design; Section 4 provides numerical details for the Baseline scenario; Section 5 presents the model-based results for decarbonization scenarios for Mayotte; Section 6 includes the discussion of the results; and Section 7 concludes the article.

2. Literature Review

Decarbonizing energy systems is a critical element in achieving global climate goals and reducing greenhouse gas (GHG) emissions. Several studies have examined decarbonization pathways in mainland regions. On the other hand, decarbonizing island-scale energy systems, especially those that are non-interconnected, presents unique challenges that require tailored approaches.

According to [9], energy systems in islands are typically small and isolated, which makes it difficult to integrate renewable energy sources (RESs) into the grid, because of the limited grid infrastructure, and often lack of interconnections. As a result, islands are highly dependent on imported fossil fuels that are expensive and contribute significantly to GHG emissions. However, the unique features of islands make them suitable for testing innovative energy solutions. For example, microgrids and off-grid solutions have been suggested as viable options for islands.

The islands' energy transition has also been examined in several studies. Energy transition refers to the shifting from a high- to a low-carbon energy system. For example, [10] discusses that the energy transition in islands involves a comprehensive approach that considers the island's characteristics, energy demand and supply, as well as its socio-economic context. The authors suggest that energy transition should involve a mix of policies and interventions, such as incentivizing energy efficiency, promoting the use of RESs and introducing energy storage solutions.

The impact of energy transition on an island's economy and society has also been explored. Specifically, the economic implications of energy transition in the island state of Hawaii have been examined by [11], where the authors found that the transition to a low-carbon energy system could have a positive impact on the economy (increased job creation, improved energy security, and decreasing energy costs). However, the authors noted that the transition could lead to higher upfront costs and potential negative effects on existing industries, such as oil and gas industries.

Despite the growing body of literature on decarbonizing the energy systems of islands, there are still gaps that need to be addressed. One major gap is the lack of focus on non-interconnected islands, which face additional challenges due to their limited access to the mainland and often rely on fossil fuels for energy generation. In the case of Mayotte, the island faces unique challenges related to its remote location and limited infrastructure. Furthermore, while there are many studies relative to the economic implications of energy transition, there is a need for more research on the social implications, such as the impact on the quality of life of island residents.

While there are already known and common methods to build an energy–economy system model for non-interconnected islands, the literature review [12–15] shows that most approaches concentrate on forecasting techniques for energy demand and supply focusing on the uptake of renewable energy generation for self-sufficiency and not in a holistic sustainable approach covering the entire energy–economy system. For example, the software EnergyPlan version 16 [16] has been used [17] for the development of alternative scenarios with a high penetration of renewable energy in the Samsø island in Denmark (which is interconnected to the mainland), Orkney in the United Kingdom (an island that is interconnected to the mainland), and Madeira in Portugal (a stand-alone system), but without considering the interactions between energy demand and supply. Many countries used different models for energy system planning and climate policy analysis, such as MARKAL/TIMES [18]; however, they have faced difficulties in integrating non-economic factors since the models incorporate linear programming cost minimization, which assumes that agents behave optimally without considering realistic behavioral elements and heterogeneity. The energy system tool LEAP [19] has been used to estimate the costs and benefits associated with high electricity production from renewable energy resources on the island of Crete [20]. The energy planning tool PLEXOS assesses several scenarios to reduce oil imports in the Caribbean Islands [21]. The possibility of the integration of solar concentrated power and desalination was examined on Dongsha island [22], concluding that the smart integration of these technologies can result in a 100% renewable island, without clearly stating how the proposed cross-sectoral solutions for increased flexibility reflect the islands' needs and available resources.

3. Materials and Methods

The MAESHA project, which focuses on the non-interconnected French island of Mayotte [23], intends to decarbonize the energy systems of geographical islands by encouraging the widespread deployment of RESs through the implementation of customized novel flexibility services. The island has a large population, and its economy is mostly based on services, due to the energy sector's heavy reliance on imported oil products—diesel-fired power plants generate about 95% of Mayotte's electricity that has a high carbon footprint. There are a number of technical, economic, and legal issues associated with the decarbonization of such an isolated economy that has sustained activity growth rates and a growing population.

3.1. Brief Description of the IntE3-ISL Model

After a careful analysis of the models and methodological approaches available at present, the selected modeling approach was based on the adaptation of a well-established energy–economy modeling suite (CompactPRIMES and GEM-E3 [22]) towards the development of an island-scale integrated tool capturing energy demand and supply by sector, heating and mobility requirements, energy efficiency, fuel mix and energy prices, storage, flexibility services, sectoral integration, and macro-economic impacts. The integrated island-scale energy–economy model (IntE3-ISL) was developed, aiming to provide efficient energy system planning and solutions related to the problems faced by non-interconnected islands, such as significant seasonal load variability, high fuel prices, weak electricity grid, poor energy infrastructure, vulnerability to climate change, and lack of energy system planning [24].

The E3-ISL energy system model is developed as a fully fledged energy demand and supply model for detailed energy projections, specifically for non-interconnected islands, and is described in detail in [7]. The model is created for precise forecasts of energy supply and demand, power planning, and impact evaluations of national and local decisions regarding energy and climate policies. It can capture intersectoral trends and price-driven interactions to reach equilibrium with a time horizon up to 2050.

The main features of this customized energy system modeling tool are: (i) detailed modeling of the energy system that considers both energy supply and demand to reflect inter-sectoral trends and price-driven interactions that adjust the model's technological resolution to that which is suitable for the island; (ii) sector-specific coverage: industrial sector, buildings/residential sector, transport, agriculture, and electricity supply. The level of granularity can be expanded to various industrial sub-sectors (types of industries), energy uses in the residential sector, transportation modes (e.g., cars, busses, trucks), and power plant types; however, it depends on the information availability for each sector; (iii) possibility for the user to model the impacts of (1) specific energy-related regulations both on the energy demand and supply sides (i.e., emission reduction policies, e.g., ETS carbon pricing, energy efficiency standards, phase-out policies, RES promoting policies, energy taxes, or subsidies), (2) alternative exogenous assumptions on important factors, i.e., population, GDP growth, industrial production, costs for RES or other energy forms; (iv) time horizon: 2015 to 2050, five-year step simulation; and (v) interface to facilitate interactions with the user of the tool, i.e., user-friendliness.

The energy system model has been coupled with the GEM-E3-ISL [22,25] macroeconomic tool, considering Mayotte as a single region; however, also accounts for its linkages to the rest of the world through endogenous trade and financial transfers. The model represents around 35 production sectors for Mayotte, including agricultural sectors, energy sectors, industrial manufacturing, multiple service-related sectors (both public and private), transport sectors by mode, construction, and multiple electricity generation technologies. It features perfect competition market regimes and includes the discrete representation of energy, transport, and power-producing technologies. The model incorporates equilibrium unemployment, energy efficiency standards, carbon pricing, and several methods of carbon revenue recycling, and is driven by the accumulation of capital, equipment, and knowledge. It can also quantify the socio-economic effects of policies and ensure that the economic system is in general equilibrium under all possible scenarios.

We soft-linked the energy system planning model (E3-ISL) and the macroeconomic tool (GEM-E3-ISL) to create a unified modeling suite (IntE3-ISL) that could develop and evaluate decarbonization pathways and assess their socio-economic impacts. To capture the overall system-wide effects of decarbonization via alternative policy scenarios, the IntE3-ISL model ensures the integration of sectoral decarbonization trajectories into an economy-wide model.

3.2. Scenario Design

The development of long-term transition scenarios that consider the regional context, particularities, and priorities should guide the transition to a clean, sustainable, and low-emission economy. In this study, we co-designed five different decarbonization scenarios examining plausible alternative configurations of Mayotte's energy–economy system based on a participatory co-design approach with local stakeholders of Mayotte [26] and MAESHA partners. These scenarios simulate different futures for how Mayotte's socio-economic situation, policy, and technology might change over the long-term and aim to explore the decarbonization implications on its economy and environment.

The scenario co-design approach intends to create carbon neutrality transition pathways for Mayotte by 2050 or earlier. The scenario analysis specifically examines island-specific dynamics regarding various mitigation options, energy consumption trends, the degree of community activation, policy focus, and technologies to achieve carbon neutrality, while covering both the medium- and long-term visions of energy transition in all economic sectors. The energy and electricity costs, impacts of high-RES deployment, and the suggested flexibility solutions on the island energy system, as well as the socio-economic effects of the various pathways, were quantified using the advanced, integrated modeling tool IntE3-ISL. The model-based scenario output was used for the quantification of key performance indicators (KPIs) during and beyond the duration of the MAESHA project.

The scenario analysis is based on several assumptions about how the primary forces that will shape Mayotte's energy–economic system up to 2050 would change over time. The IntE3-ISL modeling framework incorporates scenario assumptions, which are then used to calculate the effects on energy consumption, fuel mix, technology adoption, CO_2 emissions, necessary investment, and costs and prices of the energy system. The effects of alternative scenarios were evaluated in comparison to a Baseline scenario that simulates developments as they would occur under the conditions at present, considering a number of predetermined indicators, such as the share of renewable energy and the reduction in CO_2 emissions, among others. Table 1 summarizes the key characteristics of these five jointly developed scenarios.

Table 1. An overview of the five co-designed decarbonization scenarios for the non-interconnected island of Mayotte [23].

Identifier	Name	Policy Focus	Decarbonization Horizon
Base	Baseline	No significant change in attitudes, activities, and policies regarding the energy system Energy and climate policies implemented to date continue to 2050 but do not intensify, including reduction in low-carbon technology costs	No long-term target Used as benchmark/business-as-usual case
Decarb_Demand	Consumer-driven Decarbonization	Active involvement of communities in the transition (energy savings, demand response, V2G, car sharing, high rooftop PVs, etc.), high electrification on demand side Policies: economy-wide carbon pricing, enabling conditions [1], emission and technology standards	Decarbonization of Mayotte's energy system by 2050
Decarb_Supply	Supply side Decarbonization	Moderate community response, moderate electrification, and extensive utilization of hydrogen, e-fuels, and biofuels to decarbonise Mayotte's energy system Policies: economy-wide high carbon pricing, emission and technology standards, blending mandates in transport, uptake of clean e-fuels	Decarbonization of Mayotte's energy system by 2050
Early_Decarb	Early Decarbonization	Early policy action and high ambition both on demand and supply sides	Decarbonization of Mayotte's energy system by 2040–2045
MAESHAfocus	MAESHA-focused	Full implementation of MAESHA's proposed solutions by 2030 Achievement of MAESHA's relevant KPIs	Intermediate targets by 2030–2040 as set out in MAESHA Decarbonization of Mayotte's energy system by 2050

[1] Enabling conditions represent a set of policies aiming at the removal of uncertainties or non-price-related barriers associated with the use of new technologies or fuels. There are several relevant drivers in the model, such as perceived costs and learning-by-doing.

The E3-ISL model was used to simulate and quantify the scenario narratives, and the macroeconomic tool GEM-E3-ISL was used to assess the effects on the island's economy. The scenario assessment is based on a selected list of criteria and indicators, such as mid- and long-term energy transitions and climate targets, energy security, power system costs, and socio-economic consequences, which were computed by E3-ISL and GEM-E3-ISL models (Table 2).

The policies evaluated in the scenario description cover a wide range and include energy and carbon taxes, efficiency requirements, electrification initiatives, and encouragement for the adoption of low- and zero-carbon technologies and vehicles, among other things. E3-ISL takes into consideration both sector-specific regulations, including technology performance criteria for transportation, as well as economy-wide measures, such as carbon pricing. Policy focus and intensity vary amongst the scenarios.

3.3. The Baseline Scenario

The Baseline scenario projects how macro-economic, world fuel prices, and technology and market trends structure the evolution of the energy and transport systems and the associated CO_2 emissions in Mayotte until 2050. It offers a detailed outlook of the energy demand by sector and fuel, energy supply, power generation mix, investment, energy prices, costs, and emissions, based on the legislation that is already in force. The Baseline scenario does not represent a prognosis but illustrates the possible future status of the energy system of Mayotte until 2050, assuming the implementation of energy and climate policies to date without any strengthening. This scenario can be used by policymakers as a reference for the design of ambitious strategies that can bridge the gap between the policy setting at present and the transformation required for a carbon-neutral economy. The Baseline scenario serves as a benchmark upon which the alternative decarbonization scenarios are developed and assessed.

Table 2. Assessment criteria and key indicators for alternative transition scenarios [23].

Energy and Climate Transition	Economy and Society	Energy Security
Energy and carbon intensity of GDP	Structure of the economy, trade, employment, GDP	Import dependence (net imports/gross inland consumption
Power generation and energy mix	Energy system costs by sector	Operating reserves (FCR, aFRR, RR) [2]
RES deployment rates (RES-E share, RES-T share)	Investment expenditures by sector	Diversity of primary energy supply, diversity of electricity generation
Market uptake of clean technologies and flexibility options	Investment cost to GDP ratio/system cost to GDP ratio	
Sectoral CO_2 emission reduction rates, CO_2 emission per unit electricity generated	Evolution of electricity prices by consumer type	

[2] To ensure the reliable provision of on-demand electricity, the system requires some reserve capacity to compensate for unforeseen events, imbalances, as well as normal variations in supply and demand. In E3-ISL, minimum levels of reserves (primary, secondary, and tertiary reserves) are secured by default in all scenarios, while increased balancing services are considered when variable RESs are in operation (wind, solar). ICE and geothermal plants as well as batteries are among the plants that can provide ancillary services, reserving part of their capacity.

The Baseline scenario builds on specific assumptions about the main drivers of the future development of Mayotte's energy–economic system, including population, GDP, sectoral value added, international fuel prices, energy technology costs, and renewable energy (RE), as discussed in detail in [7]. The macroeconomic assumptions used in the study build on the demographic and economic projections for Mayotte mainly provided by international organizations, such as the United Nations (UN) and International Monetary Fund (IMF). The Baseline scenario points to an increase of 259% of Mayotte's GDP in 2020–2050.

The most recent and official source available for technology cost estimates is the European Commission in its assessments for the FIT-for-55 package [24], as well as ASSET study–Technology pathways in decarbonization scenarios [25]. The data on the potential for renewable energy sources in Mayotte were obtained by the report "Vers l'autonomie énergétique en zone non interconnectée (ZNI) à Mayotte à l'horizon 2030" of ADEME [26] and CRE's guidelines on the multi-annual energy program of Mayotte [27].

3.4. Decarbonization Scenarios

3.4.1. Consumer-Driven Decarbonization (Decarb_Demand) Scenario

This scenario achieves the decarbonization of Mayotte's energy system in 2050, assuming an active role of the citizens and local communities towards carbon neutrality. The citizen-driven energy actions contribute to increasing public acceptance of low- and zero-emission energy projects (especially small-scale rooftop PV, efficiency actions, purchase of electric cars) and provide direct benefits by increasing energy savings and lowering electricity bills. The activation and engagement of local communities can support the provision of cost-efficient flexibility services to the electricity system through demand-response and storage. This scenario considers: (i) high energy savings in all end-use sectors (buildings, manufacturing, transport) via the use of energy efficient technologies; (ii) maximum heat recovery in manufacturing sectors; (iii) high-demand-response potential, V2G, and car-sharing practices, as well as the promotion of soft mobility, reducing the amount of private cars; (iv) wide installation of rooftop solar PVs; (v) high electrification in transport with the limited use of green hydrogen and e-fuels, such as synthetic liquids and ammonia; and (vi) extensive use of biofuels in all transport modes. This scenario also considers the fuel switching of Longoni and Badamiers power plants from diesel to biodiesel in 2030 onwards, and the small-scale use of geothermal power potential after 2040.

3.4.2. Supply Side Decarbonization (Decarb_Supply) Scenario

As a fully decarbonized power sector is the fundamental building block of a net zero-emission system, this scenario focuses on the decarbonization of the energy supply and examines the potential of local renewable energy resources. The following assumptions were included: (i) fuel switching of Longoni and Badamiers from diesel to biodiesel from 2030 onwards; (ii) full exploitation of Mayotte's offshore and onshore wind potential; (iii) extensive use of the island's geothermal potential; (iv) better use of commercial solar PVs and installation of rooftop solar PVs; (v) moderate heat recovery and energy efficiency in industry; (vi) limited energy saving devices in buildings; (vii) moderate demand response and absence of V2G practices; (viii) extensive biodiesel blending in transport; and (ix) extensive use of e-fuels and hydrogen to decarbonize the transport sector. Given the relatively limited domestic renewable energy potential, the demand for e-fuels and hydrogen is met both by imports (50%) and domestic production. The entire fleet of vehicles must be changed, and the infrastructure for alternate fuels must also be developed. It also suggests significant expenditures in power-to-X and hydrogen production facilities, which increase power requirements and may create stresses on solar and wind energy sources. The main policy instruments (carbon price trajectory, technology standards, blending mandates) are similar to those of the Decarb_Demand scenario. However, Decarb_Supply assumes limited energy savings from the demand side, limited demand response, and extensive use of hydrogen and e-fuels driven by the considerable exploitation of local renewable energy resources.

3.4.3. Early Decarbonization Scenario

Unlike the aforementioned scenarios that kickstarted the decarbonization efforts in 2030, the early decarbonization scenario assumes that the implementation of transition policies and measures initiatives from 2025 onwards and will be fully materialized by 2045, leading to a carbon-free energy system earlier than 2050. The early decarbonization scenario calls for the widespread adoption of both supply side and demand-side emission reduction strategies. Early and coordinated demand- and supply side initiatives are required for the transition to carbon neutrality by 2045. The earlier decarbonization effort implies lower cumulative emissions in Mayotte; however, the rapid adoption of some clean energy technologies in the present decade—when low-carbon technology costs are still high—could indicate greater financial, regulatory, and implementation difficulties.

3.4.4. MAESHA-Focused Decarbonization Scenario

This scenario explores the impacts of the full implementation of MAESHA solutions in 2025–2030, as well as the achievement of the relational KPIs. Mayotte is assumed to reach decarbonization by 2050 or sooner. This scenario could result in the early decarbonization of Mayotte, as the transport sector is envisaged to be decarbonized by 2040.

3.5. Differences between the Decarbonization and Baseline Scenarios

Table 3 provides a comparison of the four decarbonization scenarios in Mayotte, highlighting their differences in terms of their strategies, renewable energy use, fuel switching, transport, demand response potential, vehicle to grid, and impacts on the society and economy.

Table 3. Comparison of the four decarbonization scenarios for the island of Mayotte.

Scenarios	Decarb_Demand	Decarb_Supply	Early Decarbonization	MAESHA-Focused Decarbonization
Decarbonization Strategy	• Achieved by 2050 • Citizen-driven energy actions	• Achieved by 2050 or sooner • Decarbonization of energy supply	• Achieved by 2045 • Early and coordinated demand and supply sides	• Achieved by 2050 or sooner • Full implementation of MAESHA solutions in 2025–2030
Energy savings	High in all end-use sectors via energy efficiency technologies	Limited from demand side and moderate from industry	Widespread adoption of emission reduction strategies	Not explicitly mentioned
Renewable Energy Use	Extensive installation of rooftop solar PVs	Full exploitation of Mayotte's offshore and onshore wind potential and extensive use of island's geothermal potential	Both supply and demand-side initiatives required	Full implementation of MAESHA solutions in 2025–2030
Fuel Switching	Longoni and Badamiers power plants switch from diesel to biodiesel in 2030 and onwards	Longoni and Badamiers power plants switch from diesel to biodiesel in 2030 and onwards	-	-
Transport	High electrification in transport modes with limited use of green hydrogen and e-fuels, such as synthetic liquids and ammonia	Extensive biodiesel blending in transport, extensive use of e-fuels and hydrogen to decarbonize the transport sector	Alternate fuels and hydrogen driven by exploitation of local renewable energy resources	Decarbonization by 2040
Demand Response Potential	High	Moderate	Early and coordinated demand and supply sides	Not explicitly mentioned
V2G	YES	NO	NO	Not explicitly men-tioned
Impacts on Economy and Society	Not explicitly men-tioned	Significant expenditure in power-to-X and hydrogen production facilities	Lower cumulative emissions, potential for greater financial, regulatory, and implementation difficulties	Not explicitly men-tioned

The Baseline scenario is the starting point that assumes that the energy system follows the present trends. In contrast, decarbonization scenarios aim to achieve carbon neutrality by the mid-century, via the increased uptake of clean energy forms, energy efficiency improvements, and the use of innovative technologies.

In terms of energy consumption, all decarbonization scenarios lead to a decline in final energy consumption from baseline levels due to increased electrification of end-use sectors and energy efficiency improvements. However, the Decarb_demand scenario leads to lower energy consumption than the Decarb_Supply scenario, driven by the active involvement of local energy communities, the accelerated investment in efficiency improvements, and more rapid electrification.

Relative to the energy supply, all decarbonization scenarios require increased power capacities compared to the baseline levels, mainly driven by the almost full electrification of transport and increased demand for green hydrogen and synthetic e-fuels, which represent a considerable share of the gross electricity demand by 2050, especially in the Decarb_Supply scenario. This increase implies significant capital investments in the electricity sector, especially for renewable energy sources (RESs) and storage development. The accelerated climate effort in the Early_Decarb and MAESHAfocus scenarios implies a considerable RES share in the electricity mix, even in 2030, through the rapid uptake of solar PV and wind, as well as the early electrification of the transport sector.

All decarbonization scenarios aim to reach carbon neutrality by 2050 or 2045, albeit assuming different pathways to achieve the target (early vs. late action, electricity vs. synthetic fuels, etc.). The Decarb_Supply scenario is more technology-oriented and stresses the boundaries of renewable energy potential in Mayotte's energy system due to the high demand for hydrogen and e-fuels. The fuel switch from diesel to biodiesel is a priority in the agenda of the local DSO (EDM) and is expected to contribute to emission reductions in all decarbonization scenarios.

In Table 4 we can observe the key levers of the scenario analysis as well as the independent and dependent variables.

Table 4. Independent and dependent variables of the scenario analysis as well as key levers [23].

Independent Variables/Key Levers	Dependent Variables
GDP and population growth, sectoral value added, economic and social activity projections	Technology and fuel mix on the demand side, final energy consumption
Fuel price projections (imported fuels)	Share of heat recovery in local light industries
Technology costs (capital, O&M) and learning-by-doing factors	Equipment stock and relevant investments
Technical characteristics of end-use technologies and power plants (efficiency, utilization factors, capacity factors, size, etc.)	Capacity additions by plant type (several types of capacity investments)
Present power plant inventory, decommissioning plans	Electricity generation and fuel consumption by plant
RES and storage technical potential, reserve requirements	Storage and power-to-X plants: injection or extraction from storage facilities and investments in storage equipment
Grid loss rates	Other results, such as capacity, reserved for the provision of upward and downward ancillary services by plant, curtailment of renewable generation, etc.
Policy levers, such as carbon price, carbon and technology performance standards, biofuel blending/switching, subsidies, fuel taxation, feed-in-tariffs, discount rates, etc.	Electricity, hydrogen, and e-fuel prices (domestically produced)
	CO_2 emissions
	Energy system costs and investment expenditures

4. Results of the Baseline Scenario

4.1. Energy Consumption by Sector and Fuel

The transport sector accounted for about 51% of the final energy consumption in Mayotte in 2020, while buildings (including both households and services) and industrial sectors accounted for 37% and 12%, respectively, reflecting the limited industrial development of the island. Transport will continue to be the largest energy consumer by 2050, due to the population growth and income increases, which result in a better quality of life and higher car ownership rates. Energy consumption in buildings is expected to increase, moderately driven by increasing incomes, technological advancements, and the high electrification rate.

Oil products are projected to continue dominating energy consumption with only a small decline in their share from 62% at present to 59% in 2050 (Figure 1). The Baseline scenario leads to a slight shift in the fuel mix from oil to electricity and RESs, including the use of solar water heaters in buildings [28]. By 2050, the share of electricity will increase due to the moderate market uptake of electric cars that allow for the substitution (to a limited extent) of oil products in transportation. The increasing use of electricity in buildings also contributes to an increased electricity share.

Transport is the fastest growing sector in terms of final energy consumption rates, albeit decelerating in the long term. Overall, the increase in energy consumption will reduce after 2040, mainly due to technology improvements and a higher electrification rate, as electricity is less energy intensive than oil products.

4.2. Fuel Mix by Sector

4.2.1. Manufacturing Sector

As technological advancements and energy efficiency improvements are limited in the industrial sector, final energy consumption rates follows the growth of industrial production, with limited signs of relative decoupling after 2040. Mayotte's manufacturing sector is comprised of light, non-energy-intensive industries, leaving little room for decoupling energy consumption from activity growth. Regarding the fuel mix, the relatively low electricity prices favor the further electrification of the industrial sector, with the share of electricity projected to increase from 74% in 2020 to 78% in 2050 (Figure 2), while the contribution of petroleum products and heat will decline in the long term.

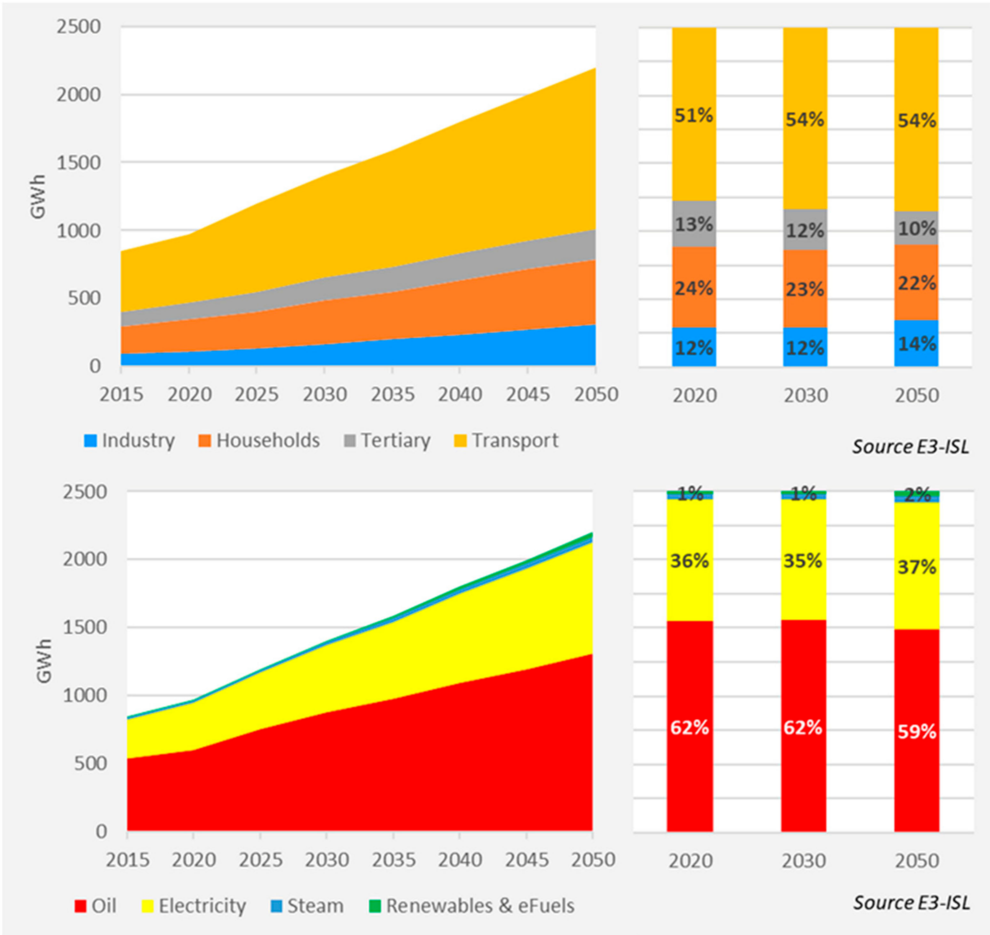

Figure 1. Baseline scenario—final energy consumption rate by main sector and fuel in 2020–2050.

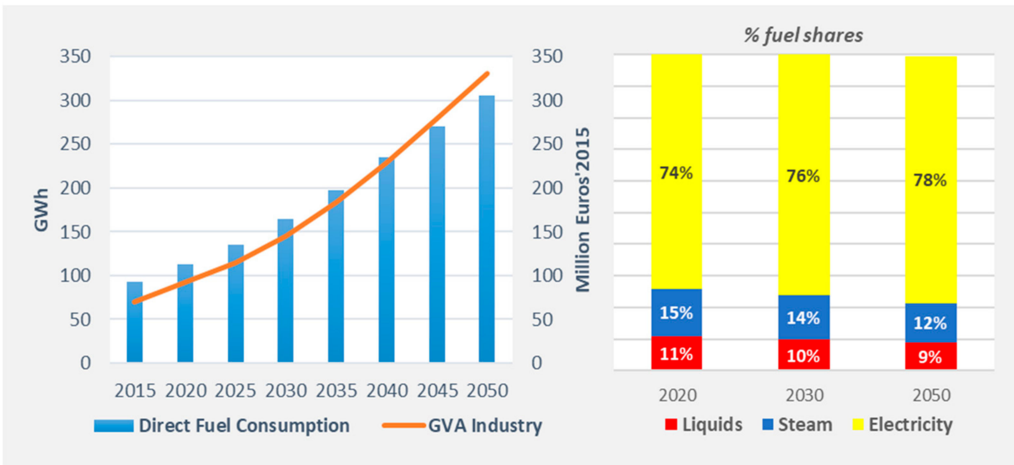

Figure 2. Baseline scenario—fuel consumption rates in manufacturing vs. gross value added and the evolution of fuel mix in the industry for the period 2020–2050; source: E3-ISL.

4.2.2. Buildings

Final energy consumption in the residential sector is projected to double in 2020–2050 following the growth of economic activity with a limited decoupling of energy demand from income growth. This slight decoupling is driven by the purchase and use of more efficient equipment and appliances (throughout the projection period), as well as the gradual saturation of the demand for useful services, because the demand for useful services tends to plateau at some point, despite the continuous income growth.

The share of electricity and solar sources is projected to increase in the Baseline scenario (Figure 3), stimulated by the extensive use of solar thermal water heaters, electric cookers—to the detriment of LPG-fired stoves—and the increasing use of electric appliances. In contrast, the share of oil-based fuels is projected to gradually decline from 22% in 2020 to 20% in 2030 and further to 16% in 2050. Efficient space-cooling systems retain the share of cooling in the energy mix of households.

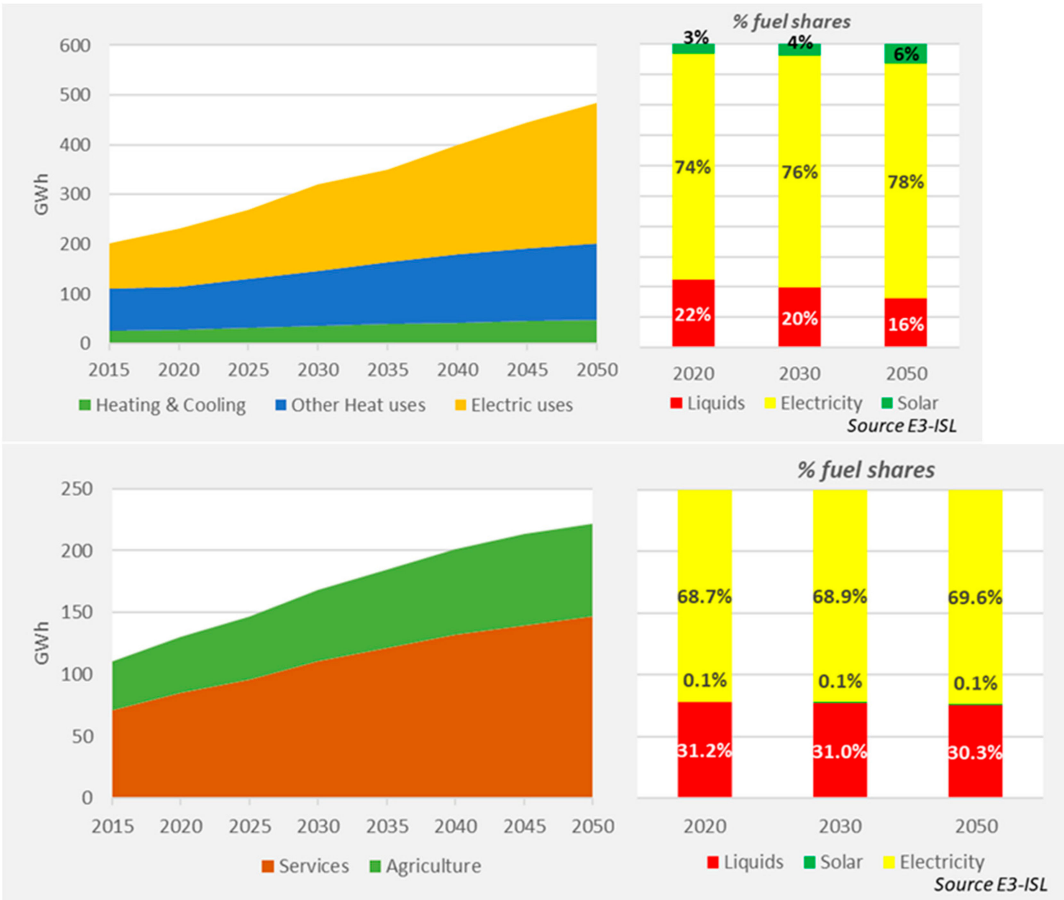

Figure 3. Baseline scenario—top: final energy consumption in residential sector by end-use and fuel mix for the period 2020–2050; bottom: final energy consumption in tertiary sector by sub-sector and fuel mix for the period 2020–2050.

The final energy demand in the tertiary sector increases (Figure 3), following the growth of sectoral value added; however, after 2035, a gradual decoupling from economic activity is projected due to the delivery of less energy-intensive, high-value-added activities and the deployment of more efficient technologies. The fuel mix in the tertiary sector presents no major differences in the 2020–2050 period, except for a slight increase in the electricity share to the detriment of liquids.

4.2.3. Transport Sector

The energy consumption rates of the transport sector are projected to constantly increase until 2050. Transport is heavily dependent on fossil fuels, with gasoline, diesel, and kerosene accounting for 100% of energy consumption at present. In the long run, following a limited electrification trend, the share of liquids slightly declines in the Baseline scenario, from 100% in 2020 to 96% in 2050 (Figure 4). This development is the result of the uptake of low-carbon passenger and light-duty vehicles (PHEVs and BEVs). Electric vehicles are primarily used in the road passenger sector, accounting for approximately 33% of the total vehicle stock by 2050. However, due to their high energy efficiency compared to conventional ICE cars and the limited electrification in other transport segments, electricity will account for only 4% of the transport fuel mix in 2050 (Figure 4). Diesel remains the dominant fuel source in automotive and marine fuels, while jet kerosene's share is increasing due to increased aviation activity.

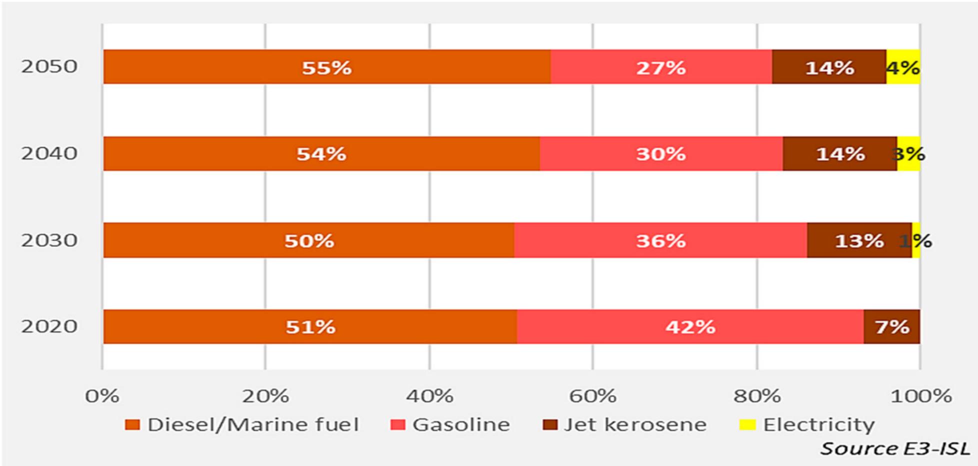

Figure 4. Baseline scenario—evolution of fuel mix in transport over 2020–2050.

4.3. Power Generation Mix

The E3-ISL model accounts for all present and candidate power plants in Mayotte, based on the input provided by local stakeholders and EDM. The Baseline scenario considers that the four older units, G01–G04, of the Badamiers plant were decommissioned before 2020, while the units G05–G08 of Badamiers will be decommissioned by 2023; however, no other plant decommissioning activity is scheduled for Longoni I and II, and Badamiers G21–24 will operate until 2050. The Baseline scenario also assumes the installation of 11.5 MW of battery storage by 2025 and the rational utilization of Longoni and Badamiers (at present, the units are operating for 2000–3000 h/year). The scenario also considers that solar PV plants that have already acquired a license to operate (reaching a total capacity of 36.6 MW) will be connected to the grid by 2030. Based on the experience of EDM on the development of PV projects in Mayotte, minor delays are projected in the Baseline scenario. The further penetration of RESs is stimulated by the market trends, their decreasing costs, and the increasing carbon price.

Diesel plants are gradually being replaced by variable RESs in Mayotte's power supply mix (Figure 5); however, they still account for the majority of the power generation (67.6% in 2050). At the same time, the cost-competitiveness of solar and wind power improves further, driven by technology learning and economies of scale, combined with increasing global oil prices and the rising EU ETS carbon price. By 2050, solar PV (23%) and wind (9%) will account for nearly 33% of total power generation. Batteries supplement the power mix, albeit to a limited extent, by compensating for the intermittent nature of variable RESs.

The Baseline scenario envisages the gradual deployment of variable RESs driven by their cost-competitiveness compared to diesel-fired plants. However, technical and regulatory barriers, such as grid constraints, as well as investment barriers (e.g., high-risk premiums, lack of access to capital) were modeled and impede such investments. The installed capacity of solar PVs is projected to increase from 18 MW in 2020 to 54 MW in 2030 and 130 MW in 2050. The investment in a new PV capacity is driven by the decreasing costs of solar panels, while wind power deployment begins from 2040 onwards. Onshore wind capacities are increasing but not as rapid as solar PVs due to the limited potential—wind capacities amount to 10 MW in 2040, increasing to 35 MW in 2050.

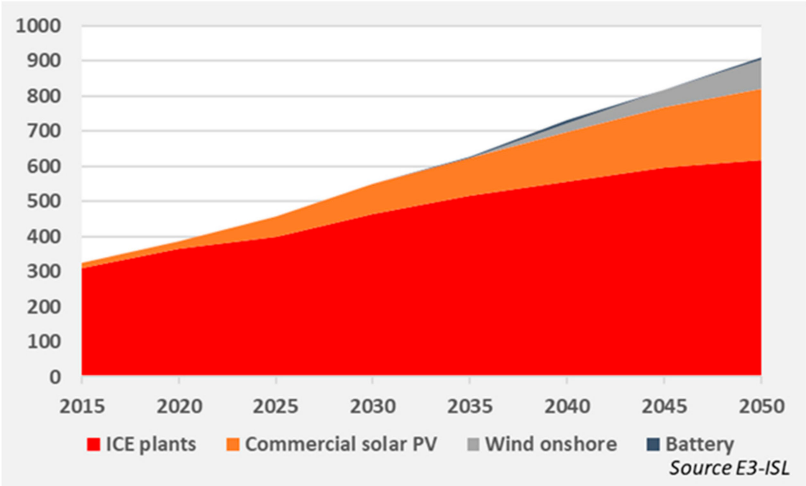

Figure 5. Baseline scenario—gross electricity generation by plant type.

E3-ISL also accounts for ancillary services used in the power system, such as primary, secondary, and tertiary reserves, which are maintained in 2020–2050. Due to the increased penetration of variable RESs, additional constraints have been imposed on the provision of balancing services from diesel plants and batteries during variable RES power generation. Diesel will continue to dominate power generation until 2050, serving the base load as well as providing the necessary balancing services that allow the uptake of variable RESs. Increased needs for battery storage lead to a growing capacity from 11.5 MW in 2025 to 16 MW by 2050. To date, the existing thermal plant capacities are underutilized; however, this should change in the future. In this respect, the capacity of thermal diesel-fired plants will remain constant by 2040 and the surging electricity demand is adequately served by Longoni and Badamiers plants and the new RES capacities, while new investments in diesel-fired plants are required after 2040.

4.4. Emissions

CO_2 emissions are expected to increase until 2050 due to the rising energy demands and continued dominance of oil products in the transport and electricity sectors, which are the highest emitting sectors, accounting for 94% of Mayotte's total emissions. The share of power generation is projected to decline from 58% in 2015 to 54% in 2050 due to the commissioning of RES capacities. On the other hand, transport emissions are growing both in absolute and relative terms, driven by the large increases in passenger and freight transport activities and the limited uptake of low-carbon vehicles in all transport segments. Emissions in buildings and industries remain relatively low compared to transport, because electricity—which emits no CO_2 at the point of use—is the dominant energy carrier to provide energy services to the buildings and manufacturing sectors.

4.5. Energy System Investments and Costs

The energy system costs for E3-ISL include (i) fuel and other variable costs, (ii) capital costs of energy-related equipment, (iii) operation and maintenance costs, and (iv) emission and energy taxation costs. Overall energy system costs are estimated to amount to 15% of Mayotte's GDP in 2020, including annual capital payments for energy technologies and equipment. The highest volume of investment expenditures is expected to occur after 2030 due to the surging electricity demand and the need to renew power plant stocks with investments in onshore wind turbines, solar PV installations, diesel ICE plants, and battery storage. However, transportation accounts for the majority of energy-related costs, as it is responsible for most of the energy consumption and imported fuels.

Electricity prices in Mayotte are not cost-reflective and insufficient to recover the overall generation, transmission, and distribution costs. The power sector is greatly subsidized by the mainland (France), and (in the absence of specific legislation) we assume that this will be sustained in the future. The pre-tax electricity price is projected to recover in the short term from low levels in 2020, propelled by rapid economic recovery, then to gradually increase in the mid-term, tending to stabilize in the long term due to the accelerated deployment of RESs combined with their decreasing RES technology costs. The latter mitigates the impact of a high carbon price after 2030. The fuel-related cost accounts for most of the electricity tariff in 2020–2050; however, this share will decrease over time (from 74% in 2020 to 63% in 2050, Figure 6). On the other hand, the share of capital costs and emission taxation will increase due to new capacity investments (primarily in solar PV and wind) and grid expansions, as well as the increasing carbon price.

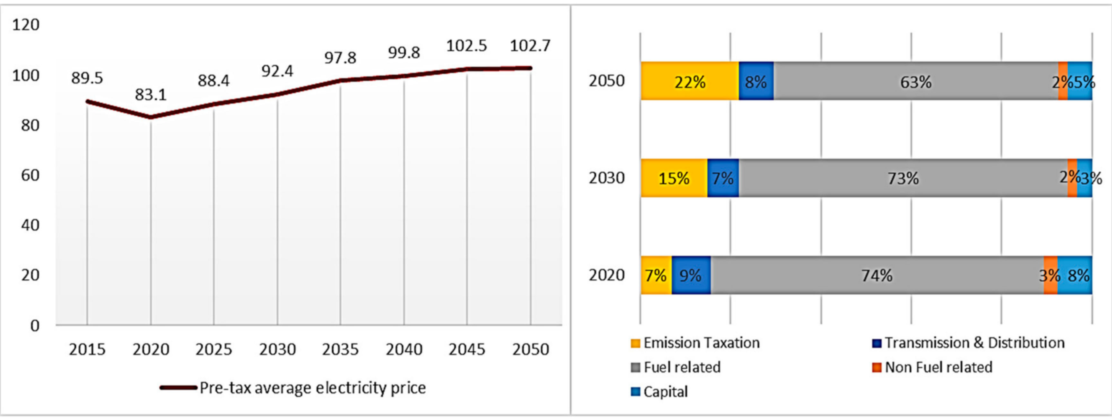

Figure 6. Baseline scenario—electricity tariff and its components in 2020–2050; source: E3-ISL.

5. Impacts of Decarbonization Scenarios

This section presents the model-based results of the decarbonization scenarios for Mayotte. These scenarios are not forecasts, but rather enable the consistent comparison of different decarbonization pathways and system configurations of the future energy system of Mayotte, the policy actions that generate them, as well as the respective energy, emissions, and socio-economic impacts. The assumptions of population, economic growth, sectoral activity, technology costs, and oil import prices are kept the same as in the Baseline scenario and in [7].

5.1. Impacts on Energy Consumption

In all decarbonization scenarios, the final energy consumption rate is projected to decline from baseline levels due to the increased electrification of end-use sectors and energy efficiency improvements. The Decarb_Demand scenario leads to lower energy consumption than Decarb_Supply (Figure 7), as the former assumes an accelerated investment in efficiency improvements, more rapid adoption of electric cars, higher energy savings in all end-use sectors, maximum heat recovery in industries, high demand response potential, and car sharing. In contrast, Decarb_Supply is based on the emergence of clean e-fuels that have a higher energy intensity than electricity. High energy savings are achieved due to the accelerated electrification of energy and mobility end-uses.

Oil products in Mayotte represent 62% of the final energy consumption at present; however, the decarbonization scenarios would lead to a large-scale reduction in oil combined with the uptake of clean energy forms. The share of oil is projected to decline in all demand sectors reaching about 52% in 2030 in the Decarb_Demand and Decarb_Supply scenarios. The accelerated climate action in the MAESHAfocus and Early_Decarb scenarios leads to a greater decline of oil's share to only 39% in 2030. The rising CO_2 prices, the large-scale electrification of end-uses, the use of e-fuels and green hydrogen, as well as ambitious sectoral policies (e.g., technology standards, fuel blending mandates) would lead to the reduction in oil's share to only 5–7% by 2050, while in the Baseline scenario, oil products are projected to account for 59% in the same period (Figure 8).

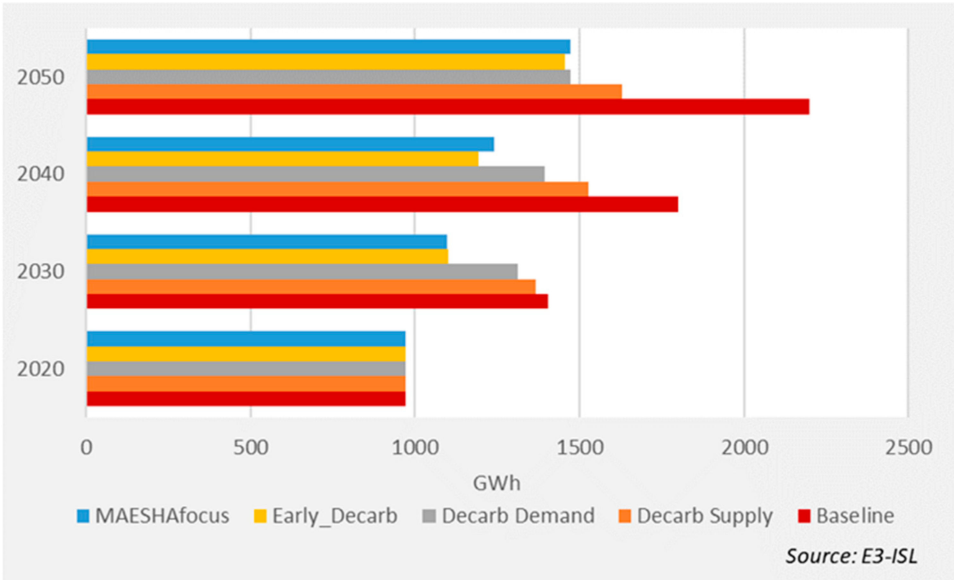

Figure 7. Evolution of final energy consumption in alternative scenarios.

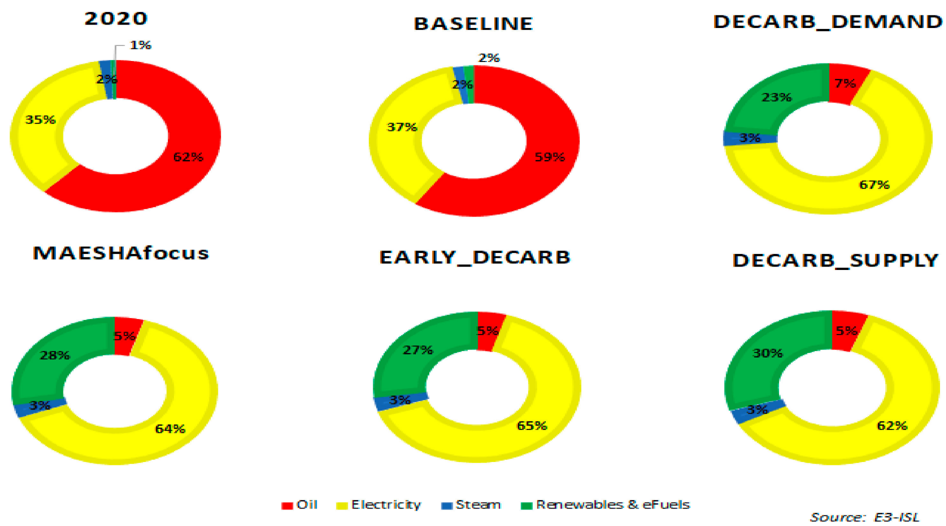

Figure 8. Fuel shares of final energy consumption by scenario in 2050.

Electricity consumption is projected to increase in 2020–2050, primarily driven by the electrification of the transport sector and secondly by the industrial and building sectors. By 2050, electricity is projected to become the dominant energy carrier in all decarbonization scenarios in Mayotte and account for 62–67% of final energy consumption rates. At present, the direct consumption of RESs represents a small share (of less than 1%) in the island's final energy consumption. High carbon prices and ambitious technology standards and fuel blending regulations would drastically increase the consumption of renewable fuels used in transport, industry, and buildings sectors, which are projected to reach 23–30% of the final energy consumption in decarbonization scenarios by 2050. Clean energy fuels, including biofuels, hydrogen, and synthetic e-fuels, are mostly used in sectors that cannot be easily electrified, such as aviation, freight transport, and navigation.

5.2. Impacts on Energy Supply

In all decarbonization scenarios, the power requirements increase, compared to baseline levels, mainly driven by the electrification of transport and the increased demand for green hydrogen and synthetic fuels, which represents a considerable share of electricity in

2050, especially in the Decarb_Supply scenario. This increase implies significant investment requirements in the electricity sector, especially for RESs and storage development. The accelerated climate effort in Early_Decarb and MAESHAfocus scenarios implies a considerable RES share in the electricity mix, even in 2030 (Figure 9), through the rapid uptake of PV and wind power. Considering the constraints relative to the limited wind potential in Mayotte [28], the first offshore-wind plants are projected to be commissioned in 2030 or 2035, depending on the scenario. The high capital costs for offshore wind power are partially compensated by the high-capacity factors boosting its competitiveness at high CO_2 prices. Geothermal potential will be partly utilized after 2040. The decreased PV and wind costs and high ETS price demonstrate that renewables (and especially solar PV) are the most cost-efficient power-generation technology in Mayotte. Therefore, in the long term, the power sector is fully transformed towards a RES-based system where more than 90% of the electricity is produced through variable renewable sources in 2050, coupled with storage.

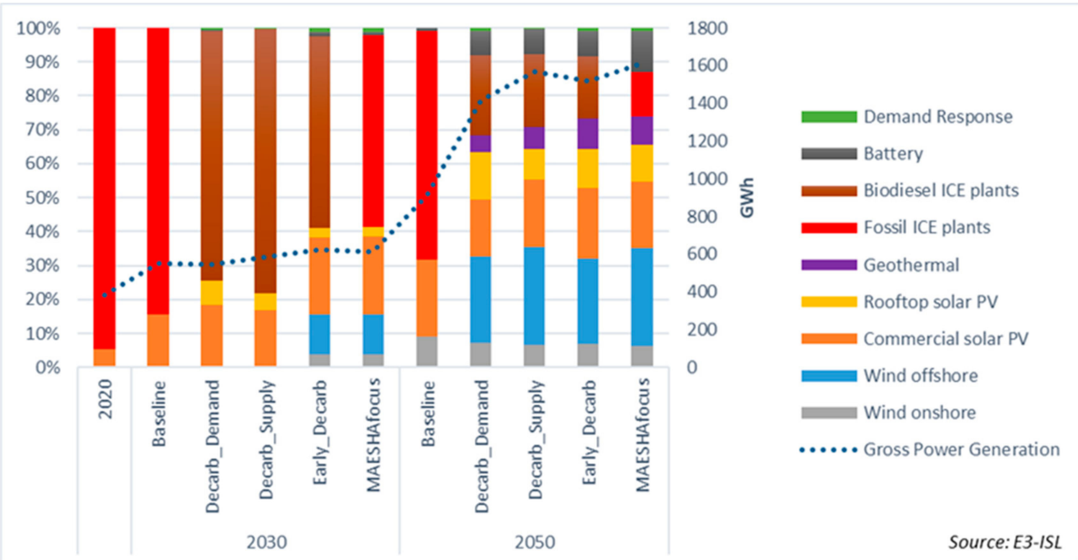

Figure 9. Gross power generation by plant type and scenario in 2030 and 2050.

The Mayotte's Longoni and Badamiers power plants still operate, but with low utilization rates using biofuels after 2030 and providing balancing services. Due to Mayotte's limited energy resources, it is assumed that 50% of hydrogen, ammonia, and synthetic kerosene requirements will be served through imports without compromising energy security.

The use of variable RESs and increased demand for clean fuels produced by electricity leads to extensive investments in battery storage, hydrogen production, and power-to-X facilities. Demand-response practices are widely applied in the Decarb_Demand scenario, and thus the need for battery storage is reduced compared to other scenarios.

5.3. Impacts on Emissions

All decarbonization scenarios aim to reach carbon neutrality by 2050 or 2045; however, they follow different pathways to achieve this target. The Decarb_Supply scenario is more technology- and less citizen-oriented and stresses the boundaries of renewable potential in Mayotte's energy system due to the high deployment of hydrogen and e-fuels requiring high amounts of wind and PV capacities. Through the use of green hydrogen and synthetic fuels, emission reductions can be achieved, while on the supply side, a significant reduction can be attained through the installation of wind and PV power and the switch from diesel power plants to biodiesel. The fuel switch from diesel to biodiesel is a priority in the agenda of EDM, and is assumed in Decarb_Demand, Decarb_Supply, and Early_Decarb scenarios.

On the other hand, MAESHAfocus envisions diesel-fired power plants gradually being underutilized and being replaced by a combination of variable RESs and storage.

The Early_decarbonisation and MAESHAfocus scenarios are characterized by rapid transformations and present a sharp decline in final energy consumption compared to the Baseline scenario, from 2025 onwards. Furthermore, these two scenarios show the best performance in terms of energy consumption for the transport sector, as they both assume that the decarbonization of this sector will be finalized in 2040–2045.

By 2050, all decarbonization scenarios project that the carbon intensity of the GDP will reach levels close to zero, driven by the assumption of carbon neutrality. However, in 2030, the Early_Decarb scenario will achieve greater reductions compared to other decarbonization scenarios triggered by accelerated transformation dynamics. More specifically, the Early_Decarb scenario shows that Mayotte is close to carbon neutrality about 5–10 years earlier than the Decarb_Demand and Decarb_Supply scenarios. In the MAESHAfocus scenario (Figure 10), the transition to carbon neutrality is smoother, although it is characterized by high ambition in the medium term. This is driven by the fact that the scenario does not consider the fuel switching of Longoni and Badamiers in 2030, since MAESHA KPIs did not account for this possible development.

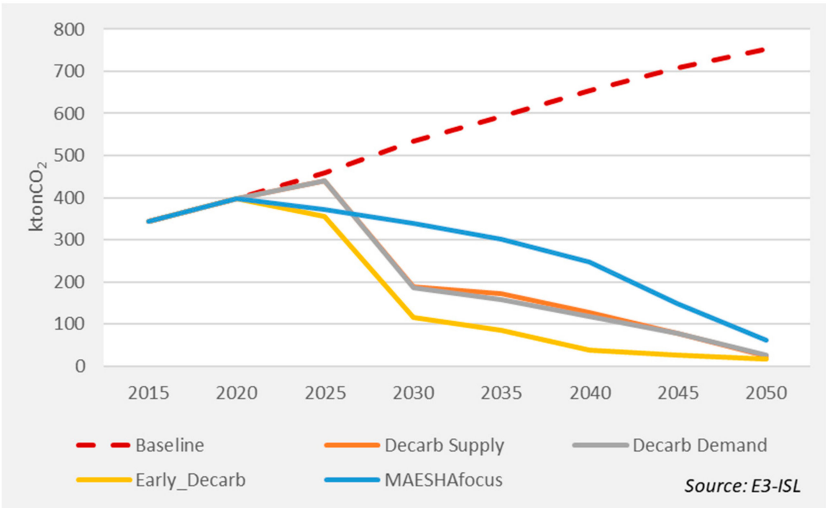

Figure 10. CO_2 emission trajectories by scenario.

5.4. Impacts on Energy Costs and Electricity Prices

The transition to carbon neutrality is projected to entail increasing energy system costs in Mayotte above the Baseline scenario levels, primarily due to increased investments in clean energy technologies, efficient equipment, and low-emission vehicles. This is mostly triggered by the increased capital expenditure to decarbonize the transport sector, which results in an increase in total energy system costs of about 2–5 percentage points of Mayotte's GDP above the Baseline levels. Lower costs are incurred in Decarb_Demand relative to other decarbonization scenarios, since Decarb_Demand assumes a gradual, not disruptive, emission reduction effort and introduction of new clean energy technologies and a limited uptake of expensive mitigation options, such as hydrogen and e-fuels that are mostly used in the Decarb_Supply scenario (Figure 11).

MAESHAFocus is the most expensive scenario in terms of total energy system costs due to the rapid decarbonization of the transport sector. This entails high capital costs to purchase zero-emission vehicles, as well as to build the required infrastructure (recharging stations, fuel production). Since the capital costs of the emerging clean technologies and vehicles are expected to gradually decline over time (learning effects), scenarios assuming a more gradual transition (Decarb_Suppply, Decarb_Demand) have lower system costs than those assuming a very rapid transformation by 2030 (Early_Decarb, MAESHAFocus).

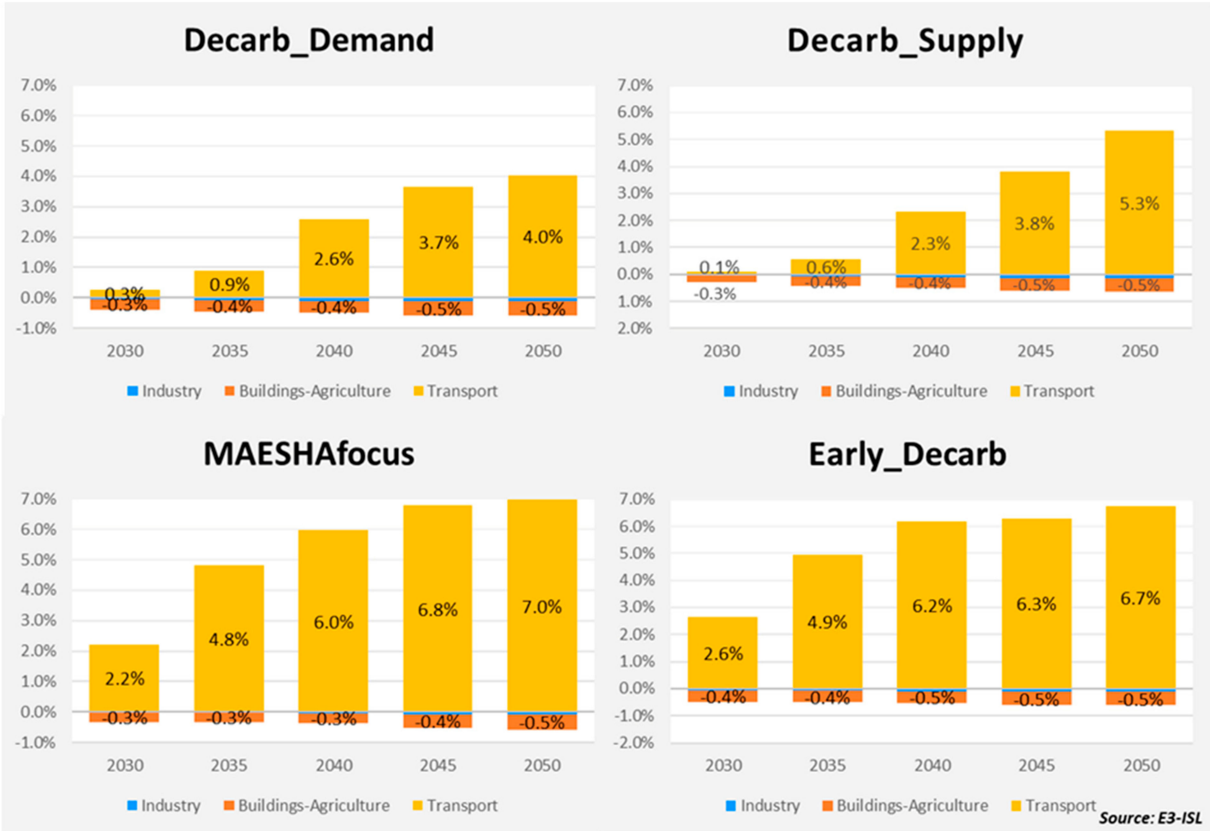

Figure 11. Energy system cost difference as % of GDP by scenario relative to Baseline scenario.

The electricity prices are projected to decline in the decarbonization scenarios relative to the Baseline scenario (assuming no changes in the market regulation), driven by the accelerated penetration of cost-efficient RESs (solar PV, wind power) that replace expensive diesel-fired power plants (Figure 12). This more than counterbalances the impact of the higher ETS carbon pricing.

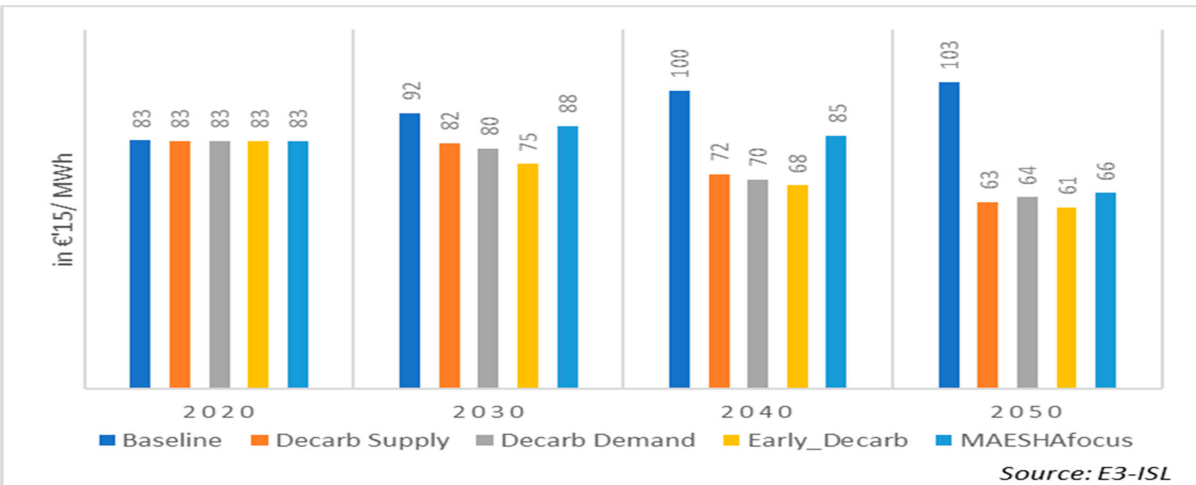

Figure 12. Evolution of pre-tax electricity prices by scenario in EUR/MWh.

5.5. Socio-Economic Impacts

In the decarbonization scenarios, the large-scale deployment of RESs reduces the average cost of electricity production in Mayotte as the diesel-fired power plants have much higher leverized cost of electricity (LCOE) than renewable-based alternatives. The reduced electricity price would benefit both domestic demand (as households would face lower energy bills) and production (as firms would reduce their production costs), hence increasing domestic activity and providing socio-economic benefits. These benefits would be much greater if there is an adequate, low-cost availability of finance [29], given that low-carbon investments are more capital-intensive relative to fossil fuels [30].

The imposition of high carbon pricing drives energy system transformation towards a more capital-intensive structure, with an increased investment in renewable energy, energy efficiency projects, and low-emission vehicles. Decarbonization would lead to increased upfront capital expenditures and lower energy purchasing costs in the long term. GEM-E3-ISL assumes the full and optimal use of available capital resources in the Baseline scenario under strict financial rules. Therefore, the reallocation of investments towards low-carbon, energy-efficient technologies in the decarbonization scenarios places pressure on the capital markets and leads to effects where firms and households finance their clean energy investments by spending less on other (non-energy) commodities.

The overall impact of decarbonization on Mayotte's economic activity is found to be minor, until 2030; however, as transformation progresses and the impacts on electricity prices become increasingly pronounced, the transition positively influences the island's GDP, which is projected to increase by 1.5–4.5% in decarbonization scenarios relative to the Baseline scenario in 2050 (Figure 13). The Decarb_Demand scenario, assuming active community involvement (engaging in energy savings, demand response, V2G, car sharing, rooftop PVs, and high electrification), is projected to generate more positive socio-economic impacts relative to the Decarb_Supply scenario, where the transition is driven by supply side changes and the high uptake of (relatively expensive) clean e-fuels and hydrogen.

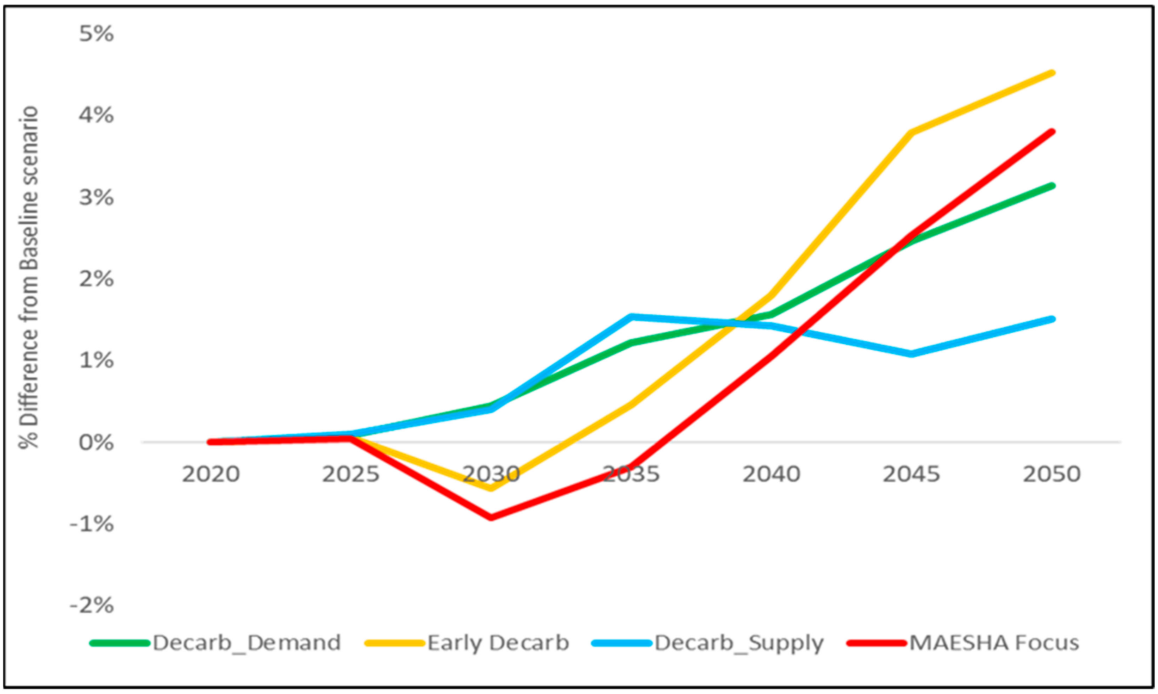

Figure 13. Impacts of decarbonization scenarios on Mayotte's GDP in 2020–2050; source: E3-ISL.

In the scenarios achieving early decarbonization effects (MAESHA Focus and Early_decarb), the rapid energy system transformation poses stresses in capital markets in 2020–2030, with negative impacts on economic activity through increased production costs. In the abovementioned scenarios, Mayotte's GDP is projected to decline by about 0.6–1% from baseline levels in 2030. However, in the longer term, the economy of Mayotte will experience the benefits of the transformation (e.g., reduced fossil fuel imports, lower electricity prices) without facing the high costs to invest in zero-carbon technologies as the decarbonization process is completed by 2040 or 2045. This means that, in these scenarios, GDP gains are even higher in 2050, amounting to more than 4% compared to the baseline levels triggered by the phasing-out of expensive diesel-fired power plants.

The carbon neutrality transition would generate employment benefits for Mayotte, relative to the Baseline scenario (Figure 14), amounting to 1–3% in 2030, rising to about 8–10% in 2050, following the growth of economic activity, which increases labor requirements. In this context, the unemployment rate, which, at present, stands at about 25% in Mayotte, is projected to decline to around 12–14% in 2050 in the decarbonization scenarios, while in the Baseline scenario, it stands at 21% in 2050. The increased labor requirements have limited effects on the wage rates, as the unemployment rate is relatively high, and the expanding sectors can attract new workers from the unemployed pool. The transition to carbon neutrality entails a shift in the economy away from imported fossil fuels and towards domestic activities related to RES deployment with employment rates rising faster than economic activity.

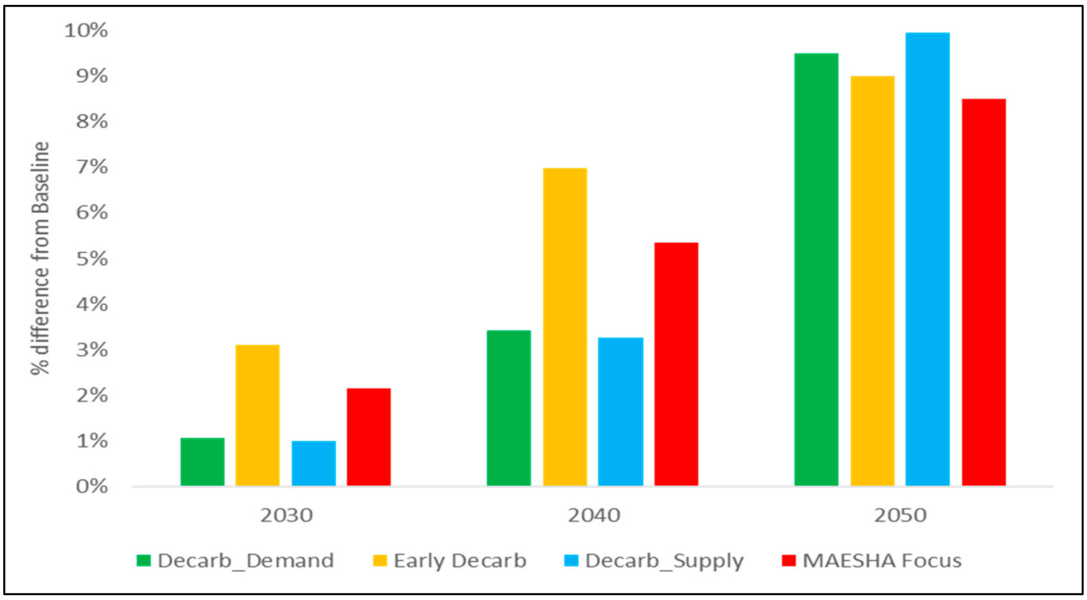

Figure 14. Impacts of decarbonization scenarios on Mayotte's employment; source: E3-ISL.

The decarbonization process is projected to lead to increased employment in all economic sectors and activities in Mayotte. New jobs are expected both in sectors directly impacted by the low-carbon transition, such as the electricity sector, but also in sectors featuring in supply chains of low-carbon technologies and indirectly benefitting from the transition; jobs are created in the construction sector, market and non-market services, as well as in the industrial sector due to increased domestic demand and exports. The positive impacts are more pronounced in the long term, leading to the creation of about 10,000–11,000 additional jobs relative to the Baseline scenario in 2050 (for comparison, the total employment in Mayotte was about 55,000 in 2020). In the short term, the increase in employment is more limited, with 1000 to 2500 additional jobs created above the Baseline scenario in 2030. The transition to carbon neutrality has clear socio-economic benefits for Mayotte triggered by the phasing-out of expensive diesel-fired power plants, even without quantifying the benefits of decarbonization related to avoided climate impacts and improved air quality.

6. Discussion

The importance of islands in the transition to clean, sustainable, secure, and carbon-free future energy systems has been discussed by policy makers, scientists, and numerous authorities [27–30]. The reviewed literature [9–19,31–45], with a focus on non-interconnected island's energy system tools, showed the existence of a gap in the detailed modelling of energy systems capturing both energy demand and supply, guaranteeing the reliability of the electricity grid in case of the increased penetration of renewable energy technologies. Furthermore, most energy system modeling approaches lack a detailed and complete representation of the key drivers influencing future energy demand and supply developments, have limited sectoral and technology granularities, fail to capture the inter-linkages between energy demand and supply and the formation of prices, and cannot represent island-scale specificities and the impacts of energy and climate policies.

The development of decarbonization pathways that meet the Paris Agreement goals are necessary for the efficient design of energy system planning and climate policies providing indications of the appropriate actions and investments to achieve net zero emissions. The modeling tools must be able to support clean transition pathways by observing the apparent challenges and opportunities, and recognizing the interactions between various dimensions, such as proper technology deployment. The characteristics and particularities of the area under consideration (in our example, non-interconnected islands) as well as the practical constraints, such as data accessibility and stakeholder engagement, must also be considered in this process.

The results of the five co-created decarbonization scenarios for Mayotte showed that the decarbonization of a non-interconnected island, such as Mayotte, is technologically and economically feasible; if regulatory, technical, policy, and economic challenges are overcome. The clean energy transition requires a cross-sectoral integration with a focus on continuous innovation, the adoption of ambitious climate policy measures, and the wide-ranging deployment of low- and zero-carbon technologies, both on the demand and supply sides of the energy system, accounting for the specificities of each individual sector. Measures and technologies could range from the use of highly efficient equipment, the widespread electrification of end-uses, the large roll-out of RES deployment, as well as the use of green hydrogen, synthetic fuels, and other future innovative technologies to reduce emissions from hard-to-abate sectors, such as freight transport and the heavy industry, which require complex manipulations to achieve the goals of the European Green Deal.

Our model-based research showed that electrification is a cost-effective decarbonization milestone as the early decarbonization of the power-grid through the large-scale uptake of renewable energy technologies facilitates the increased use of zero-carbon electricity in end-use sectors. This is accompanied by energy efficiency improvements, as the electrified equipment is more efficient than fossil fuel-based technologies (e.g., electric cars are much more efficient than conventional ICE cars). Electricity will play a key role in the climate transformation of all economic sectors, including transport, buildings, and industry. Power requirements considerably increase in all decarbonization scenarios due to the widespread penetration of electric vehicles, the increasing electrification of end-uses in buildings and industries, and the extensive use of electricity to produce green hydrogen and synthetic e-fuels. Clean fuels, including biofuels, hydrogen, and synthetic e-fuels, are used to decarbonize the hard-to-electrify parts of the economy, such as industry, heavy-duty transportation, navigation, and aviation.

The development of renewable energy sources, especially solar PV and wind, should be accelerated as they constitute a highly cost-competitive source of electricity leading to a reduction in electricity prices as expensive diesel-fired generation plants are phased out. The extensive integration of variable RESs should be accompanied by significant increases in the flexibility of the electricity system—with investments in batteries, demand response, power-to-X units with multi-day and inter-seasonal storage cycles, etc.—to ensure a reliable electricity supply. Our analysis explored the different types of flexible reserves, each coping with the different needs of the system (short-term, multi-hour, and long-term periods).

Local energy communities could also significantly contribute to energy transition practices as they unlock the untapped efficiency potential on the demand side. Achieving net zero-emissions by 2050 can be implemented in an efficient and less expensive way with the sustained support from and participation of citizens via behavioral changes—such as the use of soft mobility options, purchase of energy-efficient equipment, installation of small-scale rooftop PVs, and participation in demand-response techniques. Mayotte's energy system may be restructured at a lower cost with the assistance of local citizens, either as associations (energy communities) or individuals, relieving the pressure on the energy supply side with reduced needs for the production of expensive hydrogen and e-fuel sources.

The transition to carbon neutrality implies an increase in energy system costs in Mayotte above Baseline scenario levels. This is driven by increased investments and capital expenses for the uptake of clean energy technologies, efficient equipment, and low-emission vehicles. The latter are responsible for most of the increases in energy system costs in Mayotte. The full-scale assessment of the macro-economic impacts of energy transition using the comprehensive GEM-E3-ISL model shows that the reduced electricity prices will positively influence both households (as they would face reduced energy bills) and producing sectors with firms having lower production costs. This triggers increased demands and exports (improving firms' competitiveness due to reduced production costs), and thus leads to increased domestic activity with clear socio-economic benefits. The scenario focusing on the consumer-driven transition (Decarb_Demand) generates the greatest positive economic impacts, due to high energy savings through active consumer engagement, reducing the need to produce or import expensive hydrogen and e-fuels on a large scale. This directs us to the considerable effects of energy efficiency, electrification, and active citizen participation in the transition to carbon neutrality. In the short term, GDP gains are lower in the case of early decarbonization, as rapid energy transformation poses stresses on capital markets influencing economic activity. However, when the transformation is completed, GDP is 4% higher than baseline levels in 2050 triggered by lower electricity prices, speeding up the investments in clean energy technologies, and lowering fossil fuel imports.

7. Conclusions

The present study highlighted the methodology used to design, develop, and assess decarbonization pathways for the non-interconnected EU island of Mayotte. The research findings demonstrate that the adoption of ambitious climate policy measures, cross-sectoral integration, and widespread deployment of low- and zero-emission technologies are essential to achieving a successful clean energy transition. The study also indicated that the clean energy transition is a capital- and technology-intensive process that requires economic restructuring away from fossil fuels. However, the increased exploitation of renewable sources can reduce the average cost of electricity production in Mayotte, creating great socio-economic and energy supply benefits in the form of sustainable economic growth, consumption, investment, and employment.

The fully fledged energy–economy system model IntE3-ISL, which was introduced and applied in this study, cover both energy demand and supply in relatively high granularity in order to consider the unique characteristics of the island capture inter-sectoral trends and interactions among sectors, consumers, and system agents, and carve out a roadmap towards decarbonization. The IntE3-ISL model was used to build and assess several decarbonization scenarios for Mayotte. The comprehensive soft link between the macroeconomic (GEM-E3-ISL) and energy system planning models (E3-ISL) enabled the consistent assessment of emissions, energy system, and socio-economic effects of Mayotte's strong de-carbonization routes.

The impacts, challenges, and opportunities related to the clean energy transition in Mayotte were comprehensively assessed with the alternative decarbonization scenarios, differentiated by their policy, technology, and temporal scope. These scenarios revealed the diverse dynamics, synergies, and trade-offs among the transformation of energy end-use sectors—including transport, buildings, and industries—and the uptake of various clean energy technologies, as well as the associated costs and benefits for the citizens, the energy–economy markets, and the environment on the pathway towards achieving carbon neutrality.

The use of diverse decarbonization levers across the various scenarios provided an advantage to our research, reducing the risk of becoming overly dependent on one technology or a particular group of technologies, and evaluated the need for climate resilience, such as the capacity to survive extreme events and avoid electrical transmission failures. Significant conclusions for Mayotte's decarbonization strategies emerged from the analysis based on these scenarios, which grounded were in our thorough energy–economy modeling tool.

The decarbonization process of Mayotte as a non-interconnected island involves the substitution of imported fossil fuels and conventional technologies by low- and zero-carbon commodities and technologies. The installation, operation, and maintenance of these technologies is an activity performed domestically, thus developing local skills and jobs for the islanders. As outlined in Section 3, renewable energy expansion coupled with improved energy efficiency can enhance their resilience at an insular level against natural hazards and economic shocks by the requirement for imported fossil fuels.

Moreover, the extensive deployment of renewables will reduce the average cost of electricity production in Mayotte, and thus the electricity price, as the dominant diesel-fired plants, at present, are much more expensive than renewable-based alternatives.

The results of this analysis demonstrate that the decarbonization of a non-interconnected island is plausible, albeit challenging, as the ambition must go hand in hand with the islands' limitations and the implementation of clean energy projects.

The present study provided policymakers, stakeholders, and investors with valuable insights and a clear roadmap for the decarbonization of non-interconnected islands and offered a comprehensive approach to tackling the challenges and opportunities considering the clean energy transition.

The policy implications of the present study suggest that a holistic and comprehensive cross-sectoral approach in terms of modeling tools and methods can serve as a guide for policymakers, stakeholders, and investors towards the design and implementation of ambitious decarbonization pathways for non-interconnected islands. A key conclusion emerging from these results is that the clean energy transition of islands is plausible but requires significant efforts to overcome the challenges and seize the opportunities arising from the adoption of clean technologies, while also considering the unique characteristics of each individual sector.

While the study significantly contributes to the literature review on decarbonization pathways for non-interconnected islands, it has certain limitations. The study focused on the application of the tools on a specific island, a fact that may limit the scalability and replicability of the results for other regions.

This study can be extended in several other directions, not fully covered in this publication, and may serve as the foundation for further investigations. To better capture grid bottlenecks and storage needs, the IntE3-ISL modeling tool can be enhanced with a higher level of spatial resolution to improve the thorough depiction of distribution grids, as well as to better represent the variability of RESs and storage capacity needs. The accuracy of model-based estimates for future developments can also be improved by conducting sensitivity analyses for the main parameters that influence the model's results (e.g., technology costs, carbon price, GDP growth, etc.). The decarbonization scenarios can also integrate other policy priorities in addition to emission reduction targets, such as sustainable development goals (SDGs), energy security, and the circular economy. The abovementioned factors may allow for the more accurate long-term assessment of the required actions towards achieving a cleaner environment on the islands.

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