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D9.1

Evaluation of the environmental impact of each solution through LCA analysis

Deliverable D9.1

EVALUATION OF THE ENVIRONMENTAL IMPACT OF EACH SOLUTION THROUGH LCA ANALYSIS

Organisation: TUB
Main authors: Tim Ronan Britton (TUB), Nikolas Schöne (TUB), Anna Flessa (E3M)

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EXECUTIVE SUMMARY

This deliverable addresses the European Union's shift to renewable energy sources, particularly focusing on the challenges faced by European islands in reducing environmental impact and limiting global temperature increases. Energy System Modeling (ESM) is used to explore cost-effective decarbonization routes, with Life Cycle Assessment (LCA) applied to assess the environmental impact of decarbonized energy systems on European islands.

A set of representative and explorative transformation conditions for the energy, policy, technological, and socio-economic context of Mayotte were defined. The transformation conditions were transferred into distinct scenarios, which were integrated in the energy system planning model E3-ISL and the macroeconomic tool GEM-E3-ISL. The tools were specifically designed for the particularities of island energy systems. The modelling exercise resulted in a set of energy system topologies with distinct energy consumption, fuel mix, and emissions patterns. An ex-post link to a LCA was established, by soft-linking the ESM to an LCA model developed in OpenLCA. The LCA follows the ISO 14040/14044 LCA framework, employing OpenLCA v1.9 for evaluating five energy scenarios in Mayotte in 2050. The outputs of the energy system model (i.e., energy balance, capacity of assets) were integrated into the LCA model to expand the processes reflecting the energy system of Mayotte, and related upstream processes. Thus, the LCA captures the entire scope of Mayotte's energy system – including the transport, household, service, industry, and agricultural sector with flows and assets within.

The findings offer vital guidance for policymakers, highlighting effective decarbonization strategies. The study reveals that decarbonization measures are effective in reducing Global Warming Potential (GWP) but can lead to trade-offs in other environmental categories.

- Notably, the electricity sector's environmental impact shifts from operational processes in fossil-based systems to upstream processes in decarbonized systems, emphasizing the importance of sustainable production methods. Transitioning to biodiesel for electricity introduces trade-offs.
- The transportation sector faces challenges with the environmental performance of Battery Electric Vehicles (BEVs).
- Household-level decarbonization measures prove effective.
- Extending asset lifetimes, promoting the circular economy, and educating consumers are recommended strategies.
- A civic orientation of the energy transition actively involving the local population offers cost-efficient decarbonization and overall environmental improvements beyond GWP reduction.

Overall, this study underscores the need for informed policymaking supported by comprehensive environmental assessments such as LCA studies.

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List of Abbreviations

Abbreviation	Explanation
BEV	Battery electric vehicle
DAC	Direct air capturing
ESM	Energy system model
FCEV	Fuel cell electric vehicle
FPM	Fine particulate matter
GHG	Greenhouse gas
GDP	Gross domestic product
GWP	GWP
HB	Haber-Bosch
ICE	Internal combustion engine
IR	Ionizing radiation
LCA	Life cycle assessment
LCIA	Life cycle inventory analysis
LPG	Liquid Petroleum Gas
LU	Land use
MEU	Marine eutrophication
MRS	Mineral resource scarcity
NMVOC	non-methane volatile organic compounds
PHEV	Plug-in Hybrid Electric Vehicle
PM	Particulate matter
RES	Renewable energy sources
SMR	Steam-methane reforming
SOD	Stratospheric ozone depletion
WC	Water consumption

1. Introduction

1.1. Background

The European Union (EU) has set ambitious goals to transition it´s energy system from a fossil-based to a renewable energy-based system towards achieving net-zero emissions. The underlying motivation is to decrease the environmental impact of the energy system and contribute to limiting the increase of the global temperature to less than 1.5°C [1] in line with the Paris Agreement. In this discussion, European islands and their inhabitants take a special seat at the table – being the most vulnerable part of our European community facing both the direct effect of climate change, i.e., sea level rising, and economic impact of increasing energy costs in a fossil-based energy system [2]. At the same time, EU islands and their communities are seen as a favorable place for innovation [3] due to high costs of energy and a strong sense of community/collective action [4].

A successful transition towards sustainable energy, requires the transformation of the composition of energy sector and the incorporation of novel and innovative, zero-carbon technologies within the energy sector and its interconnected domains. These technologies play a crucial role in simultaneously meeting the ever-growing demand for energy and upholding the stability and resilience of the overall system. They encompass both energy generation and storage solutions, enabling a dynamic equilibrium in energy supply and demand. Moreover, given the intricate interdependence of the energy sector with industries and transportation, it is essential to account for cross-cutting technologies in the strategic planning of the energy infrastructure [5]. Hence, energy system planning has become technically more integrated and complex especially in geographically isolated islands. From a political perspective, the variety of technologies, their financial characteristics and relevant policy support mechanisms have increased in complexity. The effect and timing of political intervention, including fiscal support or emission constraints, are mutually interlinked with the underlying energy system. There is an apparent need to incorporate these system dynamics in energy system planning.

Within the intention of energy system planning, a common approach involves exploring potential technical routes that meet the energy demand at the lowest possible costs. Energy System Modelling (ESM) has emerged as a widely recognized and powerful tool in recent years for this purpose (see for example Ref. [6] for an overview of energy system models, their development and their use [6]). ESM enables the exploration of favorable configurations and modes of operation of an energy system and facilitates the consideration of diverse technical and economic variables. Modern ESM platforms offer a flexible incorporation of energy and climate policy measures, which are typically integrated in the form of modelling constraints. For example, a model may constrain the total amount of CO_2 emissions released within the energy system of consideration. Nevertheless, CO_2 constraints typically focus on the immediate emissions stemming from the burning of fossil fuels in the operational phase of a technology. They do not encompass the indirect emissions linked to both upstream and downstream processes associated with the products or materials needed for the energy system being examined. While state-of-the-art ESMs excel at providing detailed insights into the economic and technical ramifications of energy system transitions, a comprehensive approach to sustainable energy system planning must also encompass additional criteria and dimensions for evaluating the trade-offs associated with various clean energy transition pathways. As the primary underlying rationale and key objective for energy system transformation efforts are environmental considerations, it is of essential relevance to further develop environmental assessment methodologies within energy system planning.

Life Cycle Assessment (LCA) has emerged as a widely adopted methodology for studying the environmental impact of energy systems. While conventional energy system models may account for local emissions stemming from the operation of the energy system, LCA widens the analytical scope to encompass environmental impact across all stages of a system's life cycle—from the extraction of raw materials for energy system components, through production, operation, and ultimately to end-of-life stages (see for example DIN ISO 14041 and DIN ISO 1404) [7]. To enable an effective and efficient transformation of energy systems, the analysis of both direct and indirect emissions, stemming from upstream or downstream processes, is of essential importance. In fact, it must be noted that the entire optimal decarbonization pathway may be influenced by indirect emissions [8]. In addition to this crucial contribution, LCA encompasses the evaluation of various environmental effects that extend beyond climate change induced by greenhouse gas (GHG) emissions. As a result, LCAs reveal the manifold impacts connected with energy systems beyond the direct release of GHGs. According to Blanco et al. [5] LCA stands out for two primary reasons: firstly, by accounting for the entire life cycle of the energy system it integrates environmental impact assessment into global initiatives, guarding against the shifting of environmental burdens to other regions or life cycle stages. Secondly, by introducing a diverse range of impact categories (e.g., impacts on human health, resource utilization, land utilization, climate change, toxicity, etc.) in addition to global warming, LCA enables the identification of trade-offs across these impact categories, thereby preventing the transfer of burdens from one category to another (e.g., improving climate change metrics at the expense of increased water usage or deteriorating biodiversity). In this way, LCA has demonstrated itself to be a potent tool for evaluating the overall environmental impact of energy system technologies or processes, as well as entire energy systems [5,9]. Integrating ESM and LCA has the potential to offer a holistic perspective on the impacts of energy system interventions in the global picture of economics, climate change mitigation efforts, environmental and even repercussions beyond.

1.2. Aim, Ambition and Outline

This report systematically establishes a systematic link between ESM and LCA to assess the environmental impact of energy system scenarios depicturing a cost-optimal and decarbonized solution of a geographically isolated European island. The analysis focuses on the case study of Mayotte to demonstrate the methodology and derive results valid for geographical islands with isolated energy systems. The scope of the analysis covers the entire energy system, including a set of final energy carriers to be imported and/or locally produced, but also the provision of energy services within the five sectors of transport, households, industry, agriculture, and services.

The specific research questions, hierarchically structured, are:

1) What is the environmental impact of a future, decarbonized energy system?
2) Which is the energy system scenario with the lowest impact across environmental impact categories?
3) What i) sectors and ii) technologies decisively contribute to the environmental impact of the energy system?
4) Which trade-offs occur between GHG emission reduction and other environmental concerns?
5) What implications do policy interventions have on the environmental impact of the energy system?

The findings of the study will be of essential value for policy makers and other deciding entities in the energy sector by providing guidance on sectors, processes, and technologies to be focused on to decarbonize the energy system effectively and efficiently. The report draws attention to hot spots of the energy transition on Mayotte and potential follower islands, and the potential environmental consequences resulting from energy sector policies or energy planning interventions.

The outline of the report is as follows: Chapter 2 provides the theoretical overview of both ESM for energy system planning, and LCAs of energy systems. Chapter 3 tailors the theory of methods to the case under investigation and details the applied methodology. Chapter 4 presents and interprets the results of the LCA and provides conclusive recommendations for policy makers. The report closes with a summary (Chapter 5) and conclusion.

2. Theoretical Background

This section describes the overall theoretical background of the methodology applied in the analysis. According to the different tools used, the section first provides an overview on ESM for sustainable energy system planning (Section 2.1) and overview of LCA of energy systems (Section 2.2), to subsequently the methodological foundations of linking both disciplines (Section 2.3).

2.1. ESM for Sustainable Energy System Planning

In the pursuit of effective strategies for decarbonization of the energy sector, ESMs have emerged as crucial tools for exploring diverse scenarios and shaping the future development of energy systems. These models represent intricate mathematical depictions of energy systems, the models are available in various configurations that offer a wide range of levels of complexity and are capable of accurately capturing the intricacies of the depicted energy systems. They may also incorporate political, technical, and human considerations. A key application of ESMs is their utilization to advance climate change mitigation objectives. Their aim is to minimize the overall system cost by identifying the optimal combination of technologies to achieve predetermined goals, such as meeting specific energy demands for final energy carriers. To utilize ESM as an analytical tool for dynamic scenario analysis, a set of conditions and constraints, often of a technical, political, or environmental nature, is integrated in the model. The costs subject to minimization typically encompass expenses like fuel costs, other operational outlays, and the investment costs for necessary assets and equipment. Moreover, these costs might incorporate financial mechanisms such as a carbon price imposed on CO_2 emissions. The conceptual framework and intricacy of an ESM can vary significantly based on the primary objective and the scope of the specific analysis.

ESMs can be used to examine interactions across the energy system, possible pathways to decarbonization, the impacts of policy goals and objectives (e.g., energy security, economic competitiveness) and costs associated with certain energy scenarios. Modelling of energy systems aids to derive the quantitative analysis of energy sector scenarios for long-term energy planning. The models can be classified according to various criteria [10]:

- Purpose – Scope – whether the purpose of the model is forecasting or back casting, whether it is focused on energy demand or energy supply, etc.
- Structure – which are the internal and external assumptions? Some variables within models are determined by the model itself (endogenous) or are assumed to be determined by factors outside of the model (exogenous).
- Geographical coverage – regionally, nationally, or locally oriented?
- Sector coverage
- Time horizon and time step – the time horizon can be short-term (5 years or less), medium-term (between 5 and 15 years), or longer term (over 15 years)
- Technological detail – based on the type of technologies allowed by the models, internal databases can be used to model specific technologies (with given parameters and limited user interaction), or flexibility to new inputs could be introduced so that the users may even define modules to insert new technologies.
- Mathematical approach – top-down models (computable general equilibrium [CGE] and macro-econometric), bottom-up models (optimization or simulation approaches), hybrid models that introduce moderate technological detail within a macro-economic approach, accounting models, multicriteria models, etc.

An ESM is essential for the development of regional, national, or local decarbonization pathways, providing the necessary analytical framework to systematically explore the alternative system transitions. This transition is particularly challenging for insular systems due to the structure of the economy, the seasonality of electricity demand, the geographical location compared to the mainland, etc. The 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. Especially for non-interconnected electricity grids with high load volatility (e.g., due to touristic season), the balancing of supply and demand face great difficulties, causing fluctuations in electricity load voltage and frequency or even interruptions in electricity supply. Furthermore, the non-interconnected islands rely on imported fossil fuels (commonly diesel) for electricity supply and transportation, subject to price volatility, high electricity prices and increased CO_2 emissions, resulting in economic and energy security problems [11].

These unique characteristics of non-interconnected islands should be considered in their energy planning and decarbonization strategies, along with the development of an appropriate energy system modelling tool to assess the various clean technology options. Moreover, the shift from fossil fuels to cleaner resources poses additional challenges as it requires a new energy planning agenda given that renewable energy sources (RES) exhibit different characteristics from fossil fuels in their operation, production variability, and local impacts. The effective energy system planning of non-interconnected islands requires the development of rigorous scientific methods that can comprehensively assess the different aspects of the energy demand and supply sectors and their complex interlinkages, the means for smooth integration of variable RES, the necessary flexibility solutions, and the impacts associated with their deployment.

The modelling requirements identified for this purpose have been the following:

- Detailed and complete representation of the key drivers of energy demand by sector (i.e., socio-economic drivers like gross domestic product (GDP) and population, sectoral value added and industrial production, technology costs, heating-degree days etc.);
- Adequate sectoral disaggregation to represent key dynamics shaping up future developments in the energy markets (i.e., fuel competition in demand sectors, uptake of renewable energy for electricity generation, storage and flexibility requirements, energy pricing etc.);
- Explicit representation of energy-related and climate policies and their impacts on the development of energy demand and supply and technology uptake by sector
- Engineering-based representation of the power market to consistently simulate the energy system operation (i.e., Levelized costs of electricity -LCOE- costs of power plant types, Load Duration Curves, technical constraints of plants/industrial processes, substitution possibilities by sector, grid constraints, energy infrastructure, flexibility services and storage capacities);
- Behavioral representation of economic agents (preferences of consumers over different types of energy forms, what are the options for consumers to switch fuels in each end use?);
- Captures the inter-linkages between energy demand, supply and the formation of energy prices as well as the relations between the energy system, economy and CO_2 emissions;
- Can be adapted and tailored to island-scale specificities, especially related to decarbonization of islands with high expansion of variable renewables and flexibility services.

An overview of available models and methodological approaches, commonly used for energy planning at national and local level, has been conducted in Task 2.1 of MAESHA, with a particular focus on energy system models that use a bottom-up approach with high technology details and have been applied to geographic islands.

Table 1: Alternative energy system modelling approaches used at insular level – advantages and disadvantages [12][1].

Model	Description	Advantages	Disadvantages
LEAP	Scenario-based model to track energy demand and production, analyse energy policies and provide assessments for climate change mitigation measures	• Medium to long term energy planning • Can be applied to various geographic levels	• Exogenous energy demand • Cannot project long-term development of energy demand under alternative scenarios, • Not suitable for socio-economic impact analysis
OSeMOSYS	Linear optimization model calculating the optimal electricity investment subject to minimization of total discounted costs	• Open-source modelling system • Can be applied to various spatial levels	• Lacks a detailed representation of energy end uses • Energy demand is fully exogenous • Cannot be used for analyzing the long-term energy demand
MARKAL/TIMES	TIMES/MARKAL is linear optimization model that calculates the optimal energy supply mix to meet given energy demand subject to cost minimization.	• Covers the entire energy system • Can be utilized to analyze the impacts of energy and climate policies • Combines a technical engineering approach and an econometric approach	• Non-economic factors are difficult to be integrated • Does not perform explicit electricity pricing by sector/consumer type • Cannot assess the socio-economic effects of transition
EnergyPlan	The model aims to analyze the energy, environmental, and economic impact of various energy strategies. It is mostly used to compare a variety of transition options, rather than model one 'optimum' solution based on defined pre-conditions	• Includes both technical and market exchanges • Its aim is to model the 'finishing point' of the energy system (rather than the starting point) • The results include detailed hourly analyses of a complete energy system • Allows the user to define the energy system design	• Energy demand is exogenous • It focuses only on the technical side of the energy system, and does not cover socio-economic impacts of transition • Projections only up to 2030

[1] Other models which do not have the characteristics necessary to model the energy sector at the required granularity are: (i) MESSAGE: A system engineering optimization model, that focuses on energy system planning and analysis of climate policies. It covers a long-term time period of up to 120 years, with a 10-year time step. Thus, it is not suitable to provide consistent quantitative projections for energy demand for the next ten years. (ii) IMAGE: An energy system simulation model covering the time period to 2100 but it is not suitable for island-scale analysis as it focuses on global level with limited analysis at sub-national level.

CompactPRIMES	CompactPRIMES is an energy system model that follows the market equilibrium approach. The model accounts for the energy demand by sector and energy supply and their linkages through prices. The model is designed for medium, and long-term projections providing analytical data on an annual basis.	• Fully-fledged energy demand and supply model for single-country projections • Captures interactions between energy demand and supply and energy pricing • Medium to long-term projections to 2050 • Flexibility in scenario design and accessibility by non-modelers • Can assess the socio-economic impacts of different energy system configurations	• It cannot provide short-term energy forecasting • It does not have spatial resolution

2.2. LCA of Energy Systems

The phenomenon of 'global warming' – a continuous increase in the average atmospheric temperature caused by to the increased anthropogenic GHG emissions – is often used as a summarizing narrative for environmental effects related to climate change. However, there is a growing recognition of other anthropogenic environmental challenges, including material and resource depletion, ozone depletion, land-use, biodiversity, or toxicity. These challenges have to a varying degree geographic dependencies both in terms of their root cause and the resulting ecological damages. To enable well-founded decision-making regarding the shaping of energy-related policies and pursed future energy system configuration, it is imperative to develop effective and reliable assessment methods and tools that provide comprehensive insights into various environmental impacts. At the intersection of science, engineering, and policy, Life Cycle Assessment (LCA) stands out as a scientifically substantiated, well-defined, and well-established tool for evaluating environmental impacts across the entire lifespan of a product system. The methodology to be followed in an LCA is well-defined by standardizing bodies and is consistent for different scopes of studies. The system comprised in an LCA may contain a single product or may contain a complex system of products. While ESM generally lack a systematic approach for environmental assessment, LCAs are widely recognized as a thorough methodology for evaluating the diverse environmental impacts that occur throughout various stages of a product's life cycle. This encompasses all stages and phases from acquiring raw materials, production processes, transportation, use, and ultimately waste management. The comprehensive representation of interconnected products and processes and the high granularity of determining underlying environmental impacts provides clarity on the distribution of environmental burdens between different phases of the life cycle and among various environmental impact categories. The systematic application of an LCA enables the deliberate governance of environmental impacts.

The structure of LCAs is defined per DIN standards in DIN ISO EN 14040 and DIN ISO EN 14044. According to these industry standards, a complete LCA includes four subsequent steps: i) Definition of goal and scope, ii) lifecycle inventory (LCI) creation, iii) lifecycle impact assessment (LCIA) and iv) interpretation of results. The theoretical foundation of the steps 1 – 3 is described in the subsequent subsections. Their implementation within this analysis is elaborated in Chapter 3.

2.2.1. Goal and Scope

While the definition of the goal (including aim, target group, and purpose) is application specific, the definition of the scope of the LCA follows an established structure. DIN EN ISO 14044 specifies the essential aspects that need to be covered within the scope of the LCA:

- the product system to be studied;
- the functions of the product system or, in the case of comparative studies, of the systems;
- the functional unit;
- the system boundary;
- the allocation procedures;
- the method for impact assessment and the impact categories;
- the methods for evaluation;
- the assumptions, values and optional components, the constraints;
- the data quality requirements;
- the type of critical review, if provided;

In the following, selected technical terms that are relevant to understanding LCAs and that are continuously used in this document, are defined, and discussed.

Functional unit:

The functional unit (FU) can refer to variety of subject matters, including a product, a service, or a system. The environmental impacts calculated in an LCA is in direct reference to the respective subject matter. The FU provides a reference for relating inputs and outputs, thereby facilitating the direct comparison of alternative goods or services. By introducing a common FU for all alternatives to compare, the alternatives are set functionally equivalent – thereby a direct comparison of the alternatives via reference to the FU is possible.

In the context of the energy sector, a variety of FU have been suggested, with a comprehensive overview provided in [13]. The most used quantity to define the FU is energy (e.g., 1 kWh or 1 MJ)), followed by mass (e.g., of a specific fuel) [14]. Alternatively, Blanco et al. [5], assessing the environmental impact of technologies in different scenarios of the European energy sector in 2050, propose to define the FU not as the production of a specific product or commodity but as the satisfaction of all energy and services demands by 2050.

System boundaries

The system boundary defines which process modules must be included in the LCA. The selection of the system boundary must be consistent with the objective of the study. Within the energy system observed, any product, including materials and assets, may go through the five life cycle phases of 1. Raw materials extraction (also called 'cradle'), 2. Manufacturing and Processing, 3. Transport, 4. Retail and Use phase and 5. Waste disposal ('grave') or recycling phase. The definition of the system boundaries of an LCA consequently determines the life cycle phases to be included in the analysis. The most prominent approaches for the definition of system boundaries are:

- Cradle-to-gate: In an cradle-to-gate LCA model a product's environmental footprint is assessed from raw materials extraction until it leaves the production-"gate". The approach is useful when there is a need to simplify the downstream process of products or when downstream processes are irrelevant. (Example: [15])

- Cradle-to-grave: Cradle-to-grave includes all 5 life cycle stages, providing a complete environmental footprint. The approach is useful when expecting environmental impacts to potentially occur within any of the lifecycle phases. (Examples: [16], [17] and [18])

- Cradle-to-cradle: Cradle-to-cradle is a variation of Cradle-to-grave but exchanges the waste stage with a recycling/upcycling process that makes materials or components reusable for another product – essentially “closing the loop”. The approach might be useful when implementing circular economy models. (Example: [19])

Cut-off criteria

When gathering data for a Life Cycle Assessment (LCA), it is essential to differentiate between foreground data and background data. Foreground data constitutes primary information specifically gathered, modified, or generated to depict the product system under investigation (i.e., foreground system). Conversely, background data or background systems provide the broader context for the foreground system. Typically, background data is sourced from Life Cycle Inventory (LCI) databases, industry norms, and other secondary references.

In this study, in addition to primary data derived from the ESM scenario output of E3-ISL model (developed by E3M), the LCA relies on the widely recognized ecoinvent 3.9.1 database as a background system. This database has been integrated into the open-source software OpenLCA to facilitate the creation of the LCI.

Allocation procedure

The allocation procedure refers to the method used to apportion the environmental impacts among different co-products within an LCA. Given that a product system's life cycle often encompasses numerous multifunctional processes, it is crucial to distribute the environmental impacts among the various co-products generated by the same process in a justified manner. In line with the well-defined methodology of an LCA, distinctive allocation approaches are defined. Employing the ecoinvent database necessitates making a methodological choice among three distinct allocation approaches, namely "Allocation, cut-off by classification", "Allocation, at point of substitution (APOS)", and "Substitution, consequential, long-term" [20]. The specified allocation approach consequently establishes the linking rules for all processes within the background system. These rules, in turn, can impact the final results of the Life Cycle Impact Assessment (LCIA) [21]. Each allocation approach has advantages and disadvantages that are highly dependent on the context and the purpose of the LCA. The selected allocation procedure should be selected in alignment with the suitability and applicability of the respective system to be investigated [22]. The three system models applicable to the ecoinvent database exhibit variations in the following areas: a) treatment of by-products, b) utilization of average or unconstrained suppliers, and c) allocation of burdens for End-of-Life (EoL) treatments, described in the table below [20].

Table 2: ecoinvent allocation models.

	Allocation, cut-off by classification	**Allocation, at point of substitution (APOS)**	**Substitution, consequential, long-term**
a) Handling of by-products	Allocation (by cut-off)	Allocation (at point of substitution)	Substitution
b) Average or marginal conditions	Static representation of average conditions (evaluates the here and now) = "attributional"	Static representation of average conditions (evaluates the here and now) = "attributional"	Marginal/unconstrained consequences of change = "consequential"
c) Who carries EoL burden?	Waste producer (recyclable materials burden free; no credit)	Shared between all products in the value chain (system expansion)	Waste producer (with credit)

2.2.2. Lifecycle Inventory analysis

The lifecycle inventory analysis (LCI), involves the collection and quantification of all inputs and outputs associated with the product system into a life cycle inventory. Hence, the LCI phase provides the balance of resources and emissions upon which the assessment will be calculated. For this study, process-based data from the ecoinvent database v3.8 is embedded set into relation with upstream and downstream processes is provided by the energy system model (e.g., the impact of a gas boiler is not fixed, but dependent on the gas source that comes from E3M model). The development of the LCI follows the logic of the E3-ISL model and will be detailed accordingly in Chapter 3, which applies the methodology.

Ecoinvent was selected for the application of this study, because it is a comprehensive, consistent, up-to-date, transparent and scientifically well-established database. It's extensive coverage in the field of energy-related technologies and processes surpasses other available databases. Because of the complexity of the study and the large number of product and subsystems to be specified, the coverage was a decisive criterion in the selection of the database.

2.2.3. Lifecycle impact assessment

During the Life Cycle Impact Assessment (LCIA) phase, a comprehensive inventory of elementary flows (such as emissions and resource extractions) is transformed into a more condensed set of environmental impact scores. This transformation is accomplished using characterization factors, which signify the environmental impact per unit of stressor (for instance, per kilogram of emitted substance). The ISO14044 standard mandates that the characterization factors should be based on environmental processes linking human interventions to specific areas of protection. The conclusion of such environmental processes is termed the endpoint, while an intermediate point along the process, often referred to as the midpoint, can serve as an indicator. Impact categories are designed to address matters of direct environmental significance. This signifies, for instance, that waste is not considered a standalone impact category, but rather the impacts of waste processing should be integrated into the methodology in terms of their influence on climate change, toxicity, land-use, and so forth. The characterization factors can be calculated through two distinct approaches termed midpoint methods and endpoint methods. Midpoint characterization factors are situated along the impact pathway, typically occurring after the point where the environmental process becomes uniform for all environmental flows assigned to the respective impact category [23]. In contrast, endpoint methods quantify the cumulated consequences in terms of human health, ecosystem quality, and resource scarcity. Essentially, endpoint characterization quantifies the damage inflicted by various stressors at the conclusion of the cause-effect chain.

The selection of either a midpoint or an endpoint LCIA method is based on the context, in which the LCA results are utilized. Midpoint methods have lower uncertainty levels, but their results are more challenging to interpret, due to the multitude and intricacy of included impact categories. In contrast, the conversion of indicators into three or four damage categories for the endpoint characterization comprises a damage evaluation and allows a simplified interpretation of results. The disadvantage of the endpoint methods is that, the additional steps fate and damage modeling, introduce additional uncertainties [21]. Endpoint methods are therefore more concise, but at the same time less comprehensive.

2.3. INTEGRATING LCA AND ESM

The innovative approach of linking ESM and LCA has resulted in different methods, the most prominent of which are according to Blanco et al. [5]:

- **Ex-post analyses** use the generated output from the ESM to perform an LCA for specific technologies [24,25], sectors [26,27] or geographies [28]. The overarching goal is to assess the related environmental impacts of the energy system as optimized via ESM. Ex-post analyses usually do not entail a feedback loop to iteratively consider the obtained LCA results in the ESM. Ex-post LCA evaluations are often static in time and do not account for dynamic effects resulting from technological improvements (which may be considered in the ESM).

- The **monetization** approach quantifies environmental impacts, particularly emissions, by assigning them a monetary value. Yet, the focus has primarily been on air pollutants, overlooking a more holistic set of impact categories. Researchers have extensively explored power system models at both regional and global scales within this framework [29,30]. Furthermore, this approach has been applied to analyze energy systems [31,32], heating [33] and buildings [34]. The primary benefit of adopting the monetization approach lies in its capacity to offer insights back to the Energy System Model (ESM), enabling the optimization of the energy and technology mix while integrating sustainability considerations. Nonetheless, it's important to acknowledge that the monetization step introduces inherent uncertainty, given that it relies on a damage cost methodology rather than conducting a comprehensive analysis of factors such as dispersion and local environmental vulnerability. Apart from one case [35] where two impact categories (climate change and human health) were internalized into the ESM through monetarization, the range of impact categories beyond air pollutants is structurally neglected.

- To reduce the uncertainty involved in monetizing externalities, **multi-objective optimization** treats each environmental impact category as a separate objective. The inherent trade-offs and potential synergies among various impact categories necessitate a process of weighting to assess the relative significance of each category. This introduces a subjective element into the analysis. Furthermore, many multi-objective optimizations in the existing literature tend to concentrate primarily on GHG emissions, often overlooking other important LCA impact categories [36]. Owing to the increased model complexity, analyses have primarily been limited to the power sector [37].

- **Multi-criteria decision analysis** shares similarities with multi-objective optimization, but it is expanded by incorporating qualitative aspects (e.g., risk, social factors, political drivers). In contrast to multi-objective optimization, the environmental dimension is not considered through impact indicators [38], and there is no feedback loop that integrates LCA results back into the ESM [28]. An advantage of multi-criteria decision analysis is the holistic approach that covers a wider set of dimensions. However, weight allocation to each objective as well as selecting the most suitable solution from the Pareto front (which represents the set of optimal trade-offs between different objectives) are rather subjective.

Linking ESM and LCA poses several methodological and practical challenges, a selection of which is stated below with details provided in [5]: One fundamental principle for integrating and harmonization of ESM and LCA is the identification and systematic linking of key elements (e.g., variables and parameters). Because in principle, the research objectives and the scope of application of ESM and LCA are inherently different, the respective data requirements can vary significantly. Limitations in data compatibility can hamper the integration of ESM and LCA. In the context of energy-related activities, common elements encompass technical parameters like energy conversion efficiency, lifetime of energy technologies, and the energy mix. Challenges arise not only from generally identifying common elements, but also from identifying relevant intersections comprehensively. For example, incorporating the energy mix used in the upstream production of assets, which are integral to the broader energy system, is frequently overlooked and poses a harmonization challenge. When evaluating the life cycle impacts of a kilowatt-hour of electricity generated from wind energy, it is crucial to consider the upstream electricity mix used in producing the wind turbines. Consequently, the installed capacity of these turbines will also influence the overall electricity mix. One approach to mitigate this issue is to establish feedback loops between the LCA and ESM implementation steps, but this may be computationally intensive.

A second significant challenge pertains to the potential for double counting. When integrating LCA into ESM, additional energy and material demands from upstream processes must be accounted for. In their application, ESM already factors in these demands as part of the final demand. Adding the life cycle demand in addition to the final energy demand specified by the ESM may result in a duplication of counts for some impacts. Additionally, some processes within the model rely on inputs from other processes, potentially leading to double counting of energy or emissions.

It is common practice that CO_2 targets considered by an ESM are set based on direct emissions within a specific region. ESM models do not usually include energy and CO_2 emissions associated with imported goods and commodities. However, these emissions can be significant, and including them in the expanded perspective of ESM through LCA can greatly impact overall results [39].

Another challenge arises from the spatial differentiation in assessing environmental impacts. These impacts can range from global concerns like global warming to more localized issues such as soil pollution. Local impacts are affected by various factors including population density, vulnerability, and prevailing weather conditions, all of which influence the dispersion, fate, and effects of pollutants. While certain LCA databases make efforts to distinguish impacts by country, there are still instances where many processes lack specific regional coverage, leading to the reliance on global values [40].

Furthermore, matching processes between LCA and ESM can be difficult when dealing with multi-functional processes (i.e., processes that have multiple outputs). Allocating the environmental impact in such cases requires careful consideration and is one of the most controversial issues in LCAs [41]. Against this backdrop, some LCA databases offer their datasets in alternative versions, called system models, which differ in their approach for handling multifunctionality within the background data system (see **Fehler! Verweisquelle konnte nicht gefunden werden.**).

Another challenge pertains to projecting the future performance of technologies. The integration of LCA and ESM introduces complexities in forecasting the future performance of technologies. While some ESM models incorporate learning curves for emerging low-carbon technologies, anticipating increased efficiency, reduced fuel consumption, or higher output, uncertainties persist regarding the comprehensive life cycle impacts of such technologies. ESM is adept at illustrating learning curves or gradual efficiency enhancements, which can notably decrease resource demands, thanks to technological advancements. In contrast, LCA typically remains static.

3. Applied Methodology

3.1. Overall Procedure (ESM-LCA integration)

The overall procedure of the study expands the processes within the energy system of the E3-ISL model to a full life cycle perspective by considering manufacturing, construction and end-of-life stages including disposal. Further, while the E3-ISL model only accounts for CO_2 emissions as environmental indicators, linking the ESM to the LCA adds a broad range of impact categories besides climate change caused by CO_2 emissions. The general framework for the methodology is shown in Figure 1 followed by a brief explanation of the main steps. The figure shows the two main elements of this study: ESM and LCA. To link the ESM and the LCA, an ex-post soft-linking approach was chosen. This approach utilizes the outputs of the energy system model (i.e., energy balance, capacity of assets, fuel mix, technology mic) to expand the processes and perform an LCA. No feedback loop to manipulate the ESM optimization results is foreseen. Hence, the cost-optimal configuration of the energy system as modeled within the ESMs is not disturbed. The general structure of the ESM (see Section 3.2simulates all steps and processes of the energy system from energy resources with a respective potential and associated price curves. The resources are used to satisfy final demand services through primary (e.g. power) or secondary (e.g. boilers) conversion processes. Multiple policies can be introduced as constraints, including CO_2 emissions. The main outputs of the model include the energy balance, cost breakdown, technology mix needed, and energy flows between assets. The information used from the E3-ISL model for the LCA is mainly: (1) static, related to using efficiency, lifetime and capacity factors of energy-related technologies used to modify the original inventory from the databases and needed to ensure consistency; (2) scenario-dependent (see section 3.2). The scenario-dependent absolute values are combined with the life cycle inventory to estimate the environmental impact of energy system development. In this study, there is no feedback from LCA to the ESM optimization process. The main methodological steps followed are:

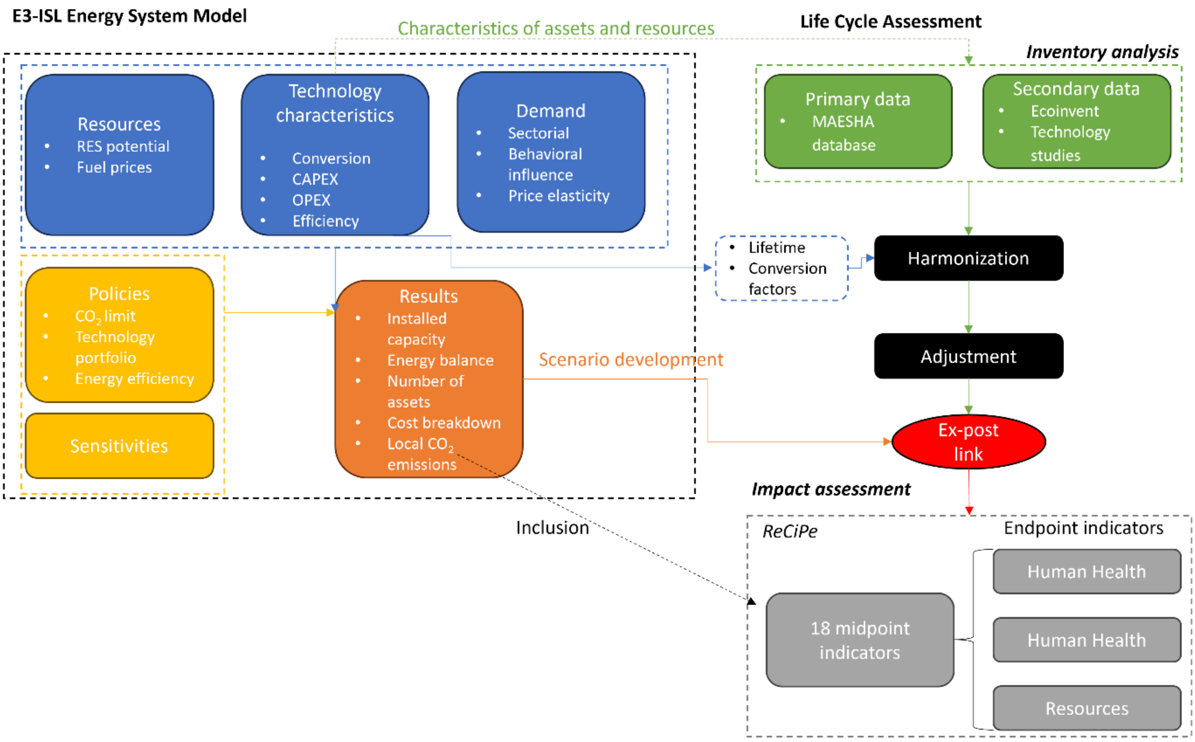

Figure 1: Framework for integrating LCA and energy modeling followed in this study. Adjusted from [5].

1. Model the energy system structure as suggested by the E3-ISL model within an LCA modeling environment. Doing so, the number of processes from the E3-ISL model may be reduced (i.e., clustered) to facilitate inventory collection (see Section 3.3.1)

2. Identify entries from the LCA database (ecoinvent v3.8) that are closest – more similar - to the processes screened (see Section 3.3.1)

3. Augment LCA data with alternative sources and individual studies derived from a literature review (see Section 3.3.1)

4. Harmonize data between E3-ISL and LCA. This refers to using E3-ISL data for specific technologies, including efficiency and lifetime and modifying the LCA data

5. Adjust LCA datasets to avoid double counting (see Section 3.3.1) for upstream emissions that are also part of E3-ISL model scope

6. Execute a set of predefined scenarios using the E3-ISL model (see Section 3.2)

7. Extract activity (energy production level) and capacity or number of assets for selected technologies in Step 1 from E3-ISL model. The step was facilitated by exporting relevant data in Excel format from the E3-ISL model (by E3M), and feeding-in the excel-based data into OpenLCA (TUB).

8. Calculate LCA mid-point indicators for each scenario (see section 3.3.4)

9. Understand drivers for changes across indicators and run additional scenarios for confirmation, detection of hot-spots and robustness of results.

3.2. Energy System Model Description

The following section details the E3-ISL ESM used within this study (Section 3.2.1). The section will essentially elaborate the energy system model scenarios specified (Section 3.2.2), which will be further investigated regarding it´s life cycle impact within the LCA.

3.2.1. Description of E3-ISL

Considering the requirements of the energy system modelling tool for small-scale island systems (see Section 2.1), the need for flexibility in the availability of data and the potential need to adapt the tool in the future to facilitate the analysis for islands, a customized modelling tool, based on the CompactPRIMES Model has been proposed according to the characteristics of the Mayotte island, that, in parallel, could be easily adapted and used for MAESHA follower islands. The island-scale version of the modelling tool is called E3-ISL model, and its features are described below (a detailed model description can be found in the MAESHA Deliverable D2.2).

- Programming language: General Algebraic Modelling System (GAMS) which is a standard state-of-the-art interface and modelling language in modelling community.
- Fully-fledged energy system model covering both energy demand and supply to capture the inter-sectoral trends and price-driven interactions;
- Basic modelling logic: market equilibrium with endogenously derived energy prices through energy demand-supply interactions to reach an equilibrium;
- Adjustment of the technological resolution of the model to those that are relevant for the island; i.e. detailed calibration of the model to historic energy system data and energy balances of Mayotte (and follower islands), customized sectoral and technology disaggregation to capture island-scale specificities, detailed modelling of energy policies, decentralized renewable generation, demand response and flexibility services
- Sectoral coverage: industrial sector, buildings/residential sector, transport, agriculture, electricity supply. The granularity depends on the availability of information for each sector, and can expand to the level of different industrial sub-sectors (types of industries), energy uses in the residential sector, transportation modes (e.g., cars, busses, trucks) and power plant types;
- Possibility for the user to model the impacts of 1) specific energy-related policies both on the energy demand and on the supply side (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 for key drivers, i.e. population, GDP growth, industrial production, costs for RES or other energy forms;
- Time horizon: 2015-2020 to 2050, 5-year-step simulation.
- The model is not a "black box"— it will be accompanied with hands-on training, tutorials, and appropriate documentation to EDM and other relevant stakeholders and authorities of Mayotte and follower islands.
- Capacity to soft link with a macroeconomic model.

The integrated island-scale modelling framework E3-ISL/GEM-E3-ISL has been developed and customized to capture adequately the complex interlinkages of the energy system with the economy as well as the specificities of the economy and the energy system of a non-interconnected geographical island, i.e. service-oriented economy, already installed fossil-fired power plants, RES potentials, load seasonality, costs of RES and fossil fuels, energy efficiency potential in industries and households, flexibility services both on demand and supply side (i.e. demand response, rooftop solar

PV, V2G, batteries, Power-to-X), etc. The main purpose of this modelling suite is to quantify and assess the energy- and emission-related as well as socio-economic impacts of various sectoral technology and policy pathways towards energy transition with optimal utilization of the available resources.

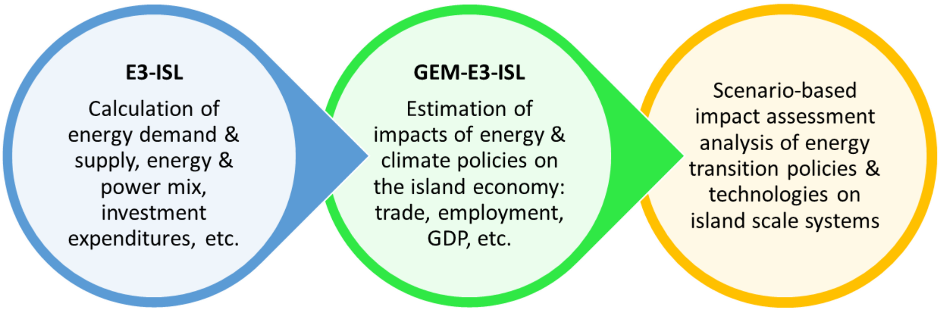

Figure 2: Energy-economy modelling framework for island-scale systems

The energy system planning model **E3-ISL** is a fully-fledged energy demand and supply model for detailed energy system projections[2], energy demand forecasting, power sector planning, as well as for impact assessment of national and local climate and energy policy decisions with a horizon up to 2050. Methodologically, it is customised to the specificities of geographical islands, and calibrated on the energy system of Mayotte. The following Figure depicts the key components, inputs and outputs of the model.

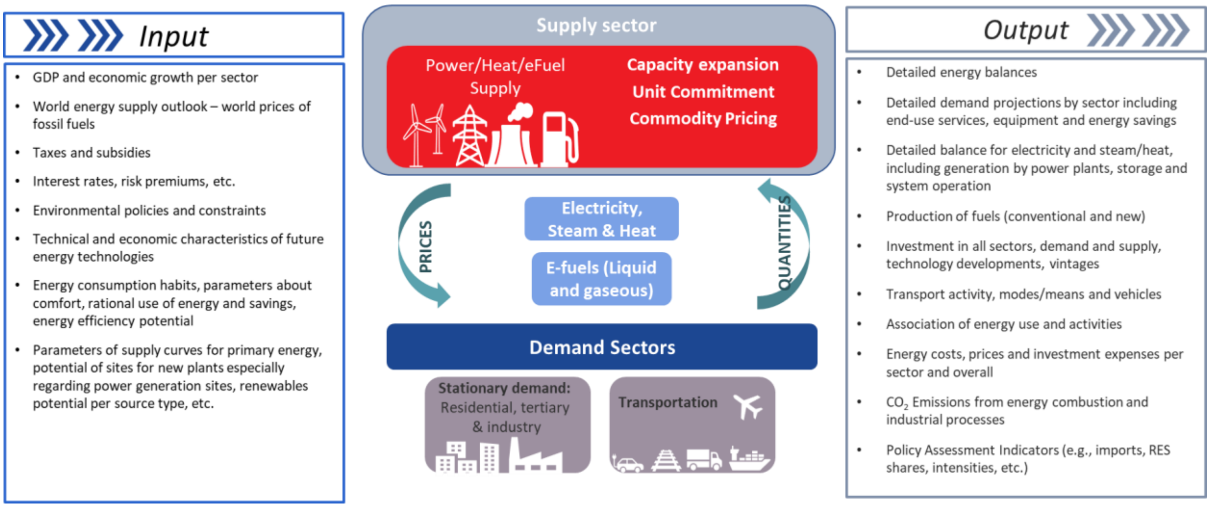

Figure 3 Structure, inputs and outputs of the E3-ISL model.

The model represents individual actors' decisions for the demand and supply of energy and the balancing of their decisions in simultaneous energy markets cleared by prices. As economic theory suggests, the simultaneous market clearing under perfect competition conditions leads to an overall optimum of economic welfare, which coincides with the minimum cost of energy for the end-users. The model explicitly projects electricity prices into the future as derived from cost minimization in the supply side and the price-elastic behaviors of demanders for energy, thus achieving market equilibrium.

[2] Model projections include structure of energy demand by sector and by energy form, power generation mix by technology, investments per energy sector, CO_2 emissions, explicit calculation of electricity prices and overall energy system costs.

The model is executed in 5-year time steps from the base year (2015) up to 2050 and it is structured in modular way allowing for different methodologies by sector depending on the specificities and the decision-making principles of the various agents in each sector. The Modules run sequentially, performing user-induced iterations. The Balancing and Reporting Modules produce the final results of the E3-ISL tool and reports them in user-friendly Excel-based files, which can be customized to include additional energy indicators relevant for Mayotte.

- **Demand Module**: it projects the demand for energy commodities and investments for energy efficiency in the industrial, tertiary, agricultural, residential and transport sectors. The module has also the capacity to simulate the inertia of the consumer's attitude on the energy-related options and decisions as well as the gradual change of their behaviours, habits and practices towards cleaner and environment-friendly choices paving the way for a clean energy transition, considering the impact of energy communities.

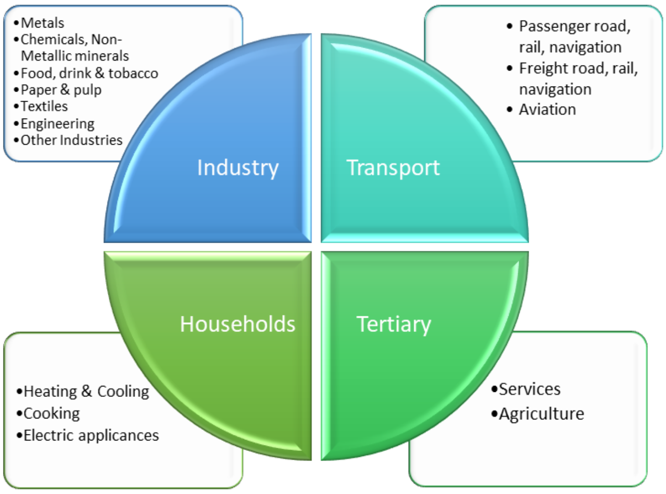

Figure 4 Sectoral coverage of E3-ISL Demand Module.

- **Supply Module**: This Module decides on how to cost-optimally serve the energy demand requirements for electricity and steam as well as hydrogen and clean fuels when eligible. The Supply Module incorporates a separate sub-module for commodity pricing. The Pricing sub-module calculates the tariffs of electricity and steam per sector of final demand considering the differential grid costs, as well as the tariffs for green hydrogen and synthetically produced fuels (clean fuels). The updated prices feed in the Demand Module in the next model iteration and fine-tune/adjust accordingly the demand for energy commodities (price-elastic behavior of energy consumers).

Table 3 E3-ISL – Power generation and storage technologies

Power generation			
Fuel	**Technologies**		
Gas	Steam Turbine	Combined Cycle	Gas Turbine
Oil	Internal combustion		
Wind	Wind onshore	Wind offshore	
Solar	Solar PV	Solar thermal	
Hydro	Hydro dam	Run of River	
Biomass	Biosolids fired	Biogas fired	Waste fired
Geothermal	Steam turbine		
Storage			

Batteries	Hydrogen	Demand response	Pump storage

Green hydrogen is anticipated to play a key role in the future as it is considered as a primary fuel for the "hard-to-abate" sectors such as metal industries and freight transport. Regarding modelling perspective, the Supply Module generates the quantity of hydrogen needed by the end-use sectors, to be channeled either for direct use or as feedstock for the production of synthetic liquids for transport such as ammonia and synthetic kerosene.

E3-ISL accommodates several climate- and energy-related policy drivers that lead to reductions in CO_2 emissions, penetration of renewable energy sources and energy savings. These drivers represent price-related and non-price-related policy instruments as well as regulatory standards. The most significant policy drivers are presented below. Among the price-related policy drivers of E3-ISL, the most significant one is carbon price. The **carbon price** represents either a carbon tax or the price of an emission allowance in case of an emission trading scheme.

Table 4 E3-ISL model – Policy drivers

Policy driver	Description	Relevant Sector
Carbon price	Implicit emission reduction target	Demand and Supply sectors
Fuel Taxation	Excise taxes imposed on fuel prices	Demand and Supply sectors
Discount rates	Risk premium, which affects the weighted average cost of capital (WACC) of an investment.	Demand and Supply sectors
Subsidies	Promotion of efficient equipment	Demand-side sectors
	Support for heat recovery	Manufacturing sector
	Promotion of renewable fuels (solar, biofuels, etc.)	Demand-side sectors
Support schemes for RES, storage, Power-to-X, CCS	Feed-in-Tariff/Feed-in-Premium mechanism for power generation by RES, battery storage, Power-to-X facilities (including hydrogen)	Energy supply sector
Phase-out/Lifetime extension	Policies for lifetime extension of power plants and retrofitting or early retirement of plants	Power supply sector
Enabling conditions	Removal of non-price-related barriers (market failures, behavior/perception, etc.) associated to the use of emerging technologies and fuels	Demand and Supply sectors
	Technology progress/Learning-by-doing reducing the technology costs over time	
Regulation for ban of equipment or fuel	Policies to forbid the use of polluting equipment/fuel	Demand-side sectors
Regulations on technology standards	Emission performance standards	Transport sector
Biofuel mandates	Mandatory blending of conventional fuels with conventional and advanced biofuels as well as e-fuels in transport sector.	Transport sector

Other features, embedded in the model, that represent the island-scale systems are:

- **Load seasonality**: The E3-ISL model accounts for the load variability within a year by using representative daily hourly load curves with a specific frequency/occurrence. These representative daily load curves vary according to season (winter, summer) and/or type of day (working day, holiday, peak, off-peak) to adequately capture the load variability and the peak load demand in Mayotte. The current version uses 6 typical days with average load, 1 typical day including the peak load of the power system, one typical day with low generation from variable renewable energy sources (rainy days, etc.) and one typical day with high RES generation (with increased flexibility needs).

- **Agent heterogeneity:** The Demand Module distinguishes three (3) agent classes with different preferences in the choice of *house equipment* and *private cars* based on the housing living standards, used as proxy to the socioeconomic status. With respect to the different agent classes, certain parameters in the model are differentiated across the agent classes such as the private discount rate for investment in energy technologies or energy efficiency, the utilization rate of equipment implying that there are different levels of demand for activity by agent class, etc.
- **Imports:** Regarding international trade, E3-ISL is linked with the international markets via the international prices that are used to import oild and gas in Mayotte. As a single-country modelling tool, it does not account for the simulation of the regional electricity markets.
- **Electricity tariff scheme**: The model simulates a well-functioning market, where the tariffs of electricity, hydrogen, and synthetically produced fuels per sector are calculated assuming that total energy system costs are recovered by agents, including also possible stranded investment costs. The tariffs distinguish between electricity generation and the provision of grid services (Transmission and Distribution). The price of electricity is calculated by type of voltage (base, medium, high) and consumer (households, industries, transport). Negative profit rate is used to simulate the current price subsidization scheme in Mayotte. Cross-subsidization between the sectors is used to calibrate the electricity prices in the base year.
- **Flexibility and balancing**: Various storage options are included in the model such as pure pumped storage plants, batteries and power-to-X plants, including the production of green hydrogen. Demand Response practices are embedded in the model and act as demand shifting (e.g., shifting the use of equipment, so as to smooth the daily peak). Another flexibility solution is the bi-directional EV charging – electricity can flow from the grid to the vehicle and vice-versa. Thus, the electric car´s battery can be used as a secondary home power source. Spinning reserves as well as non-operating reserves are considered to secure reliability of supply.

The following table shows the key outputs of the E3-ISL.

Table 5 E3-ISL model – Model outputs

Demand Module	Power Module	Balancing Module
➢ Energy Demand by sector and fuel ➢ CO_2 emissions by sector ➢ Energy Savings, Energy and Carbon Intensity ➢ Costs and cost break-down (capital, fuel, non-fuel, emissions & taxation costs)	➢ Power & Heat/Steam Generation by plant type and storage type ➢ Fuel Consumption by plant an storage type and fuel ➢ Energy-related CO_2 emissions ➢ Carbon Intensity by plant type ➢ Costs of electricity & heat supply and cost break-down	➢ Energy balance for each projection year

➢ Capacity Investments & Investment Expenditures	(capital, fuel, non-fuel, emission & taxation, grid costs) ➢ Capacity Expansion & Investment Expenditures by plant type	

In relation to an LCA, E3-ISL, as other ESMs, enables the evaluation of alternative policies, capacity evolution, covering all end-use sectors. Stages of the life cycle that are covered by ESM are generally: primary energy production (energy and emissions for extraction of resources based on simplified accounting method – N/A for Mayotte), operational (e.g. energy efficiency and conversion/transformation losses), fuel combustion (heat/steam supply and power generation, chemical transformation). In terms of emissions, the model accounts for CO_2 derived from fuel combustion and industrial processes and does not include other energy-related greenhouse gases (CH_4, N_2O), or GHG by other sources (waste, agriculture, LULUCF) or air pollutants (particulate matter, NH_3, SO_2, volatile organic compounds, NO_x). Emissions from imported materials or commodities, construction and decommissioning-disposal of assets are not considered.

3.2.2. Scenario Description

Multiple strategies towards net-zeo with different technology and policy focus, horizon of policy action, etc. were examined within Task 2.3 to define feasible energy transition pathways for the island of Mayotte. Based on a co-design approach with the MAESHA partners involved in Work Package 2 and other Work Packages such as WP4 and WP9, and the local company EDM, several narratives and variants were developed underpinning different future configurations of the energy system of Mayotte towards carbon neutrality by 2050 or sooner.

These scenarios simulate alternative visions of how the energy, policy, technology, and socio-economic context of Mayotte might evolve in the medium and long-term. Their impacts on energy consumption, fuel mix, technology uptake, CO_2 energy-related emissions, required investment, energy system costs and prices were quantified with the use the energy system planning model E3-ISL and the macroeconomic tool GEM-E3-ISL, and assessed against predetermined criteria for the future energy system of Mayotte, including the project KPIs like share of renewable energy, reduction of CO_2 emissions, etc. The scenario analysis is focused on the assessment of the medium- and long-term energy system, technology, socio-economic and emissions impacts triggered by the clean energy transition of Mayotte, with the use of the integrated energy-economy modelling framework E3-ISL/GEM-E3-ISL. The projection horizon of this analysis is from 2015 up to 2050.

The following scenarios were simulated and quantified, capturing the local specificities, circumstances, and priorities for the future development of the energy and economic sectors of Mayotte:

- The *Baseline scenario* (Base) that accounts for the existing energy and climate policies adopted by the end of 2020 (Business-As-Usual scenario).
- The *Consumer-driven decarbonization* scenario (Decarb_Demand) assumes the active role of the local communities and consumers in the clean energy transition pathway, till 2050. 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 towards carbon neutrality by increasing energy savings and lowering electricity bills. The activation and engagement of the local community also supports the provision of cost-efficient flexibility services to the electricity system through demand-response and storage.

- The *Supply-side decarbonization scenario* (Decarb_Supply) focuses on actions related to the energy supply side with limited changes in energy demand dynamics, as a fully decarbonized electricity sector is the essential foundation of a net zero energy system. In this respect, this scenario is more supply-driven and explores the potential of the local renewable energy resources in Mayotte.

➢ The *Early decarbonization scenario* (Early_Decarb) assumes the rapid enactment of transition policies and measures from 2025 onwards, leading to a decarbonized energy system earlier than 2050, in contrast to Decarb_Demand and Decarb_Supply scenarios that consider the initiation of transition efforts roughly from 2030 onwards. The clean energy transition by 2045 requires early and coordinated action in both the demand and supply sectors. The more rapid nature of the emissions reduction affects particularly the carbon-intensive sectors, such as transport, leading to accelerated transformation dynamics in the medium-term.

➢ The *MAESHA-focused decarbonization* scenario (MAESHAfocus) explores the impacts of a full implementation of MAESHA project solutions by 2025-2030 as well as the achievement of the relevant KPIs of the project, while intermediate targets for 2030 and 2040 are set before the full decarbonization of Mayotte by 2050. This scenario is characterized by high ambition in the period until 2035 and finally results in early decarbonization of Mayotte, since one of the most carbon-intensive sectors, transport is envisaged to be decarbonized by 2040.

The policies assessed cover a broad spectrum, including energy and carbon taxation, efficiency standards, electrification programs, support for the uptake of low- and zero-carbon technologies and vehicles etc. E3-ISL allows for sectoral modelling accounting for sector-specific policies such as technology performance standards in transport as well as economy-wide policies such as carbon pricing. The scenarios analyzed in this study differ in terms of policy focus and intensity.

Table 6: Overview of the five scenarios of the ESM [42]

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

The ESM by E3M provides specific energy system configurations for each of the five scenarios. All five energy system configurations allow to meet the respective energy and energy service needs of each scenario. These configurations serve as the basis for the LCA conducted in this study which constitutes the first time a comprehensive LCA of the energy system in Mayotte has been carried out, and moreover establishes an ex-post soft-linked connection between ESM and LCA, which is the first time customized and applied to a geographically isolated island.

3.2.3. Summary of Outputs

The development of the energy sector strongly depends on the long-term evolution of population, GDP, and sectoral production of Mayotte, as well as external determinants such as the energy prices (crude oil), the technology costs and EU-related climate and energy policies. The quantitative model-based analysis has been developed based a common macroeconomic outlook of Mayotte that builds on recent demographic and economic projections provided by the UN and IMF, as well as local economic reports. According to the UN world population prospects (medium variant), Mayotte's population is expected to continue growing in the next decades, reaching 495 thousand inhabitants by 2050. The growth of the island's economy is assumed to continue in the period 2022-2026 with an average annual growth rate of 4%, 4.95% in 2027-2035, and about 4% in the period 2036-2050. Accordingly, the GDP per capita in Mayotte increases from about 9,500 EUR/capita in 2019 to 18,870 EUR/capita in 2050, growing with an average annual growth of 2.3% per annum over 2020-2050.

The Baseline Scenario serves as a benchmark point upon which the transition pathways have been developed and assessed. The policies considered are those derived from the French legislation (e.g., on fuel taxation) and the relevant EU Directives (EU-ETS, technology performance standards for cars and vans). In the Baseline scenario, an increase of 110% in gross inland energy consumption of Mayotte is projected in the period 2020 – 2050, which is lower than the increase in economic activity illustrating a relative decoupling of energy demand growth from GDP. Oil products are envisaged to continue to dominate the fuel mix of the demand-side sectors with a small decline in their share from 62% in 2020 to 59% in 2050. Limited energy efficiency improvements are anticipated in buildings and manufacturing sectors following historical trends and technology advancement. The power mix is expected to differentiate from the current one, with investments in new solar PV and wind capacities driven by the decreasing costs of solar panels and wind turbines. Nevertheless, diesel oil continues to play a significant role in the power supply sector until 2050. In this respect, carbon emissions in Mayotte continue rising in the future.

On the other hand, all decarbonization scenarios achieve CO_2 emissions reductions larger than 95% in 2050 from 2015 levels, as a result of an economy-wide CO_2 price trajectory that drives mainly the low-carbon transition of power supply and industrial sectors, carbon standards for new vehicles, technology and efficiency standards, and blending mandates with conventional and advanced biofuels, as well as green hydrogen and clean e-fuels. The challenges and opportunities that emerge from the clean energy transition of the various sectors of the island are explored in terms of emission reduction, fuel mix, energy costs, and socio-economic implications.

Energy efficiency improvements and fuel switching in the buildings and agricultural sectors are found to be among the most cost-efficient mitigation actions. Investments in highly efficient appliances and emerging technologies and equipment drive the reduction of end-use energy consumption by 2050 in the building sector. Since this sector is already highly electrified, no significant differentiation in the fuel mix is observed across the decarbonization scenarios – oil phase-out leads to a higher electrification rate and further uptake of solar thermal applications, given that space-heating use is very limited in Mayotte due to climatic conditions. In agriculture and the limited industrial processes, diesel is substituted by electricity and biofuels to a great extent.

Apart from the direct electrification, that by default leads to higher efficiency, the energy savings on the demand side helps ease pressure on the energy supply side. This means that less electricity demand results in less investments in the power production sector. This can be observed with clarity in the consumer-driven decarbonization scenario, that considers the awareness and empowerment of the consumers and the emergence of local energy communities giving them a more active role in managing their energy consumption that helps reduce the investment requirements and costs on the supply side.

Transport accounts for most of the energy system costs and CO_2 emissions in the island of Mayotte. For some transport segments (i.e., private road transport), the uptake of electric vehicles is the preferred option to drive decarbonization. However, there are transport segments with hard-to-abate emissions, e.g., freight transport, aviation, and navigation, where direct electrification is very challenging and there are limited available mitigation options. The role of green hydrogen and e-fuels such as ammonia and synthetic kerosene as well as extensive use of biofuels via blending mandates and emission standards, is significant for decarbonizing such transport segments, taking advantage of the existing infrastructure to some extent. A strict regulatory framework that imposes declining emission performance standards and ambitious blending mandates would results in large-scale uptake of low-carbon fuels and reduced emissions in the road transport sector.

In all sectors, demand for electricity is projected to increase compared to 2020. The increase of the electricity share in transport is prominent – ranging from 25% to 38% in 2050 compared to 0% in 2020 or 4% in 2050 according to the Baseline scenario. The gross domestic electricity demand increases even more due to the increasing needs to produce green hydrogen in various forms, either for direct fuel consumption or for the production of synthetic e-fuels, which represents a considerable share of energy consumption in the long run, especially for navigation and aviation sectors.

In all scenarios, apart from Baseline and MAESHAfocus, EDM plans for fuel-switching of the Longoni and Badamiers ICE plants from diesel to biodiesel by 2030, have been considered. Oil phase-out is assumed to materialize within the period 2026-2029. Existing ICE plants are envisaged to participate as firm capacity in the provision of ancillary services to support the large-scale deployment of variable renewable sources like solar PV and wind. The power supply mix that serves the rapidly increasing electricity consumption is based on variable RES, accounting for 65% of the gross power generation by 2050 coupled with storage (mostly with batteries), ICE plants (using biodiesel) and geothermal plants; therefore, in all decarbonization scenarios the share of renewable energy in power generation increases to 100% after 2030. This means that emissions from electricity production decline rapidly to zero, allowing the carbon-free electricity to be used for the decarbonization of energy demand sectors, which commonly face higher transformational challenges and have limited emission reduction options. In this context, green electricity is increasingly used to electrify energy demand across sectors, both directly and indirectly through the production of green hydrogen and e-fuels. Indicatively, the gross power generation almost triples compared to 2020 levels in all decarbonization scenarios. The necessary flexibility services are secured with battery storage and demand response. From the demand-side, higher contribution in balancing is assumed in the Decarb_Demand scenario with wide demand-response by consumers and V2G practices.

The Early Decarbonization scenario considers that the transition to a net zero economy for Mayotte starts early in 2025 and is materialised by 2045 with ambitious policy endeavours both from demand and supply side. This scenario entails certain trade-offs: energy transition accelerates as all mitigation options are deployed more rapidly, and cumulative emissions in the projection period decline more than other decarbonization scenarios, albeit with higher energy system costs.

The MAESHAfocus scenario incorporates the MAESHA project KPIs and MAESHA solutions but does not consider the fuel switching of Longoni and Badamiers in 2030, since the MAESHA KPIs did not account for this possible development. Scrutinizing the results of the scenarios, it is evident that the ambition (in terms of projected emission reductions) of MAESHAfocus is similar to the Early_Decarb scenario, but the former entails higher energy system costs for Mayotte. This is stipulated by the fact that MAESHAfocus sets the clean transition of the transport sector very early in the decarbonization agenda, around 2040. The decarbonization of transport entails high costs to purchase low- and zero-emission vehicles for road, water, and air transport, as well as to build the required infrastructure (recharging stations, clean fuel production, etc.). The technology learning incorporated in the modelling implies that if these clean transport solutions are implemented early in the transition process (as in MAESHAfocus), they will lead to higher costs as their learning potential will not have been fully materialized by then.

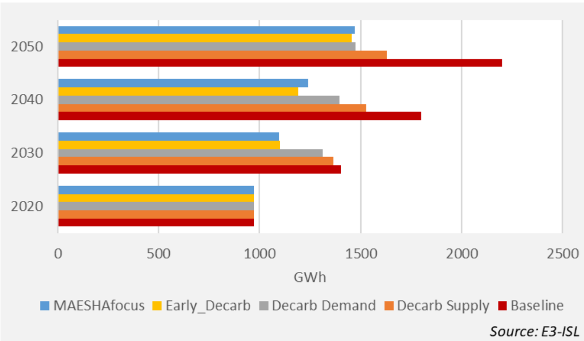

Figure 5 Final energy consumption by scenario.

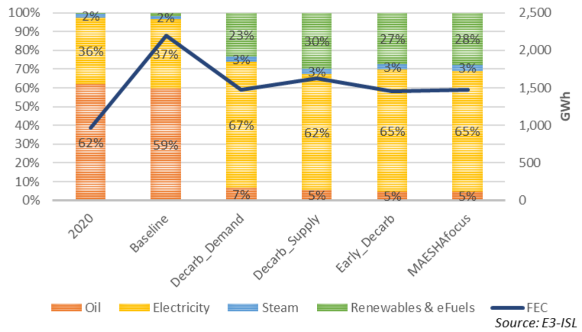

Figure 6 Final energy consumption by energy carrier and scenario.

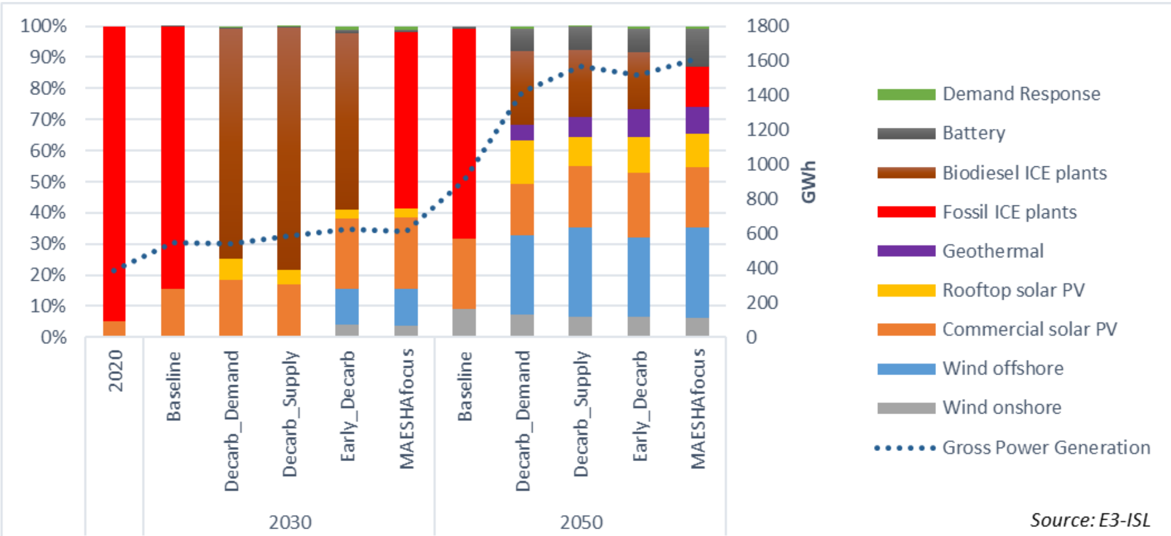

Figure 7 Gross power generation by plant type and scenario

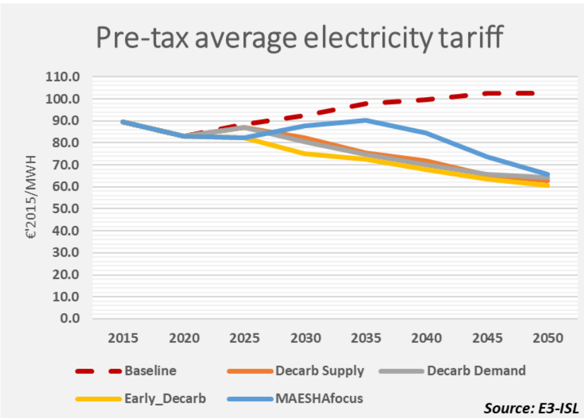

Figure 8 Pre-tax electricity tariff by scenario

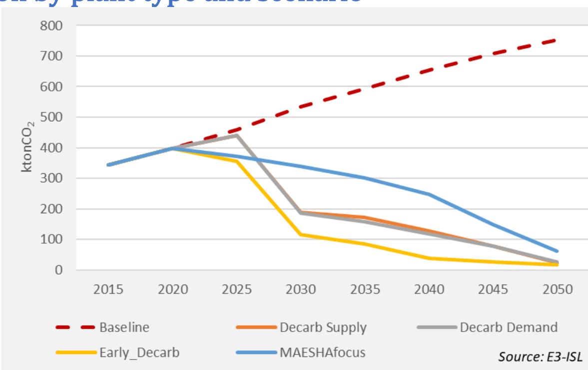

Figure 9 Emission trajectory by scenario.

3.3. Life Cycle Assessment

This section details the application of the LCA methodology (see Section 2.2 for theoretical background). First, a brief overview of the software used to model the LCA is provided (subsection 3.3.1). Subsequently, the first three of the four essential LCA phases of i) goal and scope definition, ii) inventory analysis, iii) impact assessment are detailed, while step iv) interpretation is elaborated in Chapter 4.

3.3.1. Software and Tools

The analysis was conducted according to the ISO 14040/14044 guidelines, where the environmental impact of inputs and outputs were quantified. As supporting software, the open-source LCA modeling tool OpenLCA v1.9 (GreenDelta, Germany) was used. OpenLCA offers an easy link to databases, including ecoinvent, uncertainty analysis, flexibility in parameter definition which allows for scenario simulation, visualization of system links and a separate impact assessment for each process separately. The general structure of a database established in OpenLCA to conduct an LCA exists of the following elements [43]:

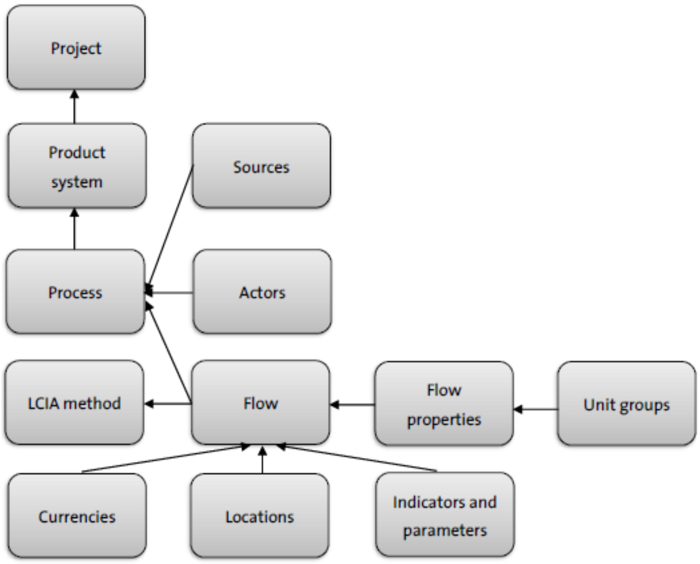

Figure 10: Database element structure and flow of information. Reprinted from [43].

- Actors: people who have provided data or modified models
- Currencies: cost can be assigned to flows and Life Cycle Costing can be performed
- Locations: important for regionalized LCA
- Sources: literature referenced
- Unit groups: groups of units (e.g. units of area include m2, ft2, sq. yd, etc.)
- Flow properties: properties of flows (e.g. length, mass, etc.)
- Flows: all product, material or energy inputs and outputs of processes in the product system under study. A flow is defined by the name, flow type, and reference flow property. OpenLCA distinguishes i) elementary flows: material or energy of the environment entering or leaving directly the product system under study, ii) product flows: material or energy exchanged between the processes of the product system under study, iii) waste flows: material or energy leaving the product system.

- Processes: production or modification of products and materials. Processes are sets of interacting activities that transform inputs into outputs. Every process is defined by an output flow as a quantitative reference with the flow type product flow.
- Impact methods: impact assessment methods imported into OpenLCA (see Subsection 3.3.4)
- Product systems: A product system contains all processes under study. The product system can consist of one process only or a network of multiple processes and is defined by the reference process. The product system is the level on which the inventory results and impact assessment is calculated.
- Projects: can be created to compare product system variants
- Indicators and parameters: social indicators, global parameters, data quality systems

A detailed user guide of OpenLCA is available online [44]. OpenLCA has proven its function in advanced LCA within the energy sector for example in assessing complex energy technologies (e.g., biomass-based power generation technologies [45]) or multi-generation and vector energy systems, e.g., [46] and residential energy systems [47])

3.3.2. Goal and Scope

Following the ISO 14040/14044 guidelines, defining the goal and the scope of an LCA study is the first step. In Section 2.2.1 the conceptual elements detailing the goal and the scope were presented on a theoretical basis. Expanding on the theoretical description, in the following, first this study's overall objective is presented, and subsequently the conceptual elements functional unit, system boundaries, cut-off criteria and the allocation process are specified for the implementation of this study.
The overall objective of this study is an in-depth environmental evaluation of explorative configurations of Mayotte's energy system in 2050. This study utilizes scenarios generated through comprehensive ESM and complements the previous scenario analysis with a holistic environmental analysis. This study's scope includes a comparison and an in-depth analysis of all energy system configuration scenarios generated by means of ESM in the MAESHA project. To conduct an LCA of the energy system configurations in 2050, all energy-consuming sectors, and both the energy supply and the energy demand side are integrated. The additional analysis dimension presented by this LCA study significantly expands the information value of the generated scenarios, as it reveals the environmental impacts of the energy system configuration beyond direct GHG emissions. In-depth environmental analysis enables the identification of drivers for environmental damages on a resource, product, process, and sector level based on full life-cycle considerations. The high-granularity environmental analysis allows a further evaluation of the energy system configurations on the one hand and an evaluation of the scenario-specific constrains and policy measures on the other hand. This study's outputs contribute to refining existing policy directives and highlighting additional focus areas in policy making.

Functional unit:
As is described in 3.2 in detail, the scope of this study covers five configuration of Mayotte's energy system in 2050, that were generated through ESM. The energy system configurations represent different energy system projections , each resulting from a different technology and policy focus and a different horizon of policy action. In consequence of the path dependent characteristic of the ESM, the final overall energy demand and type of energy requested in 2050 varies across the five scenarios modeled with E3-ISL. The type and quantity of this energy services demand is not exogenously determined and therefore not identical for all compared scenarios over the considered temporal scope. Instead, the type and quantity of energy services to be provided in each scenario results endogenously from the respective prices and price-elasticities that emerged in each respective scenario. Hence, the functional unit of this study must enable a comparison of the entire energy systems assessed with their specific energy demands, rather than constituting the provision of a fixed amount of energy. Accordingly, the function of the overall system is to satisfy all energy-based services

in Mayotte. This specifically includes demands from households, services, agriculture, industry, and transport. The goal of the LCA study is to compare different technology mixes for fulfilling this specified function. Therefore, **the FU of this study is the satisfaction of all energy services in Mayotte by 2050**. To facilitate the understanding of the results and identify trends across sectors, the impact is allocated to sectors.

System boundaries
The study applies a 'cradle to grave' approach, encompassing the extraction and processing of raw materials where available, manufacture of the components of the energy system, its operation over the lifetime, storage and use, end-of-life waste management and transportation along the whole life cycle.
The energy system under investigation has been subdivided into five sectors, whose end-use assets ultimately draw the previously sourced or produced final energy carriers: transport, industry, agriculture, services, and residential (see **Fehler! Verweisquelle konnte nicht gefunden werden.**).

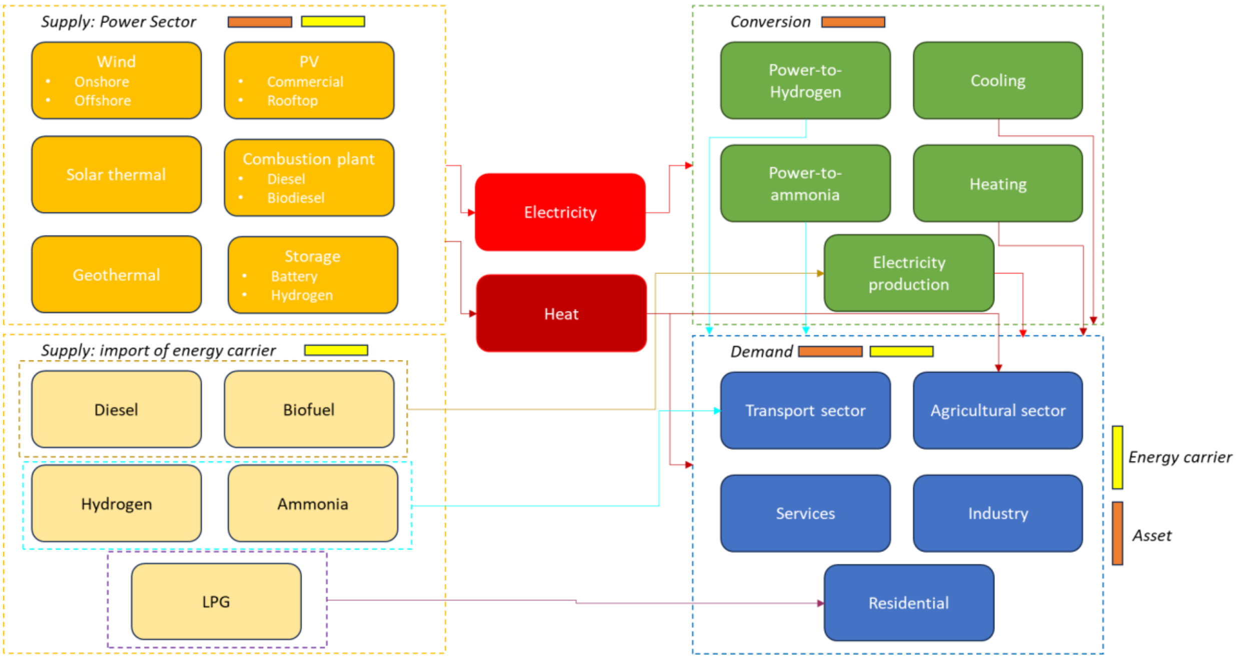

Figure 11: Sectors and end-use technologies defined within the study

Cut-off criteria and allocation process
According to the three optional allocation models within the ecoinvent system models (see Table 2 in Section 2.2.1), "*Allocation, cut-off by classification*" has been identified as the most appropriate system model for this study's context. It subdivides multi-output activities by allocation factors defined by the dataset into two or more activities, that each have just one reference product. As an attributional allocation approach, the product system relies on markets that exhibit average suppliers and conditions. By-products of EoL processes are considered part of the waste-producing system without crediting the polluter for supplying recyclable material, thus representing a *polluter pays principle*. Recyclable materials are considered burden free.

3.3.3. Inventory Analysis

In accordance with the ISO 14040/14044 guidelines, the second step in conducting an LCA is the LCI. Process data from the ecoinvent database and data derived from literature is complementing and integrated with the comprehensive outputs of the E3M model. The ecoinvent database is currently the most popularly used database for LCAs of energy systems and offers the widest geographical scope, including African countries close to Mayotte (however, no Mayotte-specific data). Other used

databases are limited in both their geographical scope and energy related processes, e.g., the NEEDS database only including Western European countries and technology scenarios from 2025 onwards, the BioEnergieDat database holding data on bioenergy for Germany only, or the JRC database including waste and transport data only.
Following the structure established by the EDM, in the following the relevant inventory for each submodule is described in detail.

3.3.3.1. Submodule Supply Side

In accordance with the structure of the ESM, 13 final distinct energy carriers are utilized in Mayotte and included in the LCA (see **Fehler! Verweisquelle konnte nicht gefunden werden.**). The final energy carriers differ in their respective place of production. While electricity, solar thermal energy, and steam is exclusively produced domestically in Mayotte, synthetic liquids, hydrogen, and ammonia, can be both produced externally and imported to Mayotte and produced locally. In this studies different distribution of locally and externally produced final energy carrier are taken into account. Fossil fuels are assumed to be imported onely due to lack of domestic resources. Due to restricted land resources biofuel is assumed to be exclusively imported. For all imported fuels the processes associated with the transportation of the fuel are included in the model.

Table 7: Place of production by final energy carriers utilized in Mayotte.

Local production	Partly Local production and external production and import	External production and import
Electricity	Synthetic liquids	Diesel
Solar thermal energy	Hydrogen	LPG
Steam	Ammonia	Gasoline
		Biofuel, conventional
		Biofuel, advanced
		Paraffin oil
		Kerosene

Locally produced final energy carriers

Electricity Supply
The electricity system of Mayotte is isolated. No connection of the electricity grid to any continental grid (e.g., Madagascar or Mozambique) exists or is foreseen. Hence, the electricity generation to satisfy the energy demand in Mayotte occurs exclusively in Mayotte. In accordance with the system structure of the ESM, the LCA model considers i) RES power plants and ii) conventional combustion power plants within the electricity generation portfolio (see **Fehler! Verweisquelle konnte nicht gefunden werden.**). The RES plants include wind onshore and offshore plants, commercial solar PV plants, rooftop solar PV plants, as well as geothermal plants. For each of these plants the electricity production process considered in the LCA model is characterized by a single asset input flow representing the construction and EoL of the corresponding plant infrastructure. The Appendix A, Table A1 and Table A2 detail the LCI of local electricity production processes, including assumption of flows, reference units, and data sources.
The ecoinvent database was consulted to represent the plant infrastructure assets for commercial solar PV, rooftop PV, wind onshore plants and geothermal plants. For modelling the production and EoL of an offshore wind turbine a new process has been created which is named "*wind offshore plant construction, 2MW*". It consists of the two ecoinvent inputs "wind power plant, 2MW offshore, fixed parts" and "wind power plant, 2MW offshore, moving parts". These input flows and their quantities

have been chosen based on the ecoinvent process "*electricity production, wind, 1-3MW turbine, offshore | electricity, high voltage | Cutoff, U – RoW*" in order to adequately model an offshore wind turbine.

The conventional power plants in Mayotte are modeled via open cycle internal combustion (IC) plants. The electricity production by means of IC plants was modeled by creating the process "*electricity production, open cycle IC plant*" which is characterized by two input flows: "open cycle IC plant, 200kW" represents the construction and EoL of the asset (analogously to the RES plants) while "*burned diesel, in open cycle IC plant*" accounts for the combustion of the previously imported diesel fuel (see *Appendix Table A3*). The upstream process of providing the IC plant flow ("*open cycle IC plant construction, 1MW*") has been created by resorting to the asset-related input flows of the ecoinvent process "*heat and power co-generation, diesel, 200kW electrical, SCR-NOx reduction | electricity, high voltage | Cutoff, U - RoW*" that represent common components for heat and electricity generation" as well as components for electricity generation. The process providing "burned diesel" ("*diesel combustion, in open cycle IC plant*") encloses diesel, lubricating oil and urea (required for exhaust gas cleaning) as inputs as well as all emission output flows associated with the diesel-based creation of 1kWh of electricity according to the ecoinvent process.

The output flows of each of the electricity production processes on Mayotte are merged in the overarching process "*electricity production@M*". The output of this process is the sum of kilowatt-hours generated by all six plant types included in the ESM and LCA tools reduced by the loss rates of high-voltage, medium- and low-voltage grid (as specified by the ESM).

In addition to the electricity production process, the construction, maintenance and EoL of the grid infrastructure in Mayotte is included in the LCA. The power grid of Mayotte is subdivided into 16 km high-voltage (90 kV), 422 km medium-voltage (20 kV), and 548 km low-voltage lines (230 V) [48,49] which have been added as three input flows to the overarching process "*electricity production@M*" in OpenLCA, applying an underlying lifetime of 40.8 years [50].

To stabilize the operation of the power grid when increasingly integrating volatile RES, battery energy storage systems are deployed in Mayotte. To model large scale battery storage, the flow "battery cell, Li-ion, NMC111", readily available in ecoinvent, was adjusted. Resorting to the energy capacity of the ecoinvent battery cell of 0.197 kWh/kg cell [51], the batteries

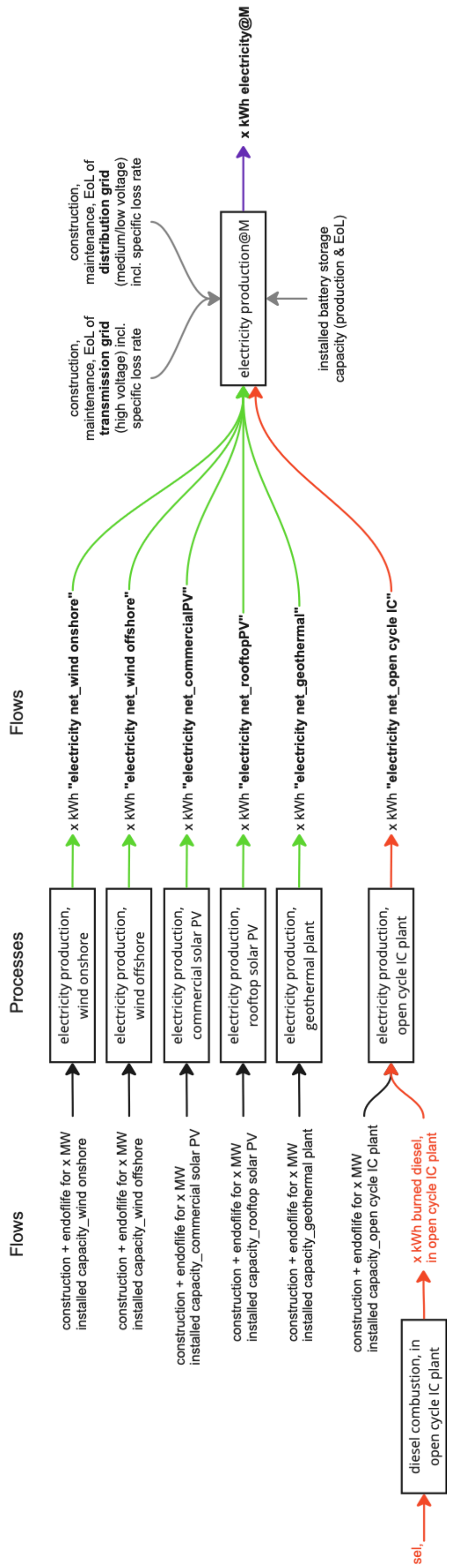

Figure 12: ***Structure of modeling the electricity supply in Mayotte.***

specified by the ESM were be expressed in kilograms to be modeled by the ecoinvent flow "battery cell, Li-ion, NMC111".
A summary of the LCI representing Mayotte's electricity production (containing RES and conventional power plants, grid infrastructure and battery storage) is presented in *Appendix table A1.*

Self-Produced Steam Supply
Steam plays a crucial role in diverse industrial applications owing to its effective capacity for storing and conveying thermal energy. Its production can be derived from a broad spectrum of energy sources, affording industries the flexibility to tailor their steam generation methods according to factors such as availability, cost-efficiency, and environmental impact. The swift and uniform heat transfer capabilities of steam render it indispensable in manufacturing processes, heating applications, mechanical systems, as well as cleaning and sterilization procedures. [52]. According to the ESM self-produced steam is required in the „Food, Drink & Tobacco industries" for thermal processes and so-called 'horizontal energy uses', which are not directly associated with an industrial process. Due to its physical properties, steam can only be produced in direct proximity to its use. Given the climatic conditions in Mayotte a local district heating network is absent. Hence, steam is exclusively produced onsite industrial facilities by diesel-fed industrial boilers.
It is noteworthy that according to the ESM the four decarb scenarios exhibit a 15-years period (from 2030 to 2045) in which diesel and biodiesel feeds are blended in the fuel mix before running entirely on biodiesel from 2045 onwards.
To model the local production of steam in OpenLCA, the process "*steam production@M*" unites the two fuel input streams of diesel and biodiesel. The ecoinvent flow "oil boiler, 100 kW" represents the installed assets (see *table Appendix A4* for the LCI). The biodiesel feed has been modeled by using the energy carrier "biofuel advanced" as a proxy.

Solar Thermal Energy Supply
Solar thermal energy operates on the principle of utilizing the sun's radiation to warm a fluid, which is subsequently employed to provide thermal energy for a range of heating applications. These energy systems generally comprise solar collectors that capture sunlight and transform it into heat, along with a heat transfer system responsible for conveying the thermal energy to its designated purpose [53].
In Mayotte, solar thermal energy is predominantly used for water heating in residential households. Increasing usage is assumed for water heating purposes in the services sector, as well as for heat generation in the industrial sectors.
Due to the absences of a district heating network in Mayotte, solar thermal energy is generated directly at the point-of-end-use. As no fuel is required, all environmental impacts associated with solar thermal energy can be attributed to the product lifecycle of the asset (i.e., the solar thermal water heater) used for the local provision of the desired heating service. A solar thermal water heater consisting of a solar collector system and an auxiliary electric heating unit are modeled to account for a solar thermal energy system.

Locally or partly externally and imported produced final energy carriers

Synthetic Liquids Supply
Synthetic fuels produced from renewable energy resources (low-carbon electricity transformed into green hydrogen and then to clean synthetic e-fuels) offer a promising solution to secure the supply of liquid fuels in airborne, maritime, and land-based transport applications that are difficult to be electrified. These fuels, derived from combining CO_2 and renewable electricity/hydrogen, have the potential to provide near-zero carbon emissions [54]. Particularly for the transportation sector, synthetic fuels are advantageous as they do not require any changes to engine design or fuel distribution infrastructure, unlike using H_2 as a final energy carrier. Therefore, synthetic fuels are the

considered a viable option for powering conventional aircrafts in the long term, as these vehicles currently rely on liquid fuels [55].

Synthetic fuels can encompass a range of substances and production methods. The Fischer-Tropsch (FT) synthesis is the main production pathway for synthetic liquid fuels which are more compatible with conventional transportation fuels than other synthetic fuels, such as methane or methanol [56]. Therefore, this study considers FT-synthesis to represent the production process for synthetic liquids supply for Mayotte in line with the ESM scenario projections.

The FT-synthesis process involves splitting CO_2 into CO via reverse water-gas shift reaction (RWGS). The CO_2 feedstock can be obtained from various sources, including flue gases, industrial byproduct CO_2, or direct air capturing (DAC). The resulting CO is then combined with (green) H_2 to form syngas, which subsequently reacts to form liquid hydrocarbons as the actual FT synthesis reaction. Ultimately the produced hydrocarbons are further upgraded to diesel/kerosene quality (see Figure 5).

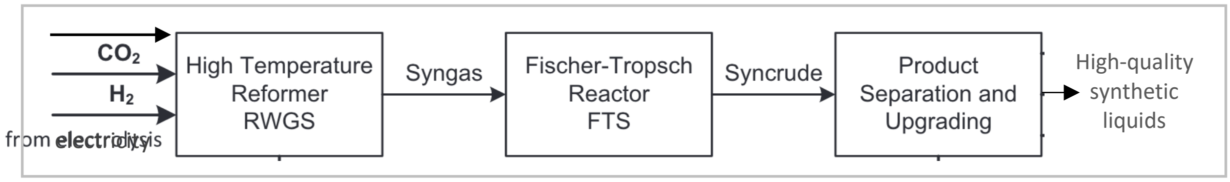

Figure 13: ***Production of synthetic liquids from CO_2 and green H_2 via Fischer-Tropsch synthesis*** **[37].**

As reported by König et al. [57], the FT-synthesis produces three distinct fuel types, namely synthetic gasoline, kerosene and diesel. However, according to the structure of the ESM, the LCA simplifies the to not differentiate between these fuel types. Instead, the term “synthetic liquids” is used as a summarizing proxy with a LHV of 43.9 MJ/kg.

Synthetic liquids production can either take place locally in Mayotte, or externally considering the import. Each production pathway consists of an upstream CO_2 production process and the main synthetic liquids production process. The LCIs for these four processes are presented in *SI Table 13* and the underlying assumptions are outlined in the following paragraphs.

Based on the flowsheet simulation results of König et al. [57], the input quantities necessary to produce 5.47 kg of synthetic liquids can be derived. This includes the required amount of CO_2, hydrogen, and electricity.

According to the ESM, the CO_2 feedstock to produce synthetic liquids is obtained through direct air capture (DAC). The process is represented in OpenLCA by a DAC system that captures CO_2 from the air using cyclic temperature–vacuum swing adsorption, as described by Deutz and Bardow [58]. Due to absence of accessible LCI data on the associated material quantities of the DAC plant infrastructure and adsorbent production, these parts have been omitted in this LCA study.

For the externally produced synthetic liquids that are imported to Mayotte, the hydrogen feed could be sourced from either grey (fossil) or green (renewable) hydrogen production. For this study, it is assumed that 100% of the imported synthetic liquids are based on a green hydrogen feed. This decision is based on the consideration that, in the baseline scenario, where no hydrogen is used in Mayotte and thus no pre-existing contractual relationships with hydrogen traders abroad exist, newly established import relationships for decarbonizing the energy system in Mayotte are likely to prioritize green hydrogen through water electrolysis. For locally produced synthetic liquids, the local electricity mix of Mayotte (year 2050) is used. To model the external production of synthetic liquids the process must rely on the global electricity mix instead of the local electricity mix. The ecoinvent database, however, reflects only the current configuration of the global electricity mix, which might not suitably represent the future configuration of the global electricity mix in 2050. For directly imported energy carriers, therefore, the scenario-specific electricity mix of Mayotte has been used as a proxy to portray a significantly decarbonized electricity mix. For other upstream processes, i.e., manufacturing of assets, the ecoinvent electricity mix as projected in 2050 (with high shares of renewable energies) is maintained.

The FT-reaction is recognized for its exothermic nature, leading to the production of excess heat [57]. However, this surplus heat can be captured and integrated into the system to lower the steam demand for the energy-intensive CO_2capturing process. Assuming the upstream DAC unit is in close proximity to the synthetic liquids production, the waste heat from FT can be employed in the DAC unit, reducing its steam requirement by 3.444MJ/kg CO_2. Consequently, there is no modeled waste heat output in both the imported and locally produced synthetic liquids, due to the reduction in steam requirements for CO_2 production via DAC.

Hydrogen Supply

Hydrogen holds great promise as a clean, renewable, and versatile energy carrier when produced from renewable energies. According to the ESM optimization, For Mayotte hydrogen plays an important role to decarbonize freight and passenger navigation as well as to power Fuel Cell Electric Vehicles (FCEV) to facilitate light- and heavy-duty transport as well as passenger mobility. Hydrogen can either be produced externally and subsequently imported to Mayotte, or it can be produced locally in Mayotte through electrolysis, see Figure 14 representing the processes within the LCA model.

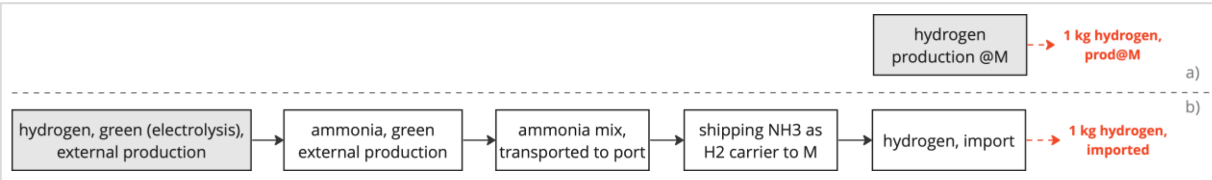

Figure 14: Process overview - Modeling a) local H2 production and b) H2 imports in OpenLCA

Today, the most common production route of hydrogen relies on natural gas to produce hydrogen via steam-methane reforming (SMR). However, alternative renewable-based methods for hydrogen production are commercially available and will be constantly improved by 2050, including water electrolysis or thermochemical water splitting. Among these, electrolysis currently shows the highest technical readiness level and market maturity and is therefore chosen as the process route to model the decarbonized *green* hydrogen production in the ESM and LCA. Since there is no suitable ecoinvent process available that represents green hydrogen production by means of electrolysis, a process ("*hydrogen production@M*") has been developed based on literature. It involves various inputs, which can be categorized into *consumables* and *assets*. The consumables include electricity and ultrapure water as feedstock, as well as cooling water. The required assets include an electrolyzer, compressors and hydrogen storage vessels, as illustrated. Figure 15 illustrates the modeled process.

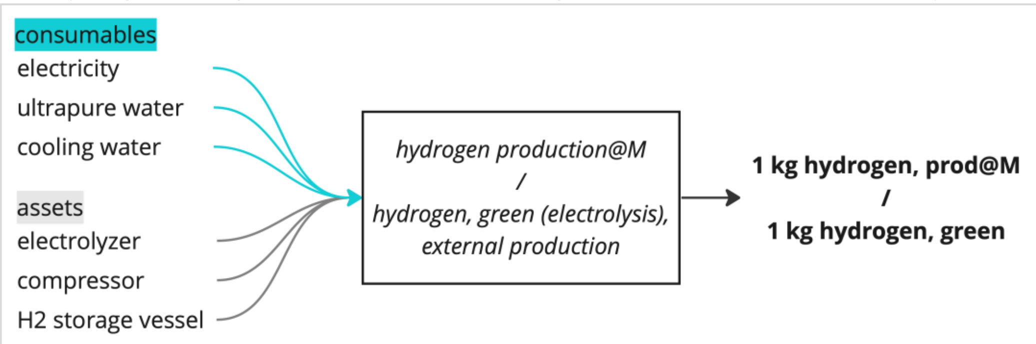

Figure 15: Inputs to model local & external green hydrogen production in OpenLCA

Bareiß et al. [59] provide a comprehensive LCI for the production of a 1MW Polymer electrolyte membrane (PEM) electrolyzer, subdividing the asset into stack ("*electrolyzer, PEM, Stack, production*") and balance of plant ("*electrolyzer, PEM, Balance of Plant, production*"). This data has been used to represent the electrolyzer in the process "hydrogen production@M" considering lifetime and installed capacity according to the ESM.

The model granularity of the ESM does not provide information on the installed capacity of compressors present in the periphery of the electrolyzers. However, Terlouw et al. [60] suggest a 300 kW compressor (represented by the ecoinvent flow "air compressor, screw-type compressor, 300kW") for each 1MW electrolyzer, which is adopted for this LCA.

To model the hydrogen storage vessels, this study adopts the assumptions of Palmer et al. [61] to represent a storage for 527 kg of hydrogen. Assuming that enough storage vessels are deployed in Mayotte to obtain the storage capacity of at least a daily production hydrogen, the quantity of hydrogen vessels per kg hydrogen produced can be derived. The input quantities for the three asset types per kilogram of hydrogen produced exhibit slight variations across the four decarbonization scenarios, based on the ESM data. To streamline the analysis and simplify the modeling process, the infrastructure quantities are assumed to follow those of the DecarbDemand (dD) scenario in all scenarios. This decision is made as the DecarbDemand scenario represents a middle-ground and cost-efficient configuration of a decarbonized Mayotte energy system, and using its infrastructure quantities across all scenarios ensures consistency and facilitates comparisons among the different decarbonization pathways.

To quantify the electricity requirements to producing 1kg of green hydrogen by means of a PEM electrolyzer, the electricity demand (directed to hydrogen production) stated by the ESM has been divided by the corresponding amount of hydrogen produced. The specific electricity demand of ~45.7 kWh/kg H_2 of the decarb demand scenario serves as an approximation for all scenarios, which is a logical assumption as the same electrolysis method is used in all scenarios developed by E3-ISL.

Moreover, the required quantities of cooling water and ultrapure water as feedstock for the production of green hydrogen are obtained from Terlouw et al. [60]. Fugitive emissions are neglected. *Table A2.1* summarizes the LCIs to model the local hydrogen production.

To model the external production of green hydrogen the process "*hydrogen production@M*" the global electricity mix was approximated with the scenario-specific electricity mix by 2050, representing a significantly decarbonized electricity mix.

As it is impractical to transport gaseous hydrogen via ship over long distances, given the low energy density, the conversion of hydrogen to ammonia and shipping in liquid form was considered [62]. At the point-of-destination, ammonia is considered to be reconverted into hydrogen via ammonia cracking. Shipping liquid ammonia is a well-established practice and currently fossil-derived liquid ammonia is transported in large quantities with tankers at either -33°C under atmospheric pressure or at 25°C at 10bar [62]. However, cracking ammonia is currently not available at scale. As first large-scale ammonia crackers are expected to be market mature in the late 2020s, the process can be considered commercially available and cost-effective in 2050. Analogous to synthetic fuels and hydrogen, only green ammonia is chosen as the energy carrier in line with the ESM model, considering the decarb scenarios' prioritization of greenhouse gas emissions reduction and the absence of pre-existing contractual relationships with ammonia producers abroad in the baseline scenario.

The external production of green ammonia and the subsequent transport from the external production sites to the exporting port have been modeled according to the rationale explained in the following subsection *Ammonia Supply*. The subsequent process *"shipping NH3 as H2 carrier to M"* models the shipping of liquid ammonia to Mayotte by ship, with an assumed average distance of 6,000 km. The electricity required to refrigerate the ammonia to -33°C under atmospheric pressure to maintain its liquid state has been accounted for in the process by assuming the global electricity mix. It is important to note that the use of imported hydrogen as a feedstock for local ammonia production in Mayotte is not considered, as it would involve importing hydrogen in the form of ammonia, only to convert it back to hydrogen and then re-synthesize ammonia. Consequently, all imported hydrogen is used exclusively in vehicles. To ensure rapid and efficient refueling, the hydrogen must be compressed up to 880bar [63]. Both the ammonia cracking and compression to 880bar have been accounted for in the final process "*hydrogen, import*".

SI Table 11 provides the LCIs to model the import pathway of externally produced hydrogen to Mayotte.

Ammonia Supply

Ammonia, a versatile compound, finds application as a reagent across various industries, including agriculture and chemicals. Recently, it has garnered attention for its potential as an energy carrier due to its high energy density, as well as its ease of storage and transport [64].

In the context of Mayotte, ammonia assumes a crucial role in the effort to decarbonize both freight and passenger navigation and aviation. Additionally, it serves as a pivotal intermediary, enabling the long-distance import of externally produced hydrogen to the region. The production of ammonia, accomplished through the Haber-Bosch (HB) process, has been in widespread use since the early 1900s. This process entails the reaction of nitrogen and hydrogen over an iron-based catalyst under high pressure and temperature conditions. Depending on whether grey or green hydrogen is utilized as the feedstock and fuel for the HB synthesis reaction, the resulting ammonia is categorized as either grey or green, respectively.

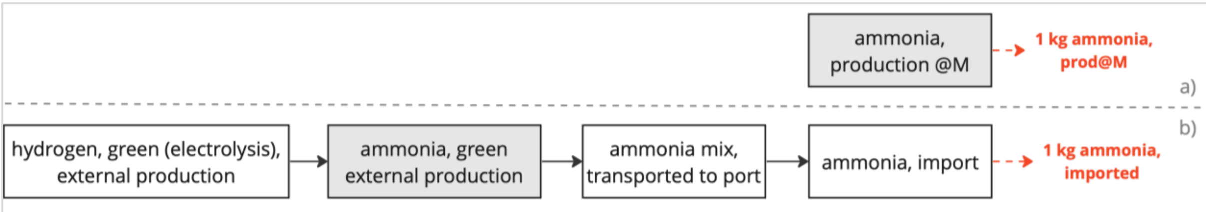

Figure 16: Process overview - Modeling a) local NH3 production and b) NH3 imports in OpenLCA

The local production of ammonia in Mayotte is facilitated via the HB synthesis reaction using solely locally produced green hydrogen as feedstock. No imported hydrogen is used as feedstock for local ammonia production in Mayotte, as imported hydrogen arrives in Mayotte in the form of ammonia for ease of transport. Hence, double reconversion is avoided for efficiency and cost reasons (see previous subsection *Hydrogen Supply*).

The underlying boundary of the process "*ammonia, production@M*" entails the actual HB-synthesis reaction starting at a readily available hydrogen feed, since the production of hydrogen is modeled separately in OpenLCA for a more modular, disaggregated allocation of impacts. As there is no suitable ecoinvent process available that covers the HB synthesis reaction based on green hydrogen, the process "*ammonia, production@M*" has been created based on literature. The required inputs are categorized into *consumables* and *assets*. The consumables include the hydrogen and nitrogen feed for the chemical reaction to form ammonia, as well as electricity and cooling water (losses) to generate favorable process conditions for the reaction (see Figure 17). While the required input amounts of hydrogen and nitrogen per kilogram green ammonia have been obtained from Singh et al. [65], cooling water losses are adopted according to Ghavam et al. [66].

Electricity is mainly needed for compressors that carry out three different compression tasks – facilitating the final ammonia separation by condensation, generating the high pressure for the actual ammonia synthesis reaction and driving the continuous synthesis loop [67]. The ESM specifies the electricity demand of a comprehensive "power to ammonia" plant, which includes the HB synthesis reaction and the upstream hydrogen production. To avoid double-counting and enable a more granular impact analysis, the LCA study applies a disaggregated process view which models hydrogen production as separated from the ammonia production process (represented by the HB ammonia synthesis reaction). Therefore, the electricity amount specified by the ESM, must be adjusted to solely consider the electricity required by plant infrastructure present in the HB ammonia synthesis reaction (without hydrogen production that is modelled seperately). The only electricity demand of the HB synthesis reaction stems from the HB compressors that carry out the three aforementioned compression tasks.

Verleysen et al. [67] describe the electricity consuming plant infrastructure of a comprehensive green ammonia production system to consist of an electrolyzer, a Pressure Swing Adsorption unit (to obtain nitrogen from the air) and HB compressors. They consume 91-95%, 0.9-1.6% and 3.4-8.1% of the total electricity demand of the comprehensive ammonia plant, respectively. Based on that, the specific electricity requirement for the HB synthesis reaction can be derived (see *Table A2.3*).
The electricity intensity per kg of ammonia produced varies only marginally across the four decarbonization scenarios, as per the ESM (see *Table A2.3*). For simplicity and consistency, the electricity intensity of the decarbDemand scenario is applied to all scenarios, as it represents a middle-ground and cost-efficient configuration of the decarbonized energy system of Mayotte.
According to the ESM the "power to ammonia" plant requires approximately 62 GWh to produce around 6,600 tons of ammonia in 2050. Therefore, the electricity demand of the aggregated ammonia plant (incl. H_2 production) is about 9.3 kWh/kg NH_3. Assuming a 5.75% electricity share (the mean of 3.4-8.1% [67]), around 0.54kWh/kg NH_3 is required by the disaggregated ammonia plant (excl. H_2 production).
While fugitive emissions of the process are negligible [65] and therefore have not been included in the model, the considerable heat creation (2.7 GJ/t NH_3) due to the exothermic nature of the ammonia synthesis reaction has been accounted for by means of the ecoinvent flow "heat, waste (emission to water, unspecified)" as it cannot be purposefully integrated within the process [68].
The modeling of the HB ammonia plant (excl. H_2 production) in OpenLCA includes the following plant infrastructure assets: ammonia synthesis reactor, condensers, HB compressors and ammonia storage vessels. The condensers are needed to separate ammonia from excess nitrogen and hydrogen by refrigerating the gas mixture until the condensation point of ammonia is reached. According to AMMPower [69], the foundation area for the upstream electrolysis (233 m^2) is nearly identical to that for the ammonia synthesis reaction (232 m^2), with ammonia storage excluded from this area. Assuming that the space is utilized similarly for both hydrogen production and ammonia synthesis in terms of equipment density and material composition, it is reasonable to consider the area as an indicator for related impacts of the assets. As a result, the electrolyzer and compressor used in the process *"hydrogen, production@M"* serve as a proxy to represent the ammonia synthesis reactor, condenser and compressors while the ammonia storage vessel is modeled by resorting to the 83m^3 hydrogen storage tank of Palmer et al. [61] as a proxy. The quantification of plant infrastructure inputs is documented in *Appendix Table A2.3* while *Appendix Table A2.5* presents the detailed LCI to model the local ammonia production in OpenLCA.

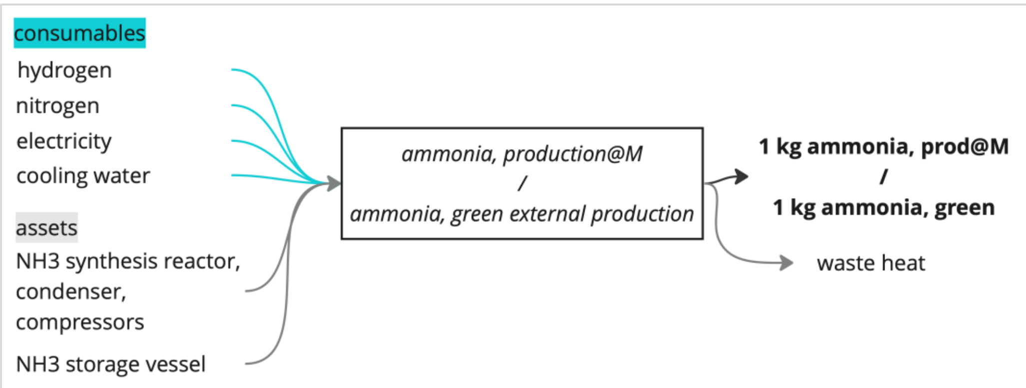

Figure 17: Inputs to model local & external green ammonia production in OpenLCA

Figure 16b presents the schematic process design for modeling the import pathway of externally produced green ammonia to Mayotte in OpenLCA. To model the external production of green ammonia the local production process "*ammonia production@M*" has been adapted by changing the hydrogen feedstock to green hydrogen provided by the process "*hydrogen, green (electrolysis), external production*" (see previous subsection "Hydrogen Supply"). Analogous to hydrogen production, the scenario-specific electricity mix of Mayotte in 2050 has been used as a proxy to portray a significantly decarbonized electricity mix. The resulting process is called "*ammonia, green external production*" (see Figure 17).

The process "*ammonia mix, transported to port*" merges all streams of green ammonia from different external production sites including transportation to the exporting port (see Figure 16).

The transport and import of liquid ammonia by ship, including the electricity requirement for a continuous refrigeration on board the ship [70], is covered by the consecutive process "*ammonia, import*" which assumes an average import distance of 6,000 km. Electricity required to refrigerate the ammonia to -33°C under atmospheric pressure to maintain its liquid state has been accounted for in the process by assuming the Mayotte-specific electricity mix. A summary of the LCIs to model ammonia imports in OpenLCA are shown in *Appendix Table 2.4*.

Externally produced Final Energy Carriers

The final energy carriers diesel, LPG, gasoline, biofuel conventional, biofuel advanced, paraffin oil and kerosene are solely produced externally and subsequently imported to Mayotte, since no local production is foreseen due to limited resources. Apart from biofuel (which requires a more detailed analysis), all final energy carriers have been modeled assuming corresponding ecoinvent production processes, which are extended by an additional input flow to account for the transportation process through tankers involved in importing the energy carriers to Mayotte.

Appendix Table A3.1 summarizes this rationale and presents the assumed import distances, means of transport and the newly created overarching import processes that have been created in OpenLCA to consolidate both external production and transportation to facilitate the import of each of the respective final energy carriers. The LCIs for the supply of each of those final energy carriers are presented in *Appendix Table A3.2*.

Due to lack of information on the exact countries of origin of each fossil fuel that is imported to Mayotte, the top partner countries for fuel imports to Madagascar in 2020 have been considered, which are the United Arab Emirates and Saudi Arabia [71]. The mean distance from Port of Mina Jabal Ali (United Arab Emirates) or King Abdul Aziz Port (Saudi Arabia) to Port of Mayotte has been approximated to be 6.000 km based on geographical information. The modeling of biofuel has been based on a more complex rationale, which is explained in the following paragraph.

Biofuel Supply

Bioethanol has emerged as a promising and sustainable alternative to conventional fossil fuels. It is produced through the fermentation of starchy biomass using the yeast Saccharomyces cerevisiae [72]. The resulting biofuel can be categorized into two main types based on the source of the starchy biomass used: first-generation biofuel, derived from edible energy crops (referred to as "conventional biofuel" in this study), and second-generation biofuel, derived from lignocellulosic substrates (referred to as "advanced biofuel" in this study). Initially, first-generation biofuels derived from edible energy crops like sugar-based crops (such as sugarcane, sugar beet, sorghum), starch-based crops (like corn, wheat, barley), or oil-based crops (such as rapeseed, sunflower, canola) showed promise in reducing reliance on conventional fossil fuels and decreasing greenhouse gas emissions [73]. However, with the emerging fuel-versus-food debate and the resulting sustainability issues (e.g. increased emissions due to land use changes), first-generation biofuels have been criticized for potentially jeopardizing food security, and competing for arable land [74]. Therefore, second-generation biofuels are regarded as the more sustainable alternative because their feedstock is lignocellulosic-based biomass that is abundant, inexpensive, and typically consists of non-edible plants creating no competition with food supply [75].

To model the import of biofuel, first the production of bioethanol via fermentation to achieve a 95% solution state using the ecoinvent process *"market for ethanol, without water, in 95% solution state, from fermentation | ethanol, without water, in 95% solution state, from fermentation | Cutoff, U"* was consulted. This process describes bioethanol production from various biomass sources such as maize,

sugar beet, wood and grass. To produce conventional biofuel, only the biomass sources derived from edible energy crops have been used to create the process *"bioethanol conventional, fermentation to 95% solution state"* in OpenLCA. The remaining lignocellulosic biomass sources have been selected to represent advanced biofuel, thus creating the process *"bioethanol advanced, fermentation to 95% solution state"* in OpenLCA.
Both biofuel streams undergo a subsequent dewatering step from 95% to 99.7% solution state. Since biofuel is not produced locally in Mayotte, but only imported, a final import process using a shipping for petroleum over an average distance of 6,000 km to reach Mayotte is used, which is a very conservative estimation assuming that nearby countries eventually would not facilitate sustainable production of biomass by 2050. Both the dewatering and the import are included in the newly created processes "*biofuel conventional, import*" and "*biofuel advanced, import*" in OpenLCA (see *Appendix Table A3.3* for the LCIs).

3.3.3.2. Submodule Demand Side

The LCA adopts the structure of the ESM to model the demand-side of the energy system in Mayotte. The ESM establishes a concise hierarchical structure, in which detailed demand processes (LEVEL1 demand processes) can be clustered by demand in 14 subsectors (LEVEL2 demand processes), which again can be clustered into LEVEL3 demand processes, which finally are summarized under the five sectors agriculture, industry, transport, households and services (LEVEL4 demand processes), see **Fehler! Verweisquelle konnte nicht gefunden werden.**. This overarching process collects the most downstream unitless reference products of the five sectors agriculture, industry, transport, households and services. Each of the lowest level demand processes (LEVEL1 demand processes) has a unitless reference product to represent the respective energy service being fulfilled to satisfy the demand. For instance, the LEVEL1 demand process "*1_AGR_LIGHT*" which models the lighting use in the agricultural sector, entails the unitless output "AGR_LIGHT" to represent the provision of this energy service. Ultimately, the process "*entireSystem*" is modeled in OpenLCA. By means of the process "*entireSystem*" all other processes are linked to form one single product system that is subsequently processed in OpenLCA to quantify the related environmental impacts (see LCIA phase in section 3.3.34). In the following, a detailed description of the LEVEL1 demand process modeling is provided.

The demand side uses the final energy carriers (see section 3.3.3.1) as inputs, thereby linking supply and demand side in OpenLCA. The LEVEL1 demand processes differ in such processes that require energy carriers that can directly be used without any transformation – i.e., electricity, solar thermal energy, steam – and such processes that demand energy carriers to be combusted (or in the case of hydrogen reconverted into electricity by means of a fuel cell). Figure 19 illustrates this essential conceptual difference.
However, each of the LEVEL1 demand processes require two distinct inputs; i) a final energy carrier (to be either combusted or used directly) and ii) an asset to represent the end-use technology in which this final energy carrier is ultimately used.
In the first case (see *Figure 18*) of LEVEL1 demand processes with a final energy carrier to be used directly (e.g., the process *"1_HOU_LIGHT"* representing the provision of lighting in households) the final energy carrier (here "electricity@M") can be used directly as an input without any modifications. The impacts related to the production of this energy carrier have already been accounted for in the upstream production processes of the supply side. For instance, no additional emissions are released when using electricity for residential lighting that have not already been accounted for when modeling the respective power plant. In addition to simply using the final energy carrier as provided by the supply side, the second required input for modeling such a LEVEL1 demand process is the asset in which the conversion of the final energy carrier ultimately takes place (here "LED, 19W"). Through this approach the entire product lifecycle of the respective end-use technology is accounted for.

In the second case (see *Figure 19*), when modeling the LEVEL1 demand process of an energy carrier to be combusted (e.g., the process *“1_HOU_COOKS”* representing residential cooking by means of LPG stoves) the final energy carrier provided by the supply side (here “LPG, imported”) requires addition transforming being used. In fact, it is necessary to model the combustion of each final energy carrier depending on the specific end-use technology in which the combustion takes place, as burning the same final energy carrier in two different assets may essentially result in two different emission profiles. Therefore, processes (e.g., *“LPG combustion, in stove”*) have been created in OpenLCA that serve as inputs for the respective LEVEL1 processes (in this example *“LPG combustion, in stove”* is the input for the LEVEL1 demand process *“1_HOU_COOKS”*. Analogous to the previous case, the second required input for modeling such a LEVEL1 demand process constitutes the asset in which the combustion of the final energy carrier ultimately takes place (here “gas stove”).

In the following two subsections the modeling of the required end-use assets as well as the combustion processes of final energy carriers in each specific end-use technology is described in detail.

Table 8: Overview of demand processes and clustering.

	LEVEL4 demand processes	LEVEL3 demand processes	LEVEL2 demand processes	LEVEL1 demand processes	
Process Name in openLCA	**Process Name in openLCA**	**Process Name in openLCA**	**Process Name in openLCA**	**Process Name in openLCA**	**Description**
entireSystem			2_Agriculture	1_AGR_ELC	Agriculture - Electric uses
				1_AGR_HEATB	Agriculture - Heating - Boilers
				1_AGR_HEATE	Agriculture - Heating - Electric
				1_AGR_LIGHT	Agriculture - Lighting
				1_AGR_PMOTD	Agriculture - Pumping & motors - Diesel
				1_AGR_PMOTE	Agriculture - Pumping & motors - Electricity
		3_Industry	2_Food_Drink_ Tobacco	1_FDDRTB_ELSP	Food, Drink & Tobacco - Horizontal energy uses - Specific electricity use
				1_FDDRTB_HT	Food, Drink & Tobacco - Horizontal energy uses - Heat uses
				1_FDDRTB_THP	Food, Drink & Tobacco - Thermal processing
	4_Transport	3_Freight Transport	2_Road Freight Transport_Heavy	1_FRHDT_DSL	Road Freight Transport - Heavy duty vehicles - ICE - Diesel
				1_FRHDT_ELE	Road Freight Transport - Heavy duty vehicles - Electric
				1_FRHDT_H2	Road Freight Transport - Heavy duty vehicles - Fuel cell
			2_Road Freight Transport_Light	1_FRLDT_DSL	Road Freight Transport - Light duty vehicles - ICE - Diesel
				1_FRLDT_ELE	Road Freight Transport - Light duty vehicles - Electric
				1_FRLDT_GSL	Road Freight Transport - Light duty vehicles - ICE - Gasoline
				1_FRLDT_H2	Road Freight Transport - Light duty vehicles - Fuel cell
				1_FRLDT_PHEVDSL	Road Freight Transport - Light duty vehicles - Plug-in Hybrid - Diesel
				1_FRLDT_PHEVGSL	Road Freight Transport - Light duty vehicles - Plug-in Hybrid - Gasoline
			2_Inland Freight Navigation	1_FRWTR_ELE	Inland Freight navigation - Electric - Electric
				1_FRWTR_H2	Inland Freight navigation - Electric - Fuel cell
				1_FRWTR_OIL	Inland Freight navigation - Oil
			2_Households	1_HOU_AIRC	Households - Thermal Uses - Air Conditioning
				1_HOU_BAP	Households - Black Appliances
				1_HOU_COOKE	Households - Thermal Uses - Cooking - Electricity
				1_HOU_COOKS	Households - Thermal Uses - Cooking - Stoves
				1_HOU_LIGHT	Households - Lighting
				1_HOU_WAP	Households -White Appliances
				1_HOU_WTHE	Households - Thermal Uses - Water Heating - Electricity
				1_HOU_WTHR	Households - Thermal Uses - Water Heating - RES
		3_Industry	2_NonEnergy_ Industry	1_NONEN_NE	Non energy uses in industry
			2_Other Industries	1_OTHR_ELSP	Other Industries - Horizontal energy uses - Specific electricity use
				1_OTHR_HT	Other Industries - Horizontal energy uses - Heat uses
				1_OTHR_THP	Other Industries - Thermal processing
	4_Transport	3_Passenger_ Transport	2_PrivatePassenger_ 2wheelers	1_PS2WL_ELE	Private passenger transport - 2wheelers - Electric
				1_PS2WL_GSL	Private passenger transport - 2wheelers - Gasoline
			2_Aviation	1_PSAIR_KERO	Aviation - Kerosene
			2_PrivatePassenger_ Cars	1_PSCAR_DSL	Private passenger transport - Private passenger cars - ICE - Diesel
				1_PSCAR_ELE	Private passenger transport - Private passenger cars - Electric
				1_PSCAR_GSL	Private passenger transport - Private passenger cars - ICE - Gasoline
				1_PSCAR_H2	Private passenger transport - Private passenger cars - Fuel cell
				1_PSCAR_PHEVDSL	Private passenger transport - Private passenger cars - Plug-in Hybrid - Diesel
				1_PSCAR_PHEVGSL	Private passenger transport - Private passenger cars - Plug-in Hybrid - Gasoline
			2_PublicPassenger	1_PSPRD_DSL	Public passenger transport - Road - ICE - Diesel
				1_PSPRD_ELE	Public passenger transport - Road - Electric
				1_PSPRD_H2	Public passenger transport - Road - Fuel cell
			2_InlandPassenger_ Navigation	1_PSWTR_ELE	Inland Passenger navigation - Electric - Electric
				1_PSWTR_H2	Inland Passenger navigation - Electric - Fuel cell
				1_PSWTR_OIL	Inland Passenger navigation - Oil
			2_Services	1_SER_AIRC	Services - Air cooling
				1_SER_ELC	Services - Electric uses
				1_SER_LIGHT	Services - Lighting
				1_SER_WHCE	Services - Water-heating & Cooking - Electricity
				1_SER_WHCR	Services - Water-heating & Cooking - RES

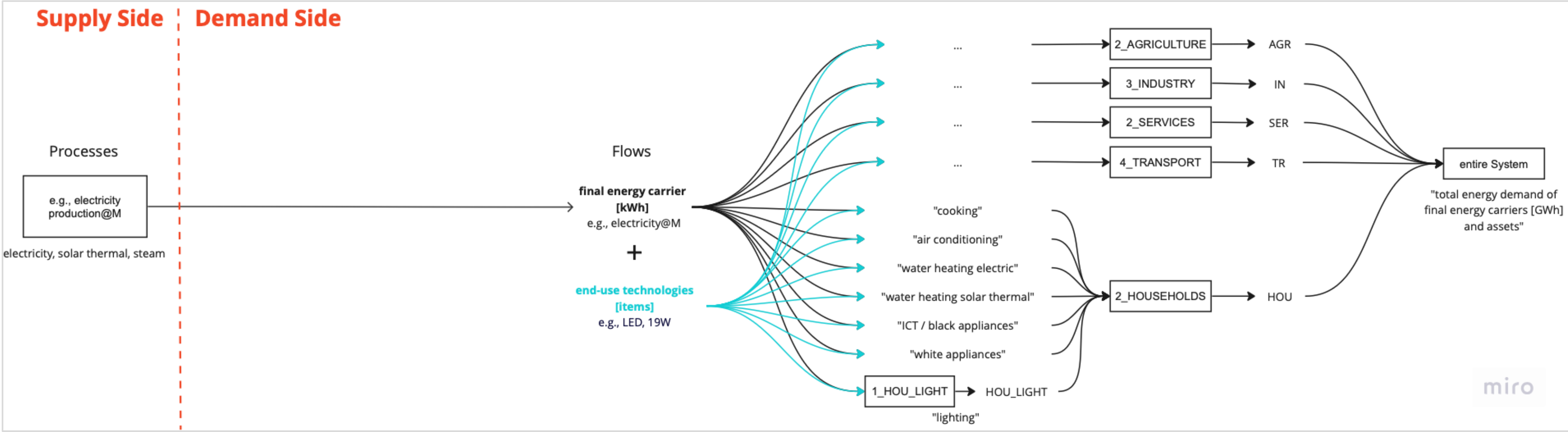

Figure 18: Conceptual design – Demand side for energy carriers to be used directly.

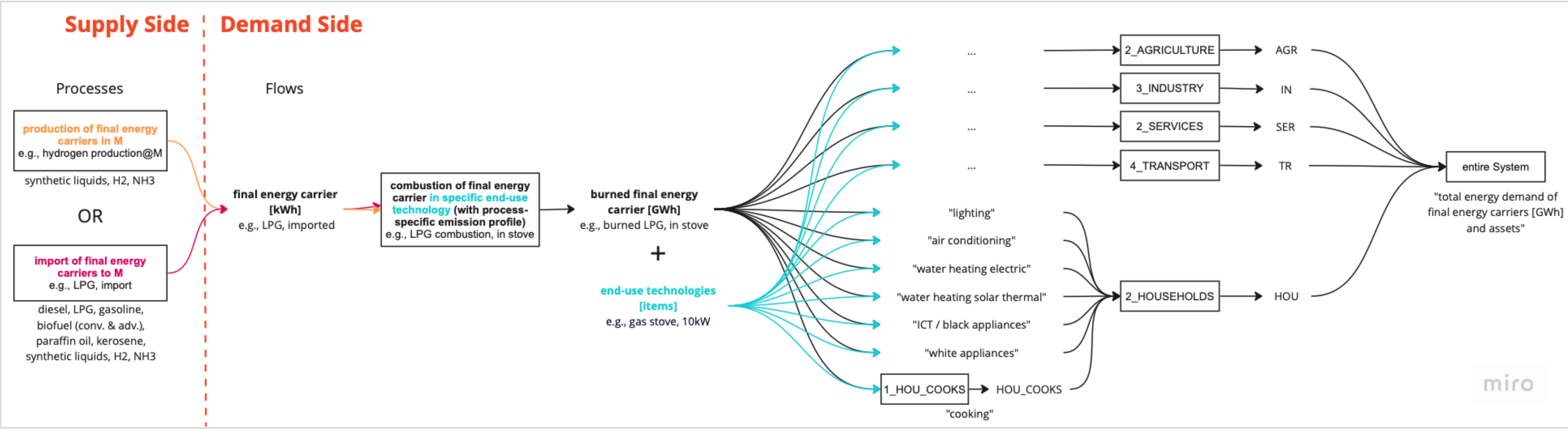

Figure 19: Conceptual design – Demand side for energy carriers to be combusted or converted by the means of a fuel cell in case of hydrogen.

Modeling the Production of end-use Assets

To model the assets of final energy use (e.g., vehicles, appliance, industrial equipments) which are present in Mayotte by 2050 according to the results of the ESM, all assets are discounted over their respective lifespan, which can exceed the considered temporal scope of 2050. This approach allows for an accurate representation of the assets allocated specifically to the year 2050. The assumed lifetimes for each end-use asset are presented in *Appendix Table A4.14*.

The majority of LEVEL1 demand processes can be accounted as vehicles (27/53). Hence, a tailored rationale to coherently model the product lifecycle of these vehicles has been developed which is presented in the following subsection, while the remaining assets are rather singular and their representation in OpenLCA is described in the succeeding subsection.

Vehicles

When modeling vehicles, both the vehicle cycle (the production of the vehicle itself and its components) and the fuel cycle (the combustion/conversion of fuel/electricity to drive the vehicle) are investigated. In accordance with the ESM, four distinct drive type technologies have been modeled in OpenLCA: i) vehicles equipped with an internal combustion engine (ICE), ii) Plug-in Hybrid Electric Vehicles (PHEV), iii) Battery Electric Vehicles (BEV) and iv) Fuel Cell Electric Vehicles (FCEV). To model the vehicle cycle this study simplifies to not differentiate between diesel and gasoline ICE vehicles as well as between diesel and gasoline PHEVs.

According to the structure of the ESM each of the different drive types can be embedded in four different vehicle categories: passenger cars, light duty vehicles, heavy duty vehicles or public busses – with the restriction that PHEV vehicles are only passenger cars or light duty vehicles. The net weight of each drive technology embedded in a passenger car has been determined according to Bauer et al., 2015 [76], while the net weights of light and heavy duty vehicles and public busses have been assumed to be 2,500 kg, 10,000 kg and 11,000 kg respectively. Moreover, Bauer et al. present a detailed analysis of the relative contributions of the key components in a passenger car for each drive technology. The relative weight of each component of a passenger car is assumed to remain constant and therefore can be scaled up to fit the net weight of the other vehicle categories. Adequate product flows to model each drive technology (by combining different key components) are available within the ecoinvent database. *Appendix Table A4.1* presents the overarching rationale and quantification of component flows to model the vehicles.

To exemplify this procedure, the modeling of a BEV is described: According to Bauer et al. [76], a BEV consists of 21 weight percent “battery” and 79 weight percent “glider/ transmission/ electric motor”. Modeling a *passenger* BEV with a total weight of 1,800kg results in 383kg of the ecoinvent flow "battery cell Li-ion NMC 111" and 1,417kg of the ecoinvent flow "passenger car, electric, without battery". To model a *light duty* BEV, the quantities of the two components are scaled up linearly to a total weight of 2,500 kg.

However, no suitable processes have been found to model the hydrogen tank and fuel cell of a FCEV. Therefore, the hydrogen tank has been modeled by using the hydrogen storage vessel described in Palmer et al. [61] as a proxy, while being in accordance with the weight in kg according to Bauer et al [76].

The fuel cell has been modeled based on the LCI provided in the supplementary material of Simons et al. [77], who adopt a 1kW-fuel cell as the functional unit to subsequently model a passenger vehicle’s fuel cell with an average power output of 45kW. The weight of a FCEV’s fuel cell is assumed to be 156kg [76]. Scaling the figures accordingly enables modeling the hydrogen tank and fuel cell for light-duty, heavy-duty, and public bus FCEVs by adapting the weight of both components to match each vehicle’s absolute weight.

To model heavy duty ICE vehicles, public busses with ICE, aviation, and two-wheelers with ICE suitable ecoinvent processes (indicated by the provider uuid in *Appendix Table A4.1*) are applied. Due to limited availability of LCI data, all inland freight navigation drive types have been modeled using the ecoinvent production process of a conventional ICE barge as a proxy. For the same reason, the inland

passenger navigation drives have been modeled via the ecoinvent production process of a conventional ICE ferry.
Finally, each set of vehicle category and drive technology is modeled as a process with the reference flow of "1 Item". This is necessary to subsequently link each process to the number of vehicles present in Mayotte, as stated by the ESM. The detailed LCIs of all vehicles which do not rely on an unaltered ecoinvent process are presented in *Appendix Table A4.2*.

Other Assets/Energy-related equipment

The **air conditioner** is modeled based on literature, as no appropriate ecoinvent process is available. A Window air conditioner with an equivalent power of 5.28kW and a weight of 55kg (10.42kg per 1kW accordingly) is taken as reference [78]. Almutairi et al. [78] specify the relative weight of each material component of the air conditioner. Subsequently, the absolute weight of each material can be determined to model the 1 kW air conditioner. Additionally, Almutairi et al. specify that 1.6kg of refrigerant is required for the air conditioning unit, represented in OpenLCA by HFC-134a (1,1,1,2-tetrafluoroethane). Moreover, the manufacturing process requires 19.7MJ of electricity per kilogram of air conditioner. The LCI of the 1kW air conditioner is presented in *SI Table 16*.
The assets related to lighting needs (required in services, agriculture and households) are modeled by using a **19-watt LED** downlight luminaire as a proxy. Since there is no suitable process available in ecoinvent, the production of a 19-watt LED has been modeled based on Tähkämö et al. [79]. The detailed LCI is shown in Appendix t*able A4.3*.
The production of the assets for **electric water heating** in the sectors services, agriculture and households are modeled by using the ecoinvent process "*auxiliary heating unit production, electric, 5kW | auxiliary heating unit, electric, 5kW | Cutoff, U – RoW*" as a proxy.
Another option for water heating in the residential and services sector entails using a **solar thermal water heater**, consisting of solar collectors and the necessary periphery (e.g., heat exchangers, storage tank, and circulation pump) as well as an auxiliary electric heating unit to ensure hot water supply also when no solar heat can be generated during nighttime or cloudy weather. The ecoinvent process "*heat production, at hot water tank, solar+electric, flat plate, multiple dwelling | heat, solar+electric, multiple-dwelling, for hot water | Cutoff, U*" consists of two assets: an "auxiliary heating unit, electric, 5kW" as well as a "solar collector system, Cu flat plate collector, multiple dwelling, hot water" which has no wattage stated explicitely. However, it is plausible to assume that both units have the same wattage, since both assets are used together as complementary options to ensure uninterrupted hot water supply. Subsequently, the process "*solar thermal water heater production*" has been created in OpenLCA consisting in equal parts of the auxiliary electric heating unit and the solar thermal heater (see Appendix t*able A4.4* for LCI).
Agricultural pumping and motor requirements are modeled by using the ecoinvent process "*water pump production, 22kW | water pump, 22kW | Cutoff, U*" as a proxy. According to the ecoinvent process description the characteristics of the pump correspond to an average pump used for agricultural irrigation: the total mass of the pump is 300 kg and the engine's nominal power is 22 kW. This pump is commonly used in ecoinvent to model both electric pumps as well as diesel-driven pumps. Therefore, it will serve also in this study as the chosen asset to represent both pump technologies.
The ESM specifies the category "**Horizontal Energy Uses - Heat Uses**" to be deployed in the two industrial branches "Food, Drink & Tobacco" as well as in "Other Industries". According to the ESM this heat provision can be based on a wide range of energy sources: LPG, gasoline, diesel, solar thermal, electricity, self-produced steam, and synthetic liquids. Determining an appropriate asset to represent this diverse set of technologies is a challenge. To address this issue, the 100-kW oil boiler specified in the ecoinvent process "*oil boiler production, 100 kW | oil boiler, 100 kW | Cutoff, U – RoW*" has been selected as a proxy.
The category "**White Appliances**" encompasses a bundle of household appliances, such as washing machines, refrigerators, and dishwashers. To model this category, a representative unit has been

created by using a weighted average of 1/3 of the three ecoinvent product flows of a washing machine, a refrigerator, and a dishwasher. The LCI of the production of such a representative unit of white appliances is presented in *Appendix A4.6*.
The category "**Black Appliances**" encompasses all information and communication technology (ICT) related household devices. To represent this category, a composite product flow "Black Appliance" has been created in OpenLCA. This is the reference flow of the newly created process "Black Appliance Production," which consists of 50% generic laptop, radio, TV users (represented by one *laptop* and one *internet access equipment*) and 50% generic computer users (represented by one *desktop computer without a screen*, one *17-inch liquid crystal display*, and one *internet access equipment*). The LCI is shown in *Appendix Table A4.7*.
Electric stoves and gas stoves have been modeled based on literature. Landi et al. [80] present an LCI for the manufacturing of a gas oven and an electric oven.
To determine the average weight in kg as well as the average installed power in kW of both an electric stove as well as a gas stove some real-world manufacturer data of stove models has been considered (see *Appendix Table A4.8*). Based on that, it has been chosen to model a 10kW generic gas stove with a corresponding weight of 48.86 kg as well as a 10kW generic electric stove with a corresponding weight of 52.48 kg. While it is a sound assumption to scale up Landi et al.'s LCI for a gas oven to describe the 48.86 kg generic gas stove (see *Appendix Table A4.9* for the LCI), the hobs of an electric stove are made of a greatly deviating material composition than Landi et al.'s LCI specifies for an electric oven. Therefore, the generic electric stove to be composed is modeled in two parts: an induction hob (based on Pina et al. [81]) and an electric oven (based on Landi et al.). Pina et al. [81] model several generations of induction hobs out of which the LCI of the newest generation has been chosen to represent the four induction hobs of the generic electric stove in Mayotte. The hob weighs 11.55 kg according to Pina et al., leaving the remaining 40.92 kg to be covered by the electric oven of Landi et al. The detailed LCI of the production of a 52.47 kg electric stove (combining the materials of the induction hobs with those of an electric oven) is shown in *Appendix Table A4.10*.
For the collective demand processes in the ESM "***Agriculture - Electric uses***", "***Services - Electric uses***", "***Food, Drink & Tobacco - Horizontal energy uses - Specific electricity use***" and "***Other Industries - Horizontal energy uses - Specific electricity use***" a generalization of the LCA was performed.
To model the assets required in the process "Agriculture – Electric Uses" a agricultural management system is used as a proxy since electricity for heating, lighting and pumping & motors in the agricultural sector is already covered by separate processes. By leveraging ICT the agricultural management system uses electricity and is modeled in OpenLCA by combining the three ecoinvent product flows of a computer, a display and an internet access equipment (see *Appendix Table A4.11*for the detailed LCI).
The necessary assets of the process "Services – Electric Uses" have been modeled by means of a 50:50 mix of black and white appliances (see *Appendix Table A4.12* for the LCI) since electricity for air conditioning and lighting is already covered by separate processes.
To model the assets required in the two industrial processes of specific electricity use it has been decided to create a 50:50 mix of a 19W-LED and a 1kW AC unit since electricity for heating as well as for process related activities is already covered by separate processes. *Appendix Table A4.13* presents the LCI exemplarily for the application in "Other Industries" while the process for the "Food, Drink, Tobacco Industry" is designed analogously.
According to the structure of the ESM, the demand process for "**Thermal processing**" in the Food, Drink & Tobacco sector as well as in "Other Industries" encompasses all specific industrial production processes, such as canning and drying. The ecoinvent process "*wood pellet factory production | wood pellet factory | Cutoff, U - RoW*" has been used as a broad proxy for the machinery required for these comprehensive processing activities. This ecoinvent process covers equipment for various activities (e.g., drying, comminution, mixing, cooling, and bagging): buildings, dryers, hammermills, hoppers, vibrating screens, conditioners, screw conveyors, cup elevators, electric motors, pellet presses, coolers, packaging machines, exhaust after treatment devices such as cyclones and electrostatic

precipitators, as well as monitoring devices. The dataset also includes tower silos and materials for storing and delivering the final product.
To link the ecoinvent dataset with the demand data of the ESM, it is necessary to determine the quantity of kW installed per unit of wood pellet factory. According to ecoinvent, the wood pellet factory has a production capacity of 50,000,000 kg/year. Moreover, the ecoinvent process "*wood pellet production | wood pellet, measured as dry mass | Cutoff, U - RoW*" requires 0.127 kWh to produce 1 kg of pellets. This is in line with Saosee et al. [82] who specify an average energy demand of 0.125 kWh when considering both electricity and diesel energy sources. Consequently, the total energy demand of the wood pellet factory is estimated to be 6,350,000 kWh/year, which corresponds to an installed power of 725 kW. This enables the linking of the ecoinvent dataset to the ESM data that expresses the end-use assets in “kW installed” for thermal processing in the Food, Drink & Tobacco industry and "Other Industries”.

Modeling the Use-Phase of Final Energy Carriers

In some of the LEVEL1 demand processes, the final energy carrier is not directly used to satisfy services but requires conversion, i.e., combustion, at the point of end-use. Hence, apart from the assets, the conversion of final energy carriers must be modeled within the LCA for such LEVEL1 demand processes, as the conversion processes release direct emissions which are not yet accounted for by the upstream production processes.
The modeling of the conversion processes follows a unform structure: a suitable econivent process, which entails the conversion of the respective final energy carrier, is identified. The inputs of the ecoinvent process are adjusted to depicture only the respective input (final energy carrier) foreseen in the ESM. Hence, the created process includes a single input flow of a certain amount of final energy carrier [kg] (e.g., diesel). The reference output flow is expressed as “burned [*final energy carrier*], in [*asset*]”, measured in energy units (e.g., MJ). The energy content of the burned final energy carrier is calculated by multiplying its input weight according to the ecoinvent process with its lower heating value as per **Fehler! Verweisquelle konnte nicht gefunden werden.** presents the lower heating values used in this study. Apart from the reference flow, each combustion process includes various emission flows as outputs, depending on the underlying ecoinvent process.

Table 9: Underlying lower heating values (LHV) of final energy carriers

final energy carrier	description of substance	LHV [MJ/kg]	source
Diesel		42.5	[83]
Synthetic Liquids	synthetic kerosene/diesel/gasoline	43.9	[83]
LPG		46.1	[83]
Gasoline		43.5	[83]
Biofuel conventional	ethanol from food-based feedstocks	26.8	[83]
Biofuel advanced	ethanol from lignocellulosic crops/ residues	26.8	[83]
Hydrogen		120.0	[83]
Ammonia		18.7	[63]
Paraffin Oil		42.0	[84]
Kerosene		43.0	[83]

The following subsections outline the underlying assumptions and calculations to create appropriate LCIs for the conversion processes of each final energy carrier.

Diesel

According to the ESM, there are 14 LEVEL1 demand processes that involve the combustion of diesel. However, not all these processes result in distinct emission profiles. For instance, the emission profile of burning diesel to generate heat in a boiler does not significantly differ between the agricultural sector (AGR_HEATB), the food, drink, tobacco industry (FDDRTB_HT), or other industries (OTHR_HT). Therefore, the 14 demand processes can be clustered into six distinct diesel combustion processes, each with a unique emission profile. The structure and derivation of the respective LCIs to model each of these six combustion processes is summarized in *Appendix Table A4.15*.
The general modeling procedure is exemplified for the process "*diesel combustion, in boiler*" (see *Appendix Table A4.31* for the LCI): Since there is no available ecoinvent process that adequately describes the combustion of diesel in a boiler and its associated emission profile, the ecoinvent process *"heat production, light fuel oil, at boiler 100kW condensing, non-modulating | heat, central or small-scale, other than natural gas | Cutoff, U – RoW*" is used as a proxy. This is a reasonable choice, given that light fuel oil is a distillate similar to diesel fuel [83]. However, the ecoinvent process contains inputs such as chimney, electricity, oil boiler and oil storage, which are not required for modeling the diesel combustion process in a boiler. Hence, these inputs are removed from the process. The reference flow is then modified to "burned diesel, in boiler" with the unit "MJ". The quantity in MJ is determined by multiplying the ecoinvent input quantity of diesel (0.02342 kg) with the LHV of diesel (42.5 MJ/kg as per **Fehler! Verweisquelle konnte nicht gefunden werden.**).

Synthetic Liquids
According to the ESM, six LEVEL1 demand processes rely on the combustion of synthetic liquids, which can be grouped into three distinct combustion processes, each characterized by a unique emission profile (see *Appendix Table 4.18*). There are no ecoinvent processes available that involve synthetic liquids such as Fischer-Tropsch (FT) fuels. Moreover, there is a lack of scientifically validated quantitative data on the emission profiles of burned FT fuels. However, some qualitative statements from scholars that describe the emission profile of synthetic fuels compared to its fossil counterparts. Styring et al. [85] observe that FT fuels show decreased SOx emissions due to the fact that these fuels entail very low shares of sulfur and aromatic hydrocarbons. In addition, Treyer et al. [86] state that synthetic kerosene from FT synthesis is characterized by reduced emissions of CO, hydrocarbons and particulate matter, while NOx emissions remain unchanged.
To convert these qualitative statements into quantitative information to develop an LCI that represents the combustion of synthetic liquids, the process *"synthetic liquids combustion, in aviation"* is modeled with an assumed 50% reduction in SO_x, CO, hydrocarbons, and particulate matter emissions compared to the ecoinvent process "*transport, freight, aircraft, dedicated freight, very short haul | transport, freight, aircraft, very short haul | Cutoff, U*". For the processes "*synthetic liquids combustion, in boiler*" and „*synthetic liquids combustion, in pumping and motors*" a reduction factor of 40% has been applied compared to their respective underlying ecoinvent processes (see Appendix *Table A4.25*). This takes into account the likelihood that combustion in aviation tends to be more complete than in less optimized applications such as boilers, pumps and motors.
The three different LCIs for the combustion of synthetic liquids must not include CO_2 emissions because the production of synthetic liquids is linked to the upstream production of CO_2 via direct air capturing. The process "carbon dioxide production, direct air capturing", however, does not include CO_2 as an input flow. Therefore, CO_2 is not reported as an emission in the final combustion of synthetic fuels to avoid double-counting.
Ultimately, all other trace elements due to impurities of fossil-derived fuels (e.g., heavy metals) have been removed from the underlying ecoinvent processes.
As shown in the LCIs of *Appendix Table A4.25 – A4.27* all three processes incorporate a parameter which specifies the percentage share at which synthetic liquids are either imported or produced locally in Mayotte. Per default, this parameter has been set to 0.5 to model a 50:50 distribution, in accordance with the ESM. This parameter represents a degree of freedom that can be adjusted in the course of a sensitivity analysis (see chapter 4.4).

LPG

The ESM presents five LEVEL1 demand processes that entail the combustion of LPG, which can be clustered into 3 distinct groups, each with its own unique emission profile (see *Appendix Table A4.17*). Tthe ecoinvent process *"heat production, light fuel oil, at boiler 100kW condensing, non-modulating | heat, central or small-scale, other than natural gas | Cutoff, U – RoW*" has been used as a proxy.

Special attention has been devoted to the combustion of LPG in stoves, given that in the baseline scenario even in 2050, LPG constitutes ca. 70% of the final energy demand for cooking. Since there hasn't been a promising ecoinvent process, the process has been modeled based on literature: Weyant et al. [87] quantify the emissions of CO, PM, elemental carbon and organic carbon resulting from the combustion of 1 MJ of LPG in a cooking stove, while the IPPC [88] provides data on CO_2, CH_4 and N_2O emission factors for stationary combustion of LPG in the residential sector. Based on that, an emission profile for the process "*LPG combustion, in stove*" has been developed in OpenLCA (see *Appendix Table A4.28* for the LCI).

Gasoline

The ESM describes a set of eight LEVEL1 demand processes that rely on gasoline combustion. These demand processes can be grouped into four different combustion processes, each characterized by its unique emission profile. Following the overarching rationale, *Appendix Table A4.16* presents the underlying assumptions and derivation of the respective LCIs required to model each of these combustion processes.

Analogous to diesel combustion, the combustion of gasoline in a boiler has been modeled by referring to the ecoinvent process *"heat production, light fuel oil, at boiler 100kW condensing, non-modulating | heat, central or small-scale, other than natural gas | Cutoff, U – RoW*" as a proxy.

Biofuel

According to the ESM, thirteen LEVEL1 demand processes depend on the combustion of conventional biofuel, which can be classified into six distinct combustion processes (see *Appendix Table A4.19*). For advanced biofuels, there is the additional demand of aviation beyond the same thirteen LEVEL1 demand processes of conventional biofuel. Consequently, the combustion of advanced biofuels is modeled by a total of seven distinct combustion processes with unique emission profiles (see *Appendix Table A4.20*).

Due to the diverse nature of different biomass sources emissions can vary significantly, depending on the underlying biomass. However, providing a detailed representation of these variations would require knowledge on the precise feedstock of biomass, which is not yet known. Accordingly, we simplify and assume the same emission profiles for conventional and advanced biofuels.

As has been stated in 3.3.3.1, bioethanol is used in this study to represent the broad class of biofuel. However, there is no consensus among scholars on the quantitative emission profile of bioethanol, and qualitative effects of bioethanol compared to the conventionally used fossil fuels vary across the literature. The comprehensive review of Thangavelu et al. [89] concludes that only CO and unburned HC emissions show a remarkable reduction compared to the conventionally used fuels, while there are no significant emission reduction of CO_2, NO_x, aromatics, acetaldehyde, carbonyls and particulate matter. Hence, the respective combustion processes of conventional gasoline and diesel are used as underlying processes to model the combustion processes of (conventional/advanced) biofuel with an assumed 50% reduction of CO and hydrocarbon emissions.

Ultimately, the LCI of the combustion of biofuel must not include CO_2 emissions because CO_2 has been captured through photosynthesis of the underlying biomass. This CO_2 has not been included as an input flow at any point upstream in the production of biomass and therefore, it must not be reported as an emission in the final combustion of biofuel to avoid distortions in the LCA results.

The LCIs of the combustion of conventional and advanced biofuel are exemplarily presented for the navigation subsector in *Appendix Table A4.33- TabeA4.34*.

Hydrogen

The ESM identifies six LEVEL1 demand processes that entail the reaction of hydrogen in a fuel cell. These six processes can be summarized by one overarching process, the general redox reaction of hydrogen and oxygen (from air) into water and waste heat (see *Appendix Table A4.21*). The stoichiometric equation for the redox reaction in a hydrogen fuel cell has been utilized to quantify the production of water per kg of hydrogen to be approximately 17.8 kg (see *Appendix Figure A4.1*).

Aside from water exhaust and waste heat no other emissions are released when reacting hydrogen in a fuel cell [90]. In order to ensure consistency with the combustion processes, waste heat has not been accounted for as an output in OpenLCA. This is owed to the fact that none of the ecoinvent combustion processes that have been used as a foundation for modeling the various combustion processes carry waste heat as an output in their LCI. The detailed LCI for the reaction of hydrogen in a fuel cell is presented in *Appendix Table A.29*.

Moreover, the LCI incorporates the parameter "share_H2_imported" which specifies the percentage share at which hydrogen is either imported or produced locally in Mayotte. Per default, this parameter has been set to 0.5 to model a 50:50 distribution, in accordance with the ESM. This parameter represents a degree of freedom that can be adjusted in the course of a sensitivity analysis (see Section 4.2.2).

Ammonia

According to the ESM there are two LEVEL1 demand processes that involve the combustion of ammonia, which can be combined into the overarching process *"ammonia combustion, in navigation"* (see *Appendix Table A4.22*). The resulting products nitrogen and water from the complete combustion of 1 kg of ammonia are quantified based on the stoichiometry of the combustion reaction (see *Appendix Figure A4.2*).

Incomplete combustion of ammonia leads to additional emissions. Nevertheless, the carbon- and sulfur-free molecular composition of ammonia results in near-zero CO_2 and SO_X emissions when burned in an engine. Furthermore, emissions of air pollutants associated with carbon (e.g., black carbon, unburned hydrocarbons, methane slip and CO) are almost eliminated [91]. Ultimately, the use of potent catalysts holds promise for achieving almost complete combustion, which minimizes the emission of unburned NH_3 and the formation of nitrous oxide [91]. Given the additional lack of quantitative data available in literature, we simplify and exclude the aforementioned trace emissions resulting from ammonia combustion. For the OpenLCA process "*ammonia combustion, in navigation*" only NOx, CO_2, and methane emissions per MJ of burned ammonia are taken into consideration - as quantified by Chalaris et al. [92].

The LCI in *Appendix Table A4.30* shows that the process incorporates the parameter "share_NH3_imported" which specifies the percentage share at which ammonia is either imported or produced locally in Mayotte. Per default, this parameter has been set to 0.5 to model a 50:50 distribution, in accordance with the ESM scenario projections. This parameter represents a degree of freedom that can be adjusted in the course of a sensitivity analysis (see Section 4.2.2).

Paraffin Oil

The ESM indicates that the use of paraffin oil is linked to two LEVEL1 demand processes: the burning of paraffin oil in stoves and the non-energy use of paraffin oil for chemical reactions within the industrial sector (see *Appendix Table A4.23*).

While the first process describes the combustion of paraffin oil in a household stove, the second does not involve combustion but rather encompasses emissions arising from the use of paraffin oil as an educt for chemical reactions. Depending on the specific chemical reaction and stoichiometry involved, the emission profile resulting from the use of paraffin oil in the industrial sector can vary significantly. Due to insufficient information regarding the specific chemical reactions taking place in the industrial

sector in Mayotte, the value chain has only been modeled until the import of externally produced paraffin oil to Mayotte.
The combustion of paraffin oil in a stove is modeled in OpenLCA based on Swensson & Kjellson [93] who quantify the emission profile of burning paraffin oil in a common stove of low-income households in South Africa (see *Appendix Table A4.31* for the LCI).

Kerosene
The ESM only states one LEVEL1 demand process that entails the combustion of kerosene: burning kerosene for aviation needs. Consequently, the process *"kerosene combustion, in aviation"* has been created in OpenLCA by adjusting the ecoinvent process *"transport, freight, aircraft, dedicated freight, very short haul | transport, freight, aircraft, very short haul | Cutoff, U"* according to *Appendix Table A4.24.*

3.3.4. Impact Assessment

As the third implementation step of an LCA, the ISO 14040/14044 guidelines specify the impact assessment. To enable an assessment of the system's impact, a methodologies needs to be selected, that dictates how the inventory of pollutant emissions and the resource consumption (based on the LCI) is converted into scores. For the purpose of this study, the author's identified ReCiPe 2016 as the most relevant methodology. The ReCiPe method is well-established and encompasses 18 midpoint indicators aggregated into three endpoint [23]. The midpoint indicators are depicted in **Fehler! Verweisquelle konnte nicht gefunden werden.**.

It is important to note that the ReCiPe method was designed for European-scale models in well-developed temperate regions [23]. The validity of some parts of the model is reduced for the region of Mayotte. However, due to it's modular character, the ReCiPe method can be adjusted and tailored to other regions and maintain accurate results, as shown by Schmidt Riviera in a case study of hydrogen cooking in Jamaica [94] and shown by Bilich et al assessing a PV microgrid in Kenya [95]. In addition, a thorough literature review on the status of LCA in Africa, including LCA on energy systems in Africa, found the ReCiPe method to be widely used by researchers in this area [13].Thus, with adjusting the ReCiPe method for this case study, we can produce accurate results while allowing for replicability on other European islands.
Further limitations of the method are the missing of erosion, salination, noise, and light as midpoint categories. ReCiPe 2008 has been designed primarily as an attempt to align the CML 2002 midpoint and the Eco-indicator 99 systems. As such, no attempts have been made to accommodate or elaborate impact categories that are missing in either of these methodologies [23].
Below we briefly describe the impact categories at midpoint level as well as the aggregating impact categories at the endpoint level.

3.3.4.1. Midpoint Level Categories

Midpoint indicators focus on single environmental problems, for example climate change or acidification. Impact categories at the midpoint are defined at the place where mechanisms common to a variety of substances come into play. An overview of the midpoint indicators applicable to this study and their respective units, is provided in **Fehler! Verweisquelle konnte nicht gefunden werden.**.
While the classifications qualitatively determine the environmental intervention, the characterization factor is the quantitative representation of the relative importance of a specific intervention. For example, the GWP of methane is 22 kg CO_2-equicalents per kg methane. With this, substances x can be multiplied by their characterization factor CF to convert into an equivalent substance of the emission compartment i and aggregated together to create a total impact score IS for each impact category in any life cycle intervention m via equation 1:

$$IS = \sum_x \sum_i CF_{x,i} * m_{x,i} \quad (1)$$

In the following, a brief indication of the main characteristics of the midpoint impact categories is provided. [23] contains a detailed description of the impact pathways and affected areas of protection, characterization factors and relation between midpoint and endpoint.

Table 10: Midpoint categories according to ReCiPe 2016.

environmental impact category	Fine particulate matter formation	Fossil resource scarcity	Freshwater ecotoxicity	Freshwater eutrophication	Global warming potential	Human carcinogenic toxicity
abbreviation	FPM	FRS	FEX	FEU	GWP	HCT
unit	kg PM2.5 eq	kg oil eq	kg 1,4-DCB	kg P eq	kg CO2 eq	kg 1,4-DCB

environmental impact category	Human non-carcinogenic toxicity	Ionizing radiation	Land use	Marine ecotoxicity	Marine eutrophication	Mineral resource scarcity
abbreviation	HnCT	IR	LU	MEX	MEU	MRS
unit	kg 1,4-DCB	kBq Co-60 eq	m2a crop eq	kg 1,4-DCB	kg N eq	kg Cu eq

environmental impact category	Ozone formation, Human health	Ozone formation, Terrestrial ecosystems	Stratospheric ozone depletion	Terrestrial acidification	Terrestrial ecotoxicity	Water consumption
abbreviation	OFHH	OFTE	SOD	TA	TEX	WC
unit	kg NOx eq	kg NOx eq	kg CFC11 eq	kg SO2 eq	kg 1,4-DCB	m3

1. Fine particulate matter formation (FPM): Indicator of the potential incidence of disease due to particulate matter emissions.

2. Fossil resource scarcity (FRS): Indicator of the depletion of natural fossil resources.

3. Freshwater ecotoxity (FEX): Impact on freshwater organisms of toxic substances emitted to the environment.

4. Freshwater eutrophication (FEU): Freshwater eutrophication refers to the excessive growth of aquatic plants or algal blooms, due to high levels of nutrients in freshwater ecosystems such as lakes, reservoirs and rivers.

5. GWP (GWP): Indicator of potential global warming due to emissions of greenhouse gases.

6. Human carcinogenic toxicity (HCT): Impact on humans of toxic substances emitted to the environment, cancer-related.

7. Human non-carcinogenic toxicity (HnCT): Impact on humans of toxic substances emitted to the environment, non-cancer-related.

8. Ionizing radiation (IR): Damage to human health and ecosystems linked to the emissions of radionuclides.

9. Land use (LU): Measure of the changes in soil quality (Biotic production, Erosion resistance, Mechanical filtration).

10. Marine ecotoxicity (MEX): Impact on marine organisms of toxic substances emitted to the environment.

11. Marine eutrophication (MEU): Indicator of the enrichment of the marine ecosystem with nutritional elements, due to the emission of nitrogen-containing compounds.

12. Mineral resource scarcity (MRS): Indicator of the depletion of natural non-fossil resources.

13. Ozone formation, Human health (OFHH): tropospheric ozone precursor emissions to damage to human health.

14. Ozone formation, Terrestrial ecosystems (OFTE): tropospheric ozone precursor emissions to damage to terrestrial ecosystems.

15. Stratospheric ozone depletion (SOD): Indicator of emissions to air that causes the destruction of the stratospheric ozone layer.

16. Terrestrial acidification (TA): Indicator of the potential acidification of soils due to the release of gases such as nitrogen oxides and sulphur oxides

17. Terrestrial ecotoxicity (TEX): Impact on terrestrial organisms of toxic substances emitted to the environment.

18. Water consumption (EC): Indicator of the relative amount of water used, based on regionalized water scarcity factors.

3.3.4.2. Endpoint Level Categories

Compared to midpoint indicators, endpoint indicators show the environmental impact on higher aggregation levels. Impact categories at the endpoint level correspond to areas of protection, describing a recognizable value for society and form the basis of decisions in policy and sustainable development. For the environmental domain, these areas of protection are human health, ecosystem quality, resource availability, and man-made environment. The areas of protection are quantified by endpoint categories, which represent the variable of direct societal concern. The endpoint categories applied in this analysis are listed in Table 11.

Table 11: Overview of endpoint categories according to the ReCiPe 2008 method.

Impact category	Abbr.	Indicator	Unit
Damage to human health	HH	Disability-adjusted loss if life years	yr
Damage to ecosystem diversity	ED	Loss of species during a year	yr
Damage to resource availability	RA	Increased cost	$

1. Damage to human health (HH): The impact category damage to human health corresponds to the area of protection human health. The ReCiPe methodology assesses damage to human health using the concept of 'disability-adjusted life years' (DALY). The DALY of a disease is derived from human health statistics on life years both lost and disabled. It sums the years of life lost and years of life disabled, without age weighting and discounting applied in the ReCiPe method.
2. Damage to ecosystem diversity (ED): The impact category damage to ecosystem diversity corresponds to the area of protection ecosystems. The ReCiPe method therefore models the loss of species during a certain time in a certain area as the basis for the endpoint indicator.
3. Damage to resource availability (RA): The impact category damage to resource availability corresponds to the area of protection resources. Unlike the Eco-indicator 99 method, the ReCiPe model bases on the geological distribution of mineral and fossil resources and assess how the use of these resources causes marginal changes in the efforts to extract future resources."

3.3.4.3. Connecting Midpoint and Endpoint Categories

The principal aim of ReCiPe 2008 was the alignment of two families of methods for LCIA: the midpoint oriented CML 2002 method and the endpoint-oriented Eco-indicator 99 method. Therefore, the method established a quantifiable link between midpoint and endpoint impact categories, where relevant. With this the link established between inventory data and midpoints can in a second step further be directed to endpoints. Symbolically: when intervention i and midpoint indicator m are coupled with characterisation factor Q_{mi}, and midpoint indicator m is coupled with endpoint indicator e with characterisation factor Q_{em}, their combined characterisation factor Q_{ei} is determined as

$$Q_{ei} = \sum_{m} Q_{em} Q_{mi} \tag{2}$$

The characterization factors are available on the website of ReCiPe 2008 via www.lcia-recipe.info.

3.3.4.4. Uncertainty in LCIA

ReCiPe 2008 groups different sources of uncertainty and different choices into a limited number of perspectives or scenarios, according to the "Cultural Theory" by Thompson 1990. Three perspectives are discerned in the method [23]:

- individualist (I): This perspective is based on the short-term interest, impact types that are undisputed, technological optimism as regards human adaptation.
- hierarchist (H): This perspective is based on the most common policy principles with regards to time-frame and other issues.
- egalitarian (E): This perspective is the most precautionary perspective, considering the longest time-frame, impact types that are not yet fully established but for which some indication is available, etc.

For the purpose of our study, we adopt the hierarchist perspective, as moderate but concern perspective respecting common policy principles.

3.3.5. Limitations of the Methodology

Throughout the LCI and LCIA phase, several challenges commonly encountered in LCA studies were addressed through modeling decisions to mitigate associated risks. This section provides a brief overview of potential limitations and mitigation measure applied. An extensive overview of limitations of linking ESM and LCA is provided in Blanco et al. [5].

1. **Data Availability**: The availability of data poses a significant limitation in LCAs. In this study, primary data from Mayotte was scarce and proxies from the ecoinvent database or relevant literature had to be used, which is a major limitation. In this study, this was evident in the absence of specific ecoinvent processes for modeling technologies related to especially the production of green ammonia, green hydrogen, and synthetic liquids. To address this, affected processes were modeled based on available literature or by using proxies with similar properties and behavior (e.g., modeling the combustion of diesel using the combustion process of light fuel oil as a proxy).
2. **Data Relevance and Completeness**: Assessing the relevance of data from LCA literature to the system being studied is challenging. Maintaining a balanced level of detail is crucial to provide a comprehensive overview without introducing unbalanced granularity, potentially deteriorating the overall results towards more detailed modeled processes. For example, in the synthesis of ammonia, the production of catalysts was omitted based on this rationale.
3. **Data Accuracy**: The quality of underlying data sources and the methods applied for data collection and analysis impact data accuracy. In this study, the quality of available ecoinvent processes was evaluated using the ecoinvent data quality pedigree matrix. When multiple processes were suitable, the one with the best quality rating was chosen. High-quality literature data was preferred for processes not available in ecoinvent.
4. **Data Uncertainty**: Various sources of uncertainty were considered, including measurement errors and variability of data used in ecoinvent processes and consulted literature. To address this, multiple sources were consulted to validate the plausibility of the adopted data.
5. **Data Consistency**: To ensure data consistency in modeling the energy system of Mayotte, preference was given to data from the reputable ecoinvent database. An overarching approach was chosen for processes grouped into comparable categories to ensure methodological inter-process consistency.
6. **Data Transparency**: Many LCAs lack accessible documentation of underlying assumptions and calculations. In this study, efforts were made to provide comprehensive insights into the quantitative LCI data used to model the energy system.

Despite the encountered challenges and risks, the measures taken to minimize such risks, including careful data source selection and thorough documentation of adaptations and assumptions, have resulted in a qualitatively sound LCI. This ensures transparency and reproducibility of the LCA study, (e.g. to other EU islands) ultimately contributing to sound data quality aligned with the study's goal and scope while minimizing potential biases in the results.

4. Interpretation of Results

Chapter 4 constitutes the fourth step of an LCA, which is the interpretation of results. The interpretation of results is divided into three areas of analysis, each described in a dedicated section. Section 4.1 describes the environmental impacts across categories for the various scenarios and sectors as depictured via the ESM by 2050. Section 4.2 identifies environmental hotspots within sectors, technologies, and processes. Finally, Section 4.3) specifies implications for energy policies and energy planning.

4.1. Environmental Performance of Energy System Configurations

We first analyze the environmental impact of the energy systems as constituted by the energy system scenarios by 2050 for each of the five distinct energy system scenarios. The energy system scenarios are described in detail in Section 3.2.2. We calculate the environmental footprint of each scenario within each of the 18 environmental impact categories, as described in Section 3.3.4. The absolute impact scores for the five scenarios are shown in Figure 20. The modelling results are further broken down in Figure 21, which depicts and compares the sectorial performance of the relevant sectors in Mayotte. In both figures, the scores of each energy system scenario are shown in relation with the baseline scenario; thus, allowing to i) understand the differences in the environmental footprint that is associated with the respective interventions to decarbonize Mayotte´s energy system compared to the status quo and ii) identify the decarbonized energy system topology associated with the least environmental footprint, specifically highlighting sectorial differences.

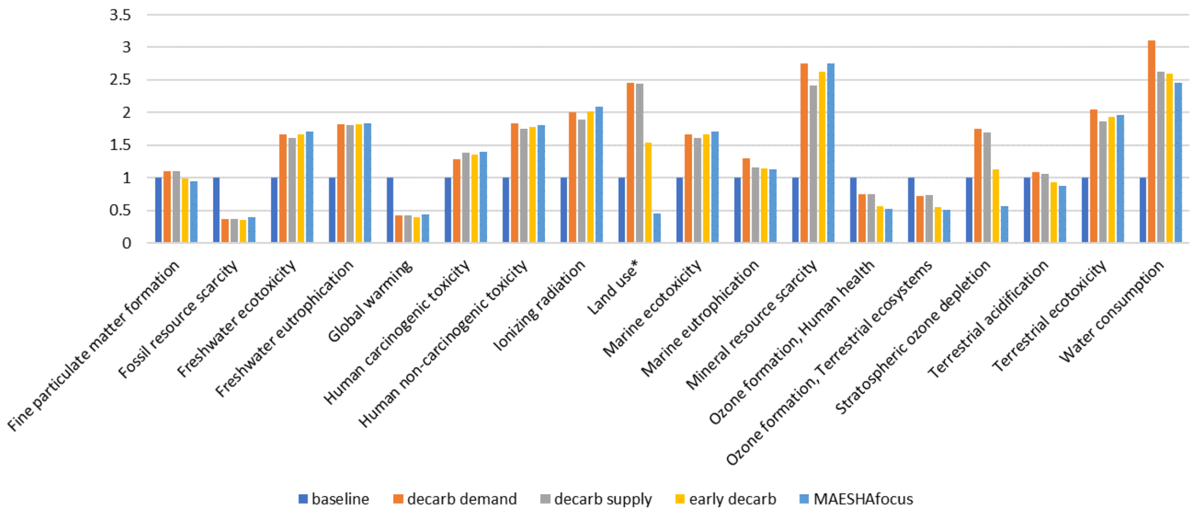

Figure 20: Environmental performance of decarbonization scenarios relative to baseline (2050). *Land use: environmental impact of the decarbonization scenarios was divided by a factor of ten.

From Figure 20 it becomes visible that with regard to a comprehensive environmental impact assessment, no global optimum across the different energy system configurations of 2050 exists. It is apparent that there is no single scenario that performs best in across all environmental impact categories.. In fact, the baseline scenario, which is the scenario reflecting an energy system configuration relying most heavily on fossil fuels, constitutes lower impact scores for 12 out of 18 impact categories, when compared to the four decarbonization scenarios. Hence, there is an argument to be made that if maintaining equal importance of all environmental impact categories, relying on fossil fuels could pose the "best" option for Mayotte. The overall damage score offers further insight into a comparison of the five scenarios, in which all impact categories are taken into account.

Calculating the overall damage scores (average of the score under each impact category compared to the baseline scenario) of the decarbonization scenarios would be as follows: 279% (DecarbDemand), 270% (DecarbSupply), 217% (EarlyDecarb), and 154% (MAESHAfocus).
However, as suggested by the efforts under the Paris Agreement, the environmental impact categories may not be equally prioritized under current policies. Specifically, reducing the GWP is a particular priority in current policies. The underlying ESM for the four decarbonization scenarios constitutes the avoidance of local GHG. The LCA analysis supports the effectiveness and robustness of measures assumed to be taken in the decarbonization scenarios. The lifecycle perspective suggests an emission reduction potential of 60-57% compared to the baseline scenario. In contrast to the ESM, the LCA includes the consideration of indirect emissions. The results show that the effectiveness of decarbonization measures hold stand also when including indirect emissions in the analysis. Further, when decarbonizing the energy system of Mayotte, generally, fossil resource scarcity, ozone formation – human health, and ozone formation – terrestrial ecosystem can be reduced.
In line with previous literature (e.g., [94]), the results of our analysis suggest that reducing the global warming potential (GWP) of an energy system is mitigated at the expense of other environmental impacts. For example, decarbonizing the energy system of Mayotte would inevitably lead to a higher occupation of land and consumption of water, and requires more mineral resources. Reducing or mitigating the environmental impact in one domain that may result in unintended consequences in other environmental domains. In our analysis, if increased efforts are sought to decarbonize the overall system – and regardless of the specific policy designs chosen in the four decarb scenarios – we find robust trends for the trade-offs and positive interlinkages between decarbonization, reducing the GWP, and other impact categories as stated in Table 12. Knowledge on the (negative) interlinkages must be considered by decision makers responsible in energy system planning, and politicians connecting the energy sector with other sectors or areas of life potentially affected by the negative trade-off caused.

Table 12: Encountered trade-offs when pursuing increased decarbonization efforts.

Across all decarbonization scenarios an improvement in GWP is accompanied by a deterioration in the following impact categories	Across all decarbonization scenarios an improvement in GWP is accompanied by improvements in the following impact categories	Inconclusive effect
Freshwater ecotoxicity	Fossil resource scarcity	Fine particulate matter formation (MAESHAfocus outperforms the baseline scenarios)
Freshwater eutrophication	Ozone formation, Human health	Stratospheric ozone depletion (MAESHAfocus outperforms the baseline scenarios)
Human carcinogenic toxicity	Ozone formation, Terrestrial ecosystems	Terrestrial acidification (MAESHAfocus and EarlyDecarb outperform the baseline scenarios)
Human non-carcinogenic toxicity		
Ionizing radiation		
Land use		
Marine ecotoxicity		
Marine eutrophication		
Mineral resource scarcity		
Terrestrial ecotoxicity		
Water consumption		

Figure 21 quantifies the absolute impact across all categories disaggregated for the relevant sectors. In accordance with the structure of the ESM, we disaggregate sectors in i) transport, ii) households, iii) industry, iv) services, and v) agriculture. In each sector, environmental impacts associated with both the final energy usage and the environmental impacts associated with the associated assets (construction, decommission and end-of-life where relevant) are included in the balance. Some quantities and scores within impact categories may not be intuitive to grasp. To ease the comprehensiveness of the findings and guide the reader in interpreting the results depicted in Figure 21, in the following, we provide a detailed description of the impact scores and it's placement in a wider context for three impact categories, namely land use, water consumption and GHG emissions. Both land use and water consumption can be considered a scarce resource on Mayotte and most EU islands.

Land use: The land-use resulting from the decarbonization is significantly higher than the land-use within the baseline scenario (primarily due to the use of biofuels, as will be elaborated in the subsequent sections). The environmental impact on land-use according to the ReCiPe method is quantified as the amount of m^2 of i) change of land cover and ii) land-use intensification due to crops, annually. Change of land cover leads to loss of habitat (and thus potential loss of species), while land-use intensification leads to soil disturbance. Based on our study, the efforts required for decarbonizing the energy system of Mayotte, as foreseen by the underlying scenarios, is manifold the land required when maintaining the use of fossil fuels. For example, the energy system as constituted via the DecarbSupply scenario required 400 km^2/a/yr crop equivalent to fulfill the energy demands in 2050. As a reference, the total land area of Mayotte is cited with 374 km^2. Hence, the land annually impacted by decarbonizing the energy system of Mayotte itself exceeds the total area of the island. Outsourcing processes, for example the production of biofuels, would therefore be a technical necessity, and associated partnerships may be closed by politicians.

Water consumption: Similarly, to the consequences of decarbonization associated with the use of land, the decarbonization measures and sourcing of associated energy system assets would impact vast amounts of freshwater. For example, the DecarbDemand scenario energy system would impact three times the amount of water negatively impacted when maintaining current policies. The $1.37*10^7$ m^3 water required within the DecarbDemand scenario again exceeds the $1.53*10^7$ m^3 water consumed annually by Mayotte´s population, which already today is challenging to supply (42,000m^3 per day [96]). However, it must be noted that the impacts associated with water consumption concerns the mining of mineral resources required to build RES assets. As the respective mineral resources are not found in Mayotte, the associated impacts on the water consumption affect locations other than Mayotte. This underlines the fact that the choice of suppliers and their environmental performance will significantly contribute the environmental impact of Mayotte´s energy system.

GHG emissions: While the decarbonization scenarios modeled in the ESM minimize the direct CO_2 emissions, the LCA offers further insights into the overall associated GHG emissions. In addition to the direct emissions, the LCA quantifies the amount of indirect emissions associated with the local decarbonization. When comparing the direct emissions caused within the baseline scenario energy system by 2050, calculated by the ESM ($0.752*10^9$ kg CO_2), we find that 43% of the emissions caused over the entire lifecycle as calculated via LCA (total: $1.3*10^9$ kg CO_2-eq.) stem from indirect emissions. Repeating the same calculation for the MAESHAfocus scenario, which produces $0.63*10^8$ kg CO_2via combustion of diesel, the share of indirect emissions over the lifecycle constitute to almost 90%. Hence, with increasing decarbonization of energy systems, the indirect emissions associated to the systems become relatively more important.

Figure 21: Sectoral performance of energy system configurations in 2050.

Considering the relative contribution of sectors on environmental impact (see Figure 21) it is evident that while in the baseline scenario transport and household sector almost evenly contribute to environmental impacts, in the decarbonization scenarios the transport sector dominates the environmental impact across all impact categories. The second most relevant sector in the decarbonization scenarios are the households. In each of the decarbonization scenarios, the transport sector constitutes to more than 50% of the environmental impact in each impact category – with up to 75% in the impact on global warming. Across the decarbonization scenarios, the transport sector has smallest percentual impact in the land-use category. The MAESHAfocus showcases a significantly lower impact in the land-use impact category than the other decarbonization scenarios. The industry has an significant impact on the land-use impact (35%) with the industrial boilers running on biofuel which is associated with land-intensive production. Further, households have higher impact on land use in the decarbonization scenarios with a higher share of solar energy in final energy demand e.g., DecarbDemand 46 GWh compared to 30 GWh in baseline scenario.

For an indepth analysis the contribution of the distinct sectors, we disaggregate the environmental performance per sector. Figure 22 presents the environmental performance of energy system scenarios by 2050 per sector and impact category, referenced against the base scenario. In the following the sectors are discussed separately and subsequently:

Transportation: All decarbonization scenario show less environmental impact than the baseline scenario caused by transportation in fossil resource scarcity, global warming, ozone formation impact on health and ozone formation potential impact on terrestrial ecosystems. The savings in these impact categories are explained by lower utilization of diesel in transportation. While for example in the base scenario 651 GWh diesel are consumed in transport by 2050, it is only 11.05 GWh and 12.02 GWh in the EarlyDecarb and MAESHAfocus scenario respectively. In contrast, the baseline scenario significantly outperforms all decarbonization scenarios in the transport sector with regard to land-use, freshwater eutrophication and water consumption. The environmental hotspot in land-use is the increased usage of biofuels in the decarbonization scenarios, especially in aviation and navigation, the production of which requires high land occupation. For example, 122 GWh advanced biofuels are used in transportation in the DecarbSupply scenario by 2050, whereas no biofuels are used in transportation in the baseline scenario. The high share of BEVs in the decarbonization scenarios induce a deterioration in human toxicity, Ionizing radiation, freshwater ecotoxicity and eutrophication, water consumption, terrestrial ecotoxicity, marine eutrophication and mineral resource scarcity, as especially the production of the battery cells and electronics require the exploitation of rare earth minerals, releasing wastewater (see Section 4.2 for details).

Households: Within the household sector, the decarbonization scenarios significantly outperform the baseline scenario by 2050 with regard to the global warming impact. Generally, the energy system configuration as proposed via the MAESHAfocus scenario poses the least environmental impact in 14 out of the 18 impact categories. This is essentially due to a i) reduction of energy intensity measure, e.g., reducing the final energy demand in the residential sector from 483 GWh (baseline scenario) to 391 GWh (MAESHAfocus scenario), which translates to a specific per capita energy intensity (kWh/capita) of 977.8 kWh/y/capita in the baseline scenario and 790 kWh/y/capita in the MAESHAfocus scenario. The reduced energy intensity within the MAESHAfocus scenario is crucial for the improved performance in comparison to the alternative decarbonization scenarios. As less diesel is consumed in the decarbonization scenarios for the provision of electricity in households, global warming, stratospheric ozone depletion, fossil resource scarcity, particulate matter formation benefit from decarbonization. Further, the decarbonization measures suggested in each scenario induce a reduction of LPG used within the household sector. For example, in the baseline scenario 75 GWh LPG are used for cooking, while, in the EarlyDecarb it is only 0.06 GWh (see Section 4.2.3 for more details).

Sector	Scenario	Fine particulate matter formation	Fossil resource scarcity	Freshwater ecotoxicity	Freshwater eutrophication	Global warming	Human carcinogenic toxicity	Human non-carcinogenic toxicity	Ionizing radiation	Land use	Marine ecotoxicity	Marine eutrophication	Mineral resource scarcity	Ozone formation, Human health	Ozone formation, Terrestrial ecosystems	Stratospheric ozone depletion	Terrestrial acidification	Terrestrial ecotoxicity	Water consumption
Transport	Base	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	dDemand	1.4	0.6	2.1	2.4	0.7	1.4	2.3	2.6	25.4	2.1	2.1	3.4	0.9	0.8	2.3	1.5	2.6	4.3
	dSupply	1.4	0.6	2.0	2.3	0.7	1.5	2.2	2.4	26.9	2.0	1.7	2.9	0.9	0.9	2.3	1.4	2.3	3.5
	eDecarb	1.3	0.6	2.1	2.4	0.6	1.5	2.2	2.6	17.2	2.1	1.8	3.2	0.6	0.6	1.6	1.3	2.5	3.6
	Mfocus	1.3	0.6	2.2	2.5	0.7	1.5	2.3	2.7	6.1	2.2	1.8	3.4	0.6	0.6	1.0	1.3	2.5	3.6
Household	Base	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	dDemand	0.6	0.2	1.0	1.0	0.2	1.0	1.0	1.0	18.2	1.0	0.8	1.0	0.5	0.5	1.2	0.6	1.0	1.2
	dSupply	0.7	0.2	1.0	1.1	0.2	1.0	1.1	1.0	17.3	1.0	0.8	1.1	0.5	0.5	1.1	0.6	1.1	1.3
	eDecarb	0.6	0.2	1.0	1.0	0.2	1.0	1.0	1.0	9.9	1.0	0.8	1.0	0.4	0.4	0.7	0.5	1.0	1.0
	Mfocus	0.5	0.2	1.0	1.0	0.2	1.0	1.0	1.0	0.9	1.0	0.8	1.1	0.3	0.3	0.2	0.4	0.9	0.7
Industry	Base	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	dDemand	0.7	0.3	1.2	1.3	0.2	1.1	1.3	1.2	30.8	1.2	0.6	1.2	0.6	0.6	1.6	0.7	1.2	1.5
	dSupply	0.7	0.3	1.2	1.2	0.2	1.1	1.2	1.2	28.1	1.1	0.6	1.2	0.5	0.5	1.4	0.6	1.2	1.4
	eDecarb	0.6	0.3	1.2	1.2	0.2	1.1	1.2	1.2	20.2	1.2	0.5	1.2	0.4	0.4	1.0	0.5	1.2	1.3
	Mfocus	0.5	0.3	1.1	1.1	0.2	1.1	1.1	1.2	8.8	1.1	0.4	1.3	0.3	0.3	0.4	0.4	1.1	1.0
Services	Base	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	dDemand	0.7	0.2	1.1	1.1	0.2	1.0	1.1	1.0	22.8	1.1	0.8	1.1	0.5	0.5	1.2	0.6	1.1	1.3
	dSupply	0.7	0.2	1.1	1.1	0.2	1.1	1.1	1.1	21.5	1.1	0.8	1.1	0.5	0.5	1.1	0.6	1.1	1.3
	eDecarb	0.5	0.1	1.0	1.1	0.2	1.0	1.0	1.1	12.3	1.0	0.7	1.1	0.4	0.4	0.7	0.5	1.0	1.0
	Mfocus	0.4	0.2	1.0	1.0	0.2	1.0	1.0	1.1	0.9	1.0	0.7	1.1	0.3	0.2	0.2	0.4	1.0	0.7
Agriculture	Base	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	dDemand	0.7	0.2	3.0	2.8	0.3	2.7	2.8	2.3	73.7	3.0	0.9	2.8	0.4	0.4	3.0	0.8	2.8	5.2
	dSupply	0.7	0.2	3.0	2.8	0.3	2.8	2.7	2.4	63.4	3.0	0.9	2.8	0.4	0.4	2.6	0.8	2.7	4.9
	eDecarb	0.6	0.2	3.1	2.8	0.2	2.8	2.8	2.5	40.1	3.1	0.8	2.9	0.3	0.3	1.7	0.7	2.8	4.2
	Mfocus	0.5	0.2	3.1	2.6	0.3	2.8	2.6	2.5	2.8	3.1	0.7	3.0	0.2	0.2	0.4	0.5	2.7	3.1
TOTAL	Base	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	dDemand	1.1	0.4	1.7	1.8	0.4	1.3	1.8	2.0	24.5	1.7	1.3	2.7	0.7	0.7	1.8	1.1	2.0	3.1
	dSupply	1.1	0.4	1.6	1.8	0.4	1.4	1.7	1.9	24.4	1.6	1.2	2.4	0.8	0.7	1.7	1.1	1.9	2.6
	eDecarb	1.0	0.4	1.7	1.8	0.4	1.4	1.8	2.0	15.4	1.7	1.1	2.6	0.6	0.6	1.1	0.9	1.9	2.6
	Mfocus	1.0	0.4	1.7	1.8	0.4	1.4	1.8	2.1	4.6	1.7	1.1	2.8	0.5	0.5	0.6	0.9	2.0	2.5

Figure 22: Environmental performance of energy system scenarios by 2050 per sector and impact category relative to the baseline scenario.

Industry: With only minor industry being present in Mayotte, the picture of impact categories caused by the industry sector is determined by the consumption of diesel required for electricity generation. Further, the fuel consumed in boilers (e.g., baseline scenario 42 GWh) is substituted by biomass and waste in decarbonization scenarios (e.g., DecarbSupply 52 GWh). Hence, decarbonization measures in the industry sector in Mayotte have the potential to impact fossil resource scarcity, particulate matter formation, global warming, and ozone depletion.

Services: Like the household sector, within the services sector the energy system configuration of the MAESHAfocus scenario is associated with the lowest environmental impact across the majority (12/18) of impact categories. In contrast to the DecarbSupply scenario, which performs worst in nine categories, the MAESHAfocus scenario system configuration suggests demanding less final energy (176 GWh compared to DecarbSupply (198 GWh)), especially in electric uses (71 GWh vs. 90 GWh). Further, the conventional power plants in the DecarbSupply utilize a biofuel to supply electricity to a high share (556 GWh/1420 GWh), whereas MAESHAfocus relies on diesel to generate 169 GWh of 1308 GWh, while no biofuel is used in electricity generation (see Section 4.2.1 for details).

Agriculture: Within the agricultural sector, the baseline scenario poses the least environmental impact in 10 out of 18 impact categories. Even though the final energy demand of decarbonized scenarios is reduced compared to the baseline scenario, electricity use is higher. The electricity mix and the associated infrastructure, including storages (e.g., MAESHAfocus: 198 GWh storage vs. 7.2 GWh storage in base scenario), induces the deterioration in some categories (see hotspot analysis in Section 4.2).

Reflecting on the aforementioned section we can conclude:

- The LCA results confirm the effectiveness of the decarbonization measures induced in the ESM scenarios. The effective reduction in the reduction of the GWP can be confirmed, when taking the entire life cycle and therefore also indirect emission into account.
- Reducing the energy sector emissions of Mayotte will most likely lead to trade-offs in other environmental categories, which must carefully be evaluated. Associated partners, e.g., suppliers of energy system assets or fuels, must be evaluated to reduce their environmental impact finally associated with Mayotte.
- The sectoral disaggregation of environmental impacts shows that minimizing the direct emissions within the transport sector in Mayotte will deteriorate the overall environmental performance of the sector compared to when maintaining a current fossil fuel-based system.
- Decarbonizing the household sector on Mayotte (especially via the measures suggested under the MAESHAfocus scenario) shows a great potential for reducing the total environmental burden of the sector, including LPG phase-out and a RE-dominated electricity mix.

Previous visualizations of results that were provided in this report showcased the absolute environmental impacts and the absolute impact of respective sectors (see Figure 20, Figure 21, and Figure 22). For completeness, in addition to the absolute impact of sectors within the five scenarios in Figure 23, Figure 24, Figure 25, Figure 26, and Figure 27 the relative contribution of the relevant sectors are depicted for each of the scenarios. The relative contribution provides may support the identification of potentials for policy-induced incentives and may provide additional insights into the balancing of policy measures to be considered.

Building on the discussion of the environmental performance of the energy system configurations and the findings from the initial sector analysis in this section, hotspot areas are further discussed in the following (Section 4.2). The subsequent analyses will focus dive into the electricity production, transport sector, and household sector to identify the respective driving influencers of environmental. Further, as major contributor to indirect emissions, the environmental impact from assets deployed in the energy system will be evaluated.

BOX: Relative contribution of sectors on environmental impact per ESM scenario

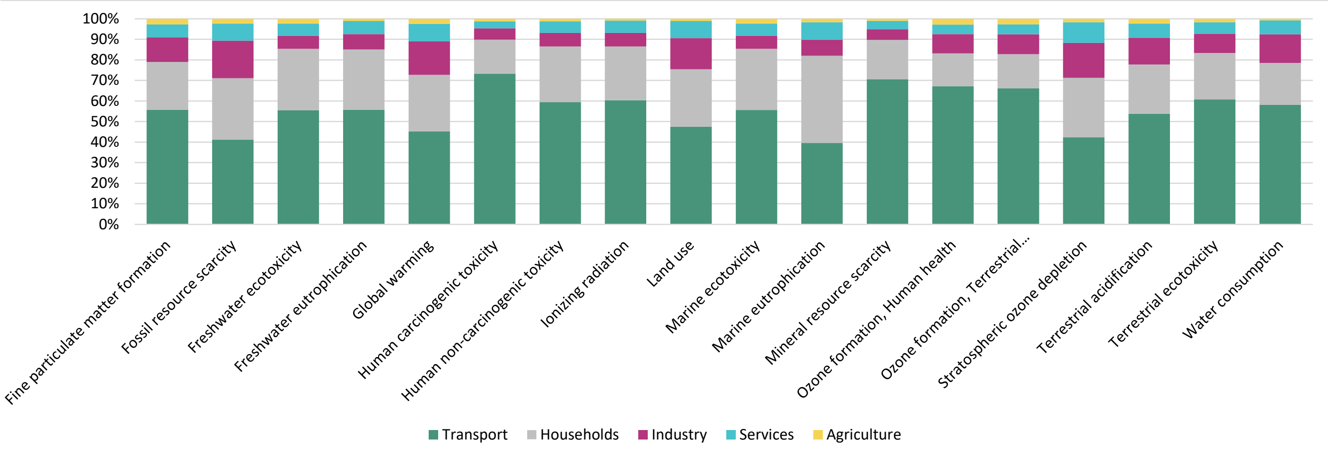

Figure 23: Relative contribution of sectors on environmental impact in the baseline scenario, 2050.

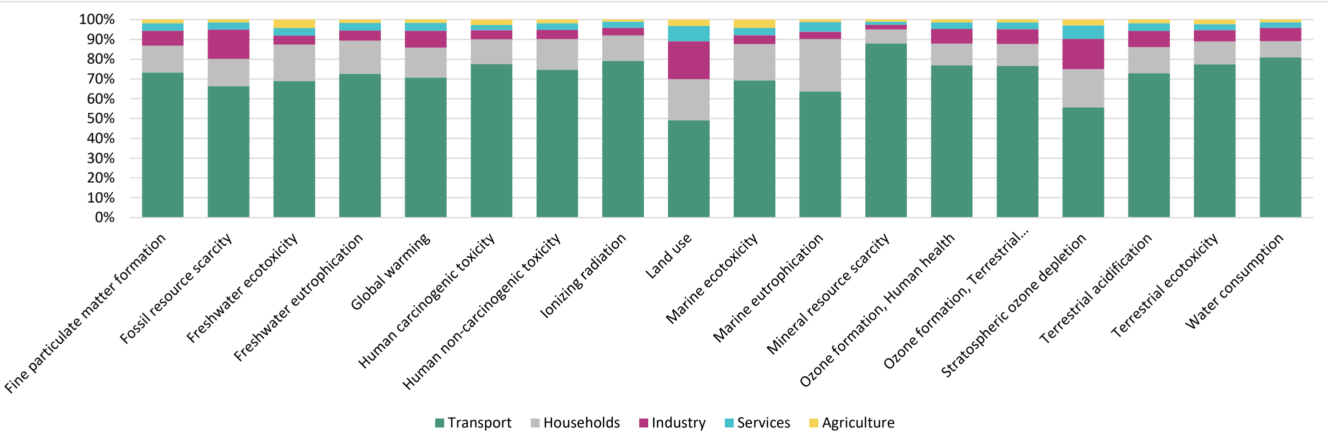

Figure 24: Relative contribution of sectors on environmental impact in the DecarbDemand scenario, 2050.

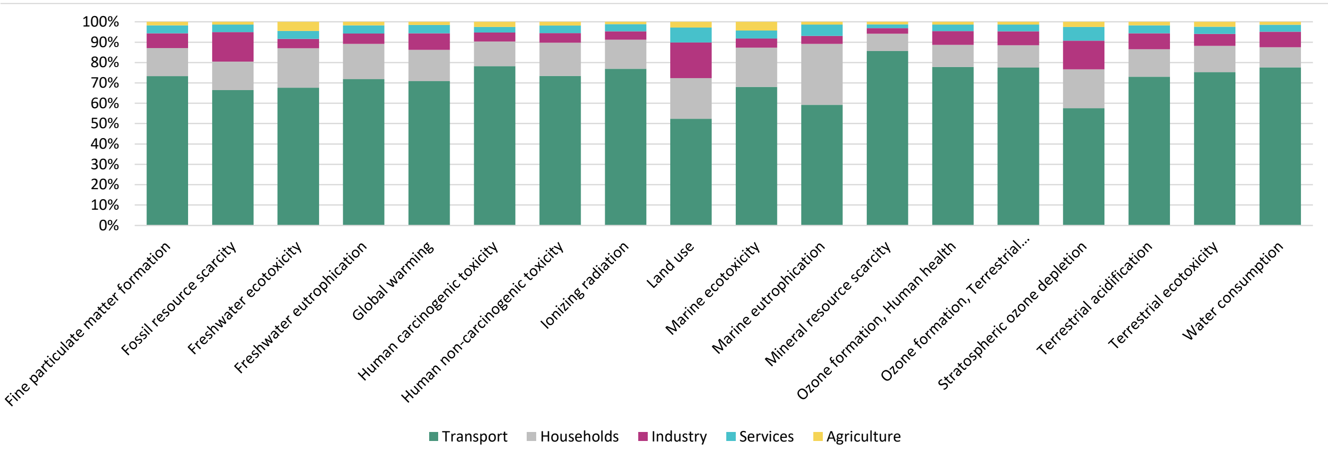

Figure 25: Relative contribution of sectors on environmental impact in the DecarbSupply scenario, 2050.

BOX: Relative contribution of sectors on environmental impact per ESM scenario (continuation)

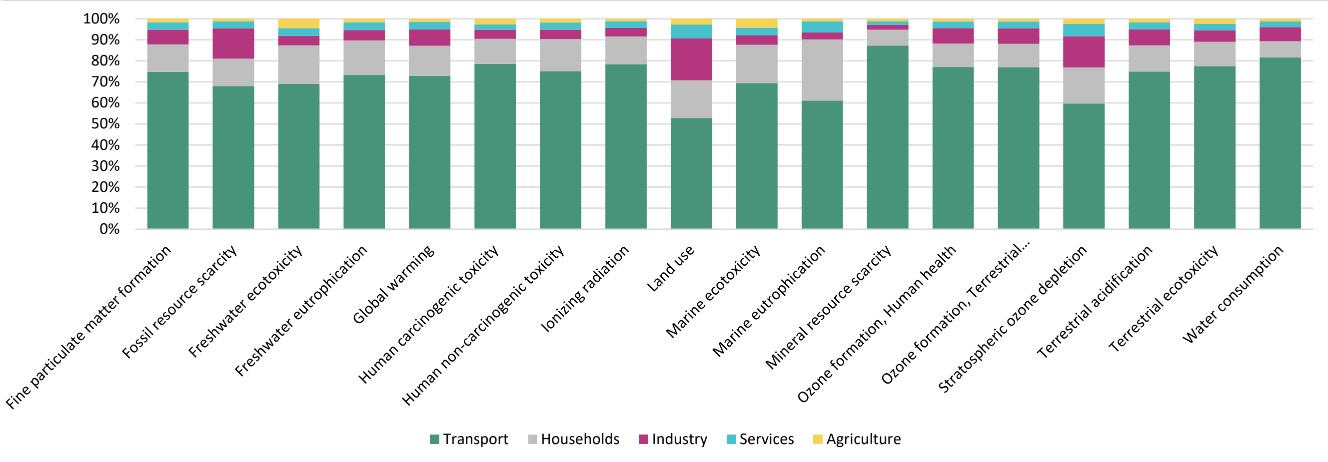

Figure 26: Relative contribution of sectors on environmental impact in the baseline scenario, 2050.

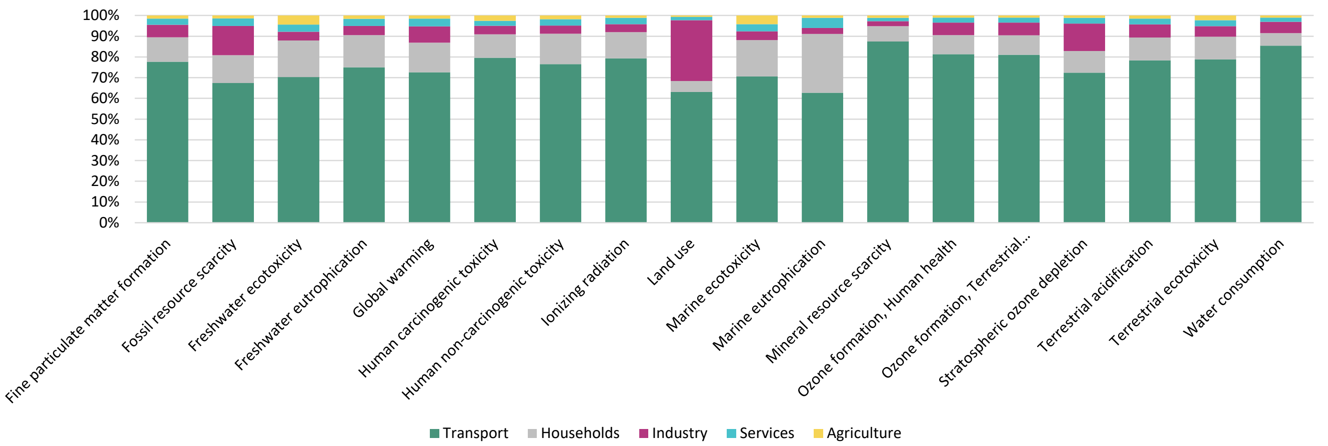

Figure 27: Relative contribution of sectors on environmental impact in the MAESHAfocus scenario, 2050.

4.2. Analysis of Sectoral Hotspots

Based on the observations of the previous section and project-related focus of analysis, the subsequent section investigates in detail the roots and causes of environmental impact in the i) electricity sector, ii) transport sector, iii) household sector, and iv) lifetime of assets. Appendix Table A5.1 holds a table showcasing the structure of analyzing the results of the LCA per impact category.

4.2.1. Electricity Sector

The scenarios as defined per ESM differ in their assumed priorities for the future, economic, and energy-related assumptions as well as political decisions. As many of these assumptions impact the power generation sector, the power plant park and conclusive electricity mix of the resulting energy system scenarios as projected by the reference year of 2050 differs between the scenarios. For a detailed description of the scenarios, the underlying policy assumptions, and the resulting differences in the power generation sector, we refer to MAESHA Deliverable 2.3. The essential differences in the resulting power generation sector are summarized in Figure 28, and Figure 29. Figure 28 shows the installed power capacity per type of power plant scenario by 2030 and 2050, while Figure 29 presents the amount of generated electricity per type of power plant. Notably, both the baseline and MAESHAfocus utilize diesel in the conventional internal combustion (IC) plants whereas the remaining scenarios utilize biodiesel. Further, it must be noted that while the installed capacity of IC plants remains constant across the four decarb scenarios, their energy generation – thereby amount of (bio)diesel utilized – decreases, as the IC plants are increasingly utilized as a flexibility option to balance the intermittent nature of renewable energy sources only rather than producing bulk electricity.

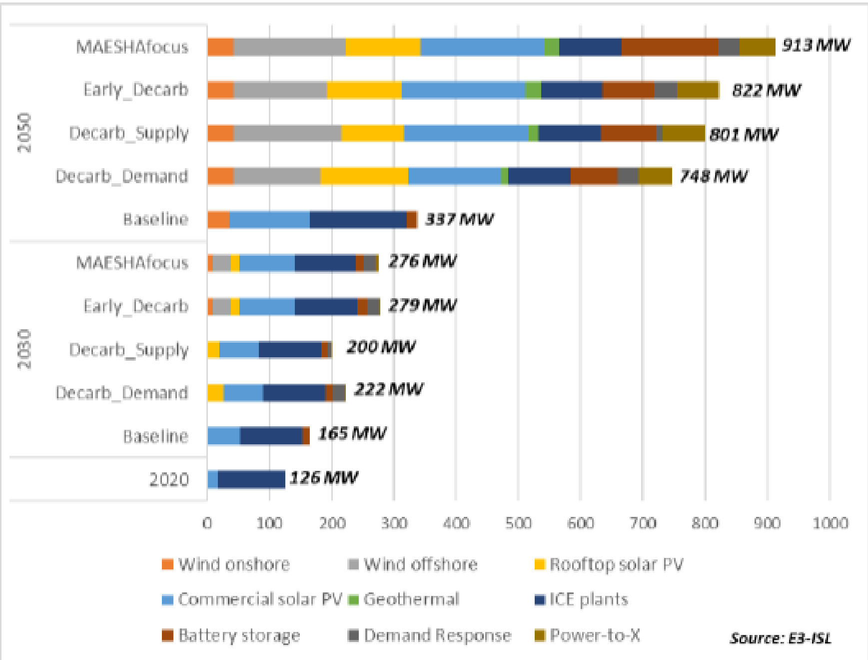

Figure 28: Electricity system configurations in Mayotte according to the ESM in 2050

In contrast to the IC power plant, the electricity produced by RES power plants approximately increases linearly with the installed capacity across the decarbonization scenarios. With the proportion of electricity production from renewable energy sources increasing, in addition to IC power plants providing flexibility to the grid, additional battery storage is required to balance supply and demand. Battery storage is utilized to store excess energy during periods of high renewable energy generation and to provide electricity during low generation periods.

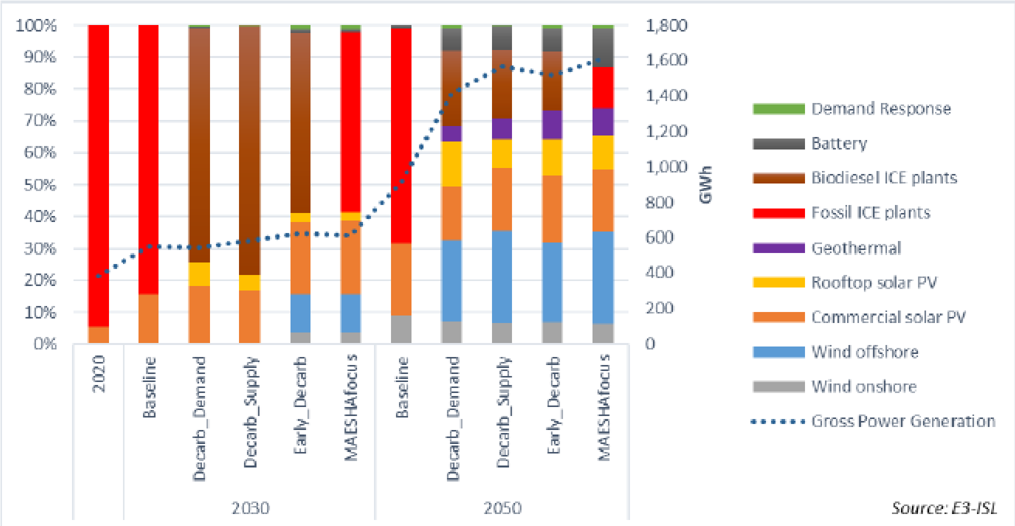

Figure 29: Local electricity production in Mayotte according to the ESM in 2050 [GWh]

The different power plant park configurations across the scenarios cause a difference in the total energy production. Further, the total electricity demand, encompassing direct use as well as electricity needed for the local production of hydrogen and its derivates ammonia, and synthetic liquids, varies across the five scenarios. The variation is due to the different configurations of the overall energy system in accordance with the ESM. The five scenarios are specifically designed to represent differences in the underlying assumptions, for example in terms of the efficiency of end-use assets, energy-saving consumer behavior, or the degree to which the transport sector relies on hydrogen. To compare the environmental impact of the respective resulting electricity mixes, we must define a harmonized reference value (functional unit), for which we choose the electricity generation of 1 GWh. Figure 30 shows the relative contribution of electricity generation per technology type across the five scenarios by 2050. It is crucial to note that this rationale relies on the assumption that the chosen electricity system configuration can be scaled up from 1 GWh to meet the specific electricity demand of each scenario.

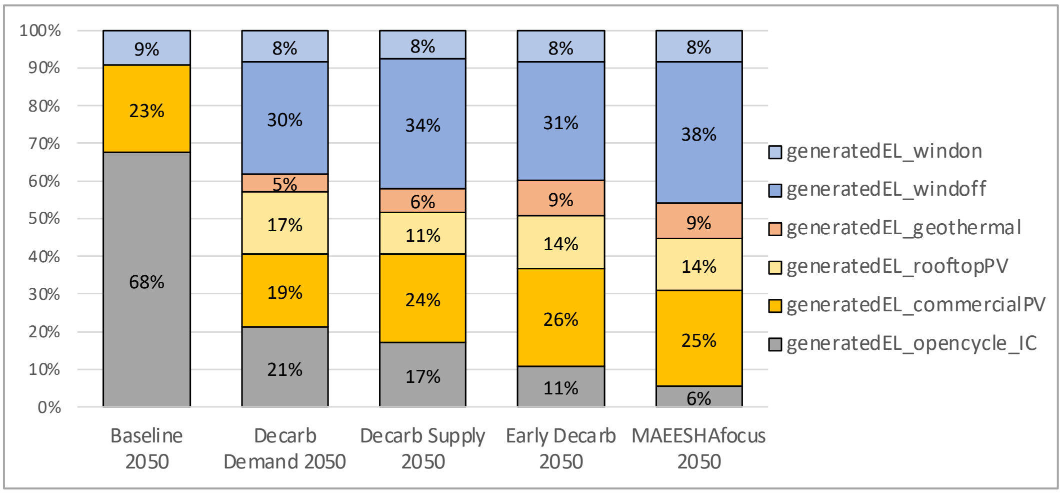

Figure 30: Local electricity mix per GWh in Mayotte according to the ESM in 2050

Figure 31 compares the environmental impact of the different electricity mix scenarios that result when producing 1 GWh of electricity in 2050. We observe a variation of the environmental impact in certain impact categories even across the scenarios avoiding any use of fossil fuels. Further, we observe that all decarbonization scenarios outperform the fossil-fuel based baseline scenario in 7

categories, while causing higher environmental impact in 8 categories. Hence, the increased use of RES and the reduction in use of diesel improves the environmental impact of the power production plant park across the entire life-cycle. The notable reduction in GWP observed across all four decarbonization scenarios (ranging from -83% to -87%) in comparison to the baseline scenario serves as a robustness indicator. This outcome affirms that the decarbonization policies adopted in the decarbonization scenarios successfully achieve substantial GWP reductions compared to the continuation of existing policies (as represented by the baseline), even when assessed from a holistic LCA perspective that considers the entire value chain and life cycle. Again, it is noteworthy to consider the share of direct and indirect emissions stemming from electricity generation. While the ESM, representing the direct emissions, consider $4.6*10^5$ kg CO_2 to be emitted in the base scenario by 2050 per GWh, the LCA calculates $6.55*10^5$ kg CO_2-eq. to be caused via electricity production per GWh. Hence, 30% of the emissions related to the electricity generation are accounted for indirect emissions. Within the decarbonization scenarios (except MAESHAfocus scenario) all emissions can be related to indirect emissions. The early decarb scenario, causing the lowest amount of CO_2 emissions, after all releases $8.3*10^4$ kg CO_2 equivalent per GWh.
However, the results again indicate that improvements in some environmental impact categories – especially GWP – may be achieved through trade-offs in others. In three impact categories - stratospheric ozone depletion, water consumption, and land-use the trends are less robust, as some decarbonization scenarios show less impact than the baseline scenario, while the others show higher impact.

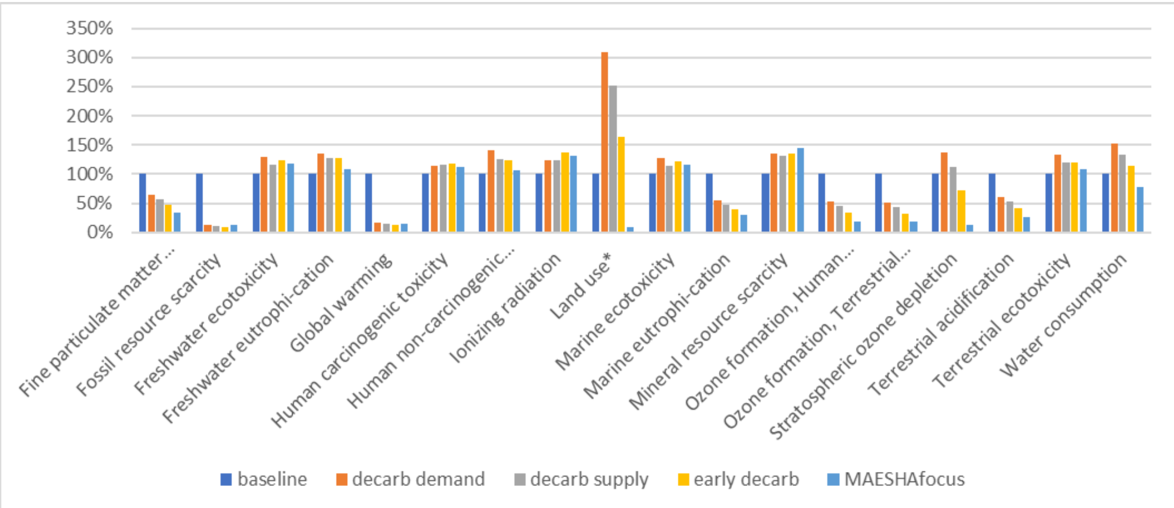

Figure 31: Environmental performance of electricity mix per GWh in 2050 in reference to the base scenario.
***Land use impact of the decarbonization scenarios is divided by a factor of ten.**

Upon initial examination, it becomes apparent that a global optimum, representing a scenario consistently outperforming all others across all environmental impact categories, cannot be identified. When considering all impact categories to be equally important, the MAESHAfocus scenario might indicate to be the most preferable option, exhibiting the smallest overall impact score (1288%) compared to all other decarb scenarios (4730% DecarbDemand; 4017% DecarbSupply; 3056% EarlyDecarb) as well as compared to the baseline (1800%). However, it is important to note that the MAESHAfocus scenario does not achieve the best performance in all environmental impact categories in comparison to the other four scenarios (see Figure 31Figure 31).

The environmental performance of the scenario-specific electricity production configurations in the 17 impact categories beyond GWP goes beyond the scope of the ESM, making them novel findings of this study. Hence, we further explore the (technological) drivers of environmental impacts in the electricity production system in Figure 33. We evaluate the trade-offs across the environmental impact categories for each environmental impact category. **Fehler! Verweisquelle konnte nicht gefunden werden.** indicates that the environmental impact of the baseline scenario is driven by the operation of diesel-based power plants, and emissions released during the combustion of diesel. The combustion of diesel releases SO_2, NO_x, and PM with high FPM, nitrogen oxides and non-methane volatile organic compounds (NMVOC), which have high ozone formation potential and harmful for the stratosphere. Earlier in the lifecycle, the production of oil as an upstream process in diesel production causes a negative impact on fossil resource scarcity.

While the environmental impact of a power production system relying on fossil fuels is dominated by the operation of IC plants, the environmental impact of decarbonized electricity systems is influenced by the assets within. Many RES plants, and storage systems, require mineral resources, the production of which may cause environmental footprint in especially ionizing radiation (IR) and mineral resource scarcity (MRS). The deterioration of the decarbonization scenarios in the domain IR (between 124% and 136% of the baseline scenario) is almost exclusively attributed to the global ecoinvent electricity mix, which includes a certain proportion of nuclear power. This global electricity mix is incorporated as part of the ecoinvent database in the underlying manufacturing processes to model the power plants and batteries deployed in the respective decarbonized electricity systems. Since Mayotte does not utilize nuclear power within its electricity mix, the responsibility for the performance in terms of IR lies with nations that do rely on nuclear power. It is worth noting that the performance of Mayotte's electricity mix in terms of IR will automatically improve if there is a shift away from nuclear power in the global electricity mix.

Especially the MAESHAfocus scenario performs poor in the mineral and resource scarcity (145% in reference to the baseline scenario). The deterioration of MAESHAfocus in this domain is largely driven by the manufacturing of batteries that are used to balance intermittent RES electricity production, as well as the manufacturing of RES power plants. The production of the battery cells and the electronic components require the exploitation of cobalt, nickel, manganese (silicon, copper, iron, magnesium, aluminum, molybdenum etc.).

When decarbonizing electricity systems via increased utilization of biodiesel in IC plants, trade-offs in land-use must be considered. The production of biodiesel is land-intensive with changes of the available land cover and land-use intensification. The production of biodiesel exhibits a high land occupation due to intensive forests for wood chops, while the combustion releases emissions like conventional diesel. To further investigate the impact of the usage of biodiesel, we analyze the change in environmental impact a fuel switch from conventional diesel to biodiesel would cause in the framework of the MAESHAfocus scenario. To further investigate the impact of the usage of biodiesel, we analyze the change in environmental impact a fuel switch from conventional diesel to biodiesel in would cause within the MAESHAfocus scenario. Therefore, the MAESHAfocus scenario has been adapted assuming the use of biodiesel, while all other parameters remain the same as in the original configuration of MAESHAfocus. The results are then compared to the original diesel-based configuration of MAESHAfocus to analyze the implications of the biodiesel switch. Figure 32 illustrates the relative deviation between the performance scores of the diesel-based and the biodiesel-based MAESHAfocus configuration (percentage points), both in terms of the performance of the electricity mix per GWh, and the performance of the overall energy system of Mayotte. The effects on the electricity mix are depicted by the lighter-shaded bars on the left, while the darker-shaded bars on the right represent the effects on the overall energy system.

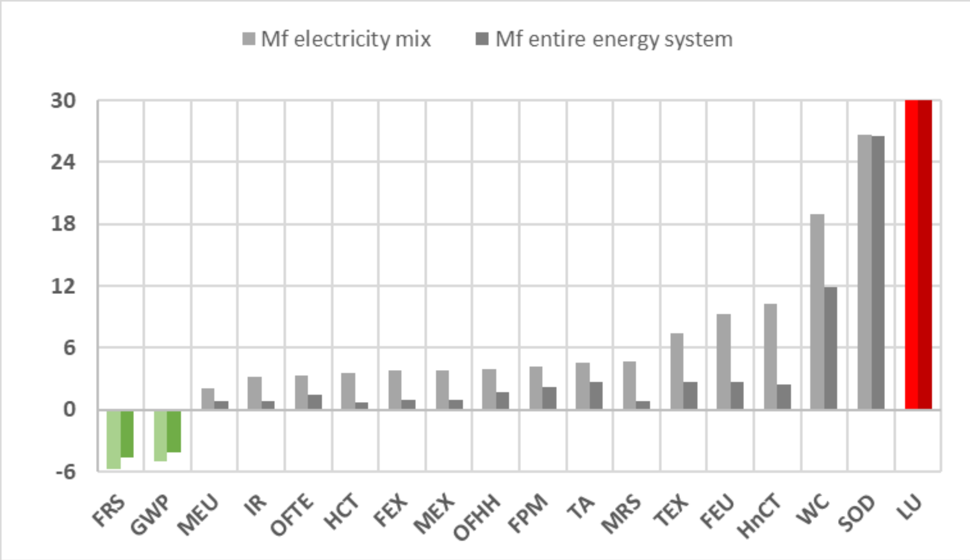

Figure 32: Switching from diesel to biodiesel: implications for the Mf a) electricity mix b) entire system.

A switch to biodiesel yields improvements of 5 and 6 percentage points (pp) in terms of environmental impact in the GWP and fossil resource scarcity categories, compared to the conventional diesel configuration. However, the performance in all other 16 environmental impact categories deteriorates. While 10 impact categories show deteriorations of up to 10 percentage points, which can be considered trade-offs in the context of mitigating global warming, there are significant deteriorations in water consumption (19 pp), stratospheric ozone depletion (27 pp), and land use (718 pp) due to the biodiesel production.

Conclusive remarks: We conclude on the preceded:

- The decarbonization policies and measures as assumed under this study promote a substantial reduction of the GWP impact of the electricity sector compared to the continuation of existing policies (as represented by the baseline). The trend is robust when considering the indirect emissions over the lifecycle of the system in addition to direct emissions released during power production.
- While the environmental impact of fossil fuel-based electricity systems is dominated by operational processes (i.e., combustion of diesel), the environmental footprint in decarbonized electricity systems stems from upstream processes and construction of energy system assets. Thus, sustainable production methods and alternative resources to currently depleted minerals should be fostered.
- A fuel switch from conventional diesel to biodiesel for usage in the electricity sector reduces the GWP but is associated with many trade-offs, i.e., land-use. Policies or decisions suggesting a switch to biodiesel must therefore carefully be considered and measures for sustainable biodiesel production methods may be fostered.

Figure 33: Environmental impact of the electricity sector per GWh: technological drivers.

4.2.2. Transport Sector

Analogous to the electricity sector, the different transport-related policies, measures, and priorities as assumed in the energy system scenarios lead to different assets and use of energy in the transport sector. We compare the environmental impact resulting from the different assumptions based on the lifecycle of the transport sector related assets and their operation as determined via the ESM by 2050.

Figure 34 quantifies the relative environmental impact associated with the transport sector for the four decarbonization scenarios with the baseline scenario as a reference. The baseline scenario presents a continuation of current policies and a resulting fossil-fuel-based transport sector. In addition, Figure 35 provides in-depth insights into the contribution individual processes to the environmental impacts of the transport sector for the baseline scenario and the MAESHAfocus scenario. We disaggregate the environmental impact across the different categories per process. For the means of simplification, we focus on a visual representation comparing the base scenario and the MAESHAfocus scenario system configuration by 2050, as the MAESHAfocus is the best-performing decarbonization scenario when considering equal weighting of the impact categories.
As the transport sector is dominated by the environmental impact of the entire energy systems (see Section 4.2.), we observe a similar trend as in the previously analyzed sectors. Again, decarbonization measures show a robust trend to reduce the GWP (ca. 35%) compared to maintaining current sector-specific measures. Further, the decarbonizing of transport in Mayotte would reduce the impact of ozone formation on human health (-37%) and ozone formation terrestrial ecosystems (-38%). Avoiding the use of diesel and related upstream processes reduces the fossil resource scarcity (-40%). However, these environmental improvements may be encountered by increased environmental impact in all other environmental impact categories, which will be detailed below.

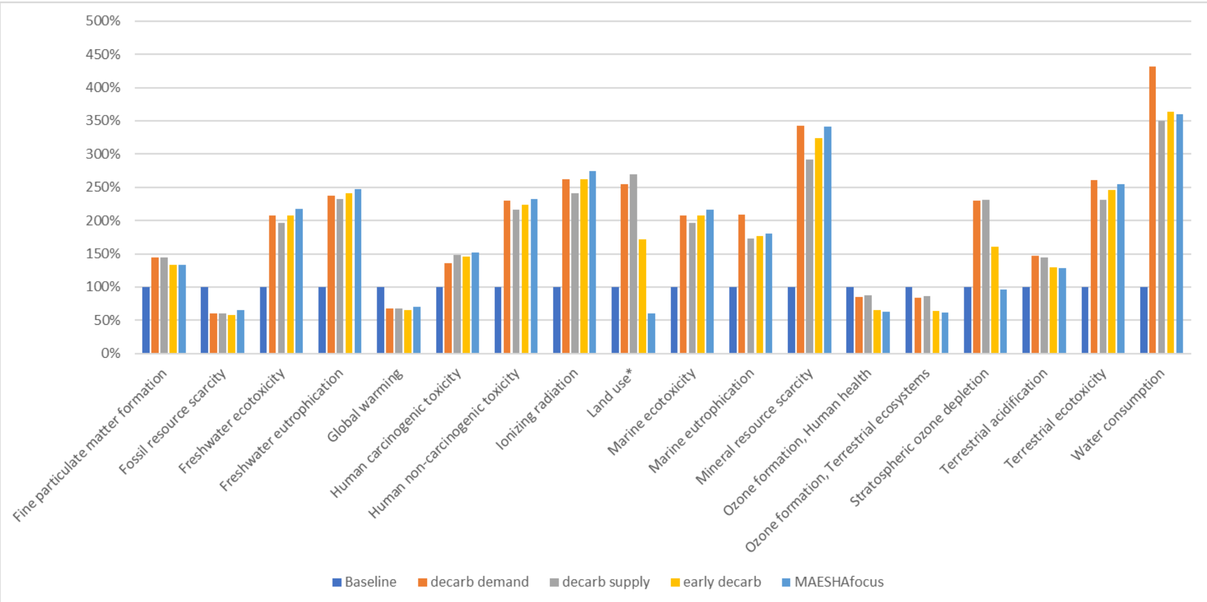

Figure 34 Environmental performance of the transport sector normalized in reference to the base scenario.
***Land use impact of the decarbonization scenarios is divided by a factor of ten.**

The environmental impact within the baseline scenario is driven by operational prosses of the sector including the production of fossil fuels, and combustion of diesel. This is a in line with the findings regarding the electricity sector (Section 4.2.1). In the baseline scenario, the combustion of other fuels (kerosene, gasoline) contributes less to the environmental impact in Mayotte, due to less usage. By 2050, 651 GWh diesel are required within the transport sector according to the ESM, while only 322 GWh gasoline and 166 GWh kerosene are utilized respectively. Diesel combustion in ICEs in the transport sector entails a low efficiency. Hence, the total energy demand in the transport sector is higher when relying on fossil fuels than when switching to the alternatives battery electric vehicles (BEVs) or fuel cell electric vehicles (FCEVs). To illustrate the higher total anergy consumption we compare the energy consumption between the scenarios. In the baseline scenario total energy demand in the transportation sector adds up to approximately 700 GWh compared to 300 GWh in the decarbSupply scenario, which presents the maximal total energy demand among all decarbonization scenarios. The combustion of diesel contributes to the emission of fine particulate matter, through the release of SO_2, NO_x, and PM with high FPM potential. Furthermore, it deteriorates ozone formation, as the diesel combustion releases nitrogen oxides and non-methane volatile organic compounds (NMVOC), which have high ozone formation potential.

To detail the drivers of environmental impact within the transport sector, we disaggregate the transport sector into i) road transport, ii) marine navigation, and iii) aviation. In the following, each subsector will be analyzed separately. To accurately isolate and assess the differences specific to the decarbonized scenario-based road transport configurations, the analysis is conducted in an electricity-mix-adjusted manner, assuming the implementation of the MAESHAfocus electricity mix for each of the five scenarios. Hence, any variations in performance encountered will solely arise from differences in the road transport subsector configuration and not from underlying differences in the electricity mix, which were analyzed in Subsection 4.2.1. In the following, each subsector i) road transport, ii) marine navigation, and iii) aviation will be analyzed separately.

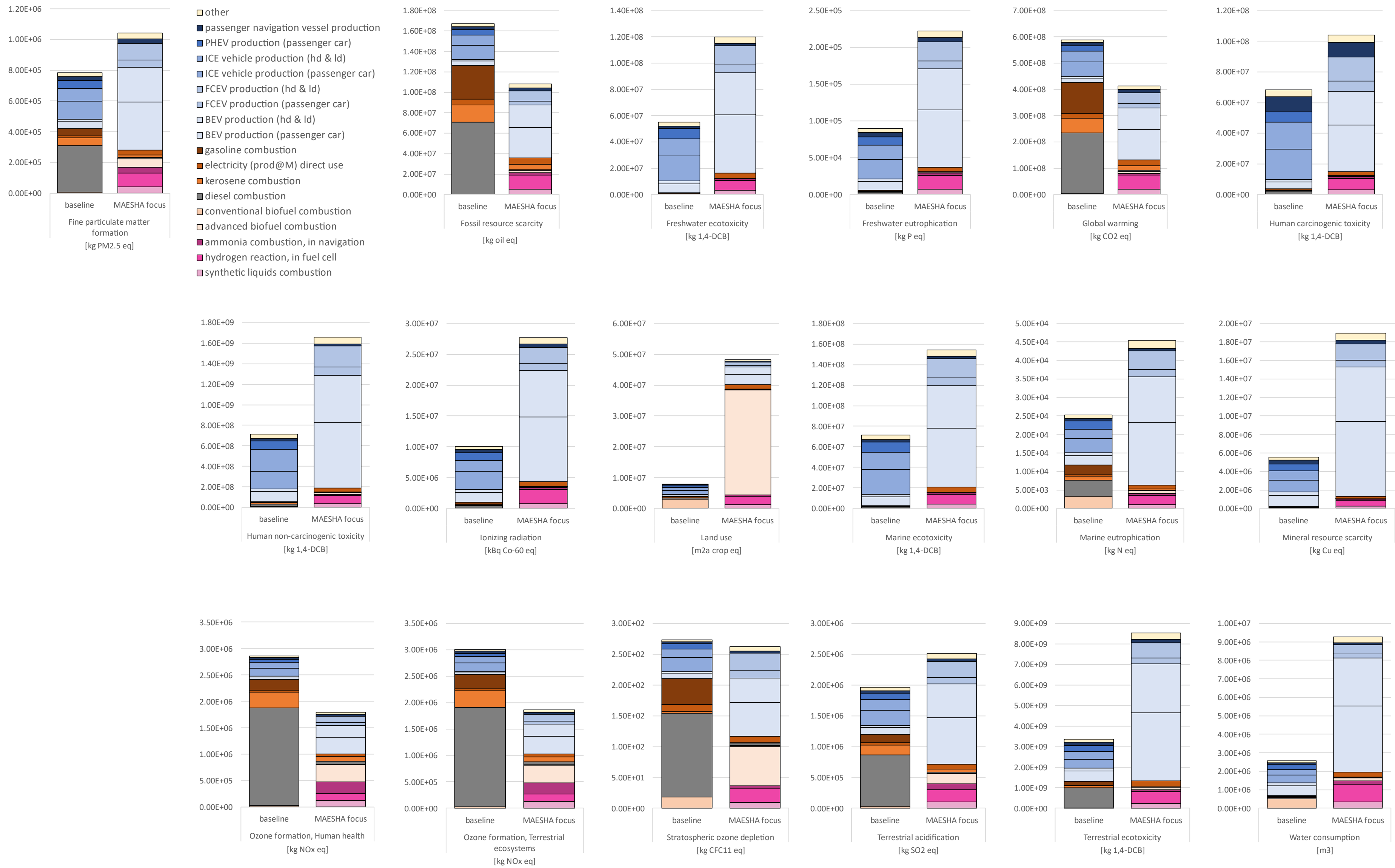

Figure 35: contribution of processes to environmental impact in the transport sector, comparing the MAESHA focus scenario and Base scenario.

Road transport

The road transport in Mayotte is dominated by passenger cars. As of 2023 passenger cars are exclusively conventional ICEs vehicles. When maintaining the current efforts in the sector regarding policy-induced adaption, as is represented by the baseline scenario, it can be expected that 91% of the 176,317 vehicles may run on conventional fuels by 2050. Depending on the political instruments and efforts to increase the market penetration with climate friendly alternatives, the different decarbonization scenarios, as explored via ESM, show a varying composition of vehicle fleet, composed of primarily BEVs and FCEVs. The composition of the vehicle fleet in the five investigated scenarios is depicted in Figure 36. Notably, the share of BEVs exceeds the share of FCEVs in all decarbonization scenarios, with the extrema being the decarbDemand (only 2% FCEVs, 97% BEVs). The total number of vehicles in 2050 is in the same magnitude in all scenarios. The slight variations can be attributed to differences in the modelled economic development.

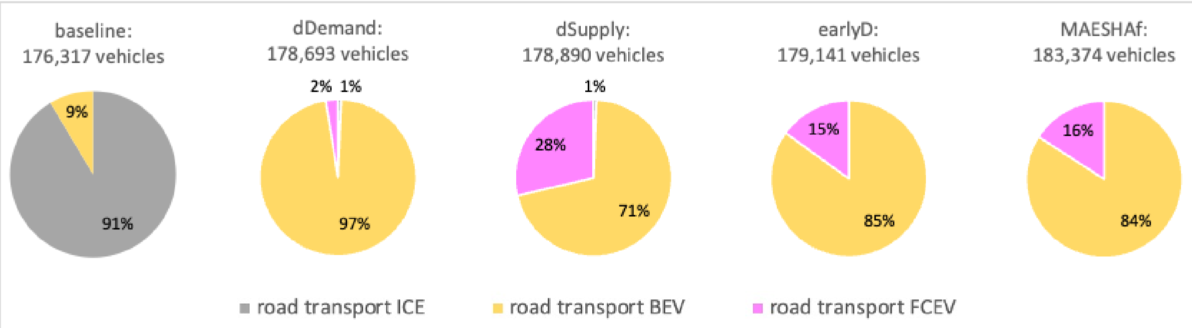

Figure 36: Scenario-specific road vehicle fleet by drive technology according to the ESM.

The results of the LCA suggest that there is a potential for overall environmental improvements through the promotion of BEVs and FCEV. Figure 37 shows that for selected environmental impact categories, namely GWP, ozone formation impact on human health and terrestrial, and stratospheric ozone depletion there is a potential for a reduction in the environmental impact by 2050. Strengthening decarbonization measures in the transport sector, as is contained in the decarbonization scenarios, shows robust trends to improve the GWP impact over the entire lifecycle. However, the reduction in GWP is associated with trade-offs in other environmental impact categories, as the measures lead to an increase in 13 out of 18 impact categories.

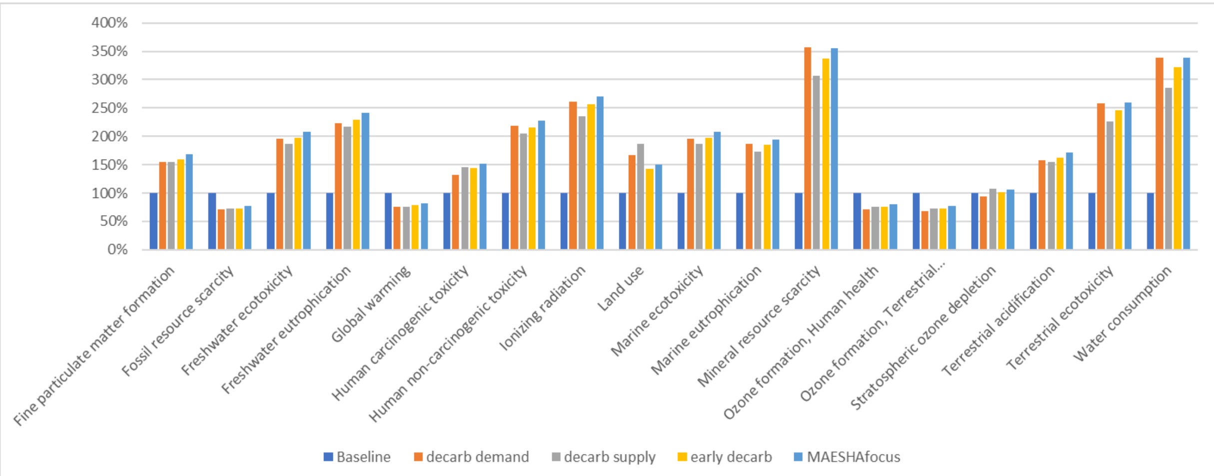

Figure 37: Environmental impact across scenarios within road transport, with the electricity mix being harmonized to the MAESHAfocus scenario-specific mix.

In all decarbonization scenarios the majority of vehicles in operation in 2050 are BEVs. The environmental impact of the vehicle as an asset dominates the overall environmental footprint of the transportation sector within the decarbonization scenarios, as is shown in Figure 35. When considering the lifecycle of BEVS, many environmental impact categories become relevant. For example, the copper production, which is an upstream process of the battery cell production, and waste treatment processes of batteries emit copper ions, zinc II, silver I and antimony ion into water resources, which cause freshwater ecotoxicity. The treatment processes of sulfidic tailings from copper/cobalt/gold/silver mine operations emit phosphate into water sources, leading to freshwater eutrophication. These treatment processes are required as part of the production and beneficiation of copper/cobalt to produce copper collector foil, cathodes, and anodes for the battery cell. The treatment processes of electric arc furnace slag required in producing steel, e.g., for the glider and electric motor of a BEV emit chromium and other toxic trace elements into water sources, which are carcinogenic intense. Further, non-carcinogenic toxicity is a consequence of the treatment processes of sulfidic tailings, copper slack and smelting of copper concentrate, which emit trace elements including arsenic, zinc II and lead II. The value chain of battery cell production is very electricity intense (e.g., upstream production of cobalt). As the global electricity mix is assumed to entail a certain share of nuclear energy (consistently across all scenarios) it does require treatment of tailing from uranium milling which releases radon, increasing the ionizing radiation level. The treatment processes of sulfidic tailings from copper mine operation and EoL treatment of scrap copper and used gliders emit copper ions, zinc II, silver I and antimony ions (and other toxic trace elements), promoting marine ecotoxicity. Rare earth mine operation and beneficiation releases wastewater rich in nitrogen, ammonium, and nitrate, which accelerate marine eutrophication. These operation and beneficiation processes are for instance, part of the value chain of lithium carbonate and cobalt production, which are required to produce battery cells. Further, the battery cells and electronics of a BEV require the exploitation of cobalt, nickel, manganese (silicon, copper, iron, magnesium, aluminum, molybdenum etc.), which not only reduces the resources of the minerals but also is water and electricity intense.

The fundamental significance of BEVs, as the primary cause of environmental impacts across the impact categories inevitably raises the question, whether from an environmental perspective it is feasible to support a switch towards FCEVs, or if the mode of transport is a lose-or-lose situation and only reduction of vehicles is environmentally sound. To elaborate on this question, we consider the two decarbonization scenarios that pose that showcase the strongest deviation in terms of the vehicle fleet composition. In the DecarbDemand scenario, 97% of the road transport's end-use assets are BEVs (see **Fehler! Verweisquelle konnte nicht gefunden werden.Fehler! Verweisquelle konnte nicht gefunden werden.**). Alternatively, DecarbSupply advocates for a more balanced approach between BEVs and FCEVs, with 71% of the road transport's end-use assets being BEVs and 28% being FCEVs. These configurations present two deviating target configurations with the aim of decarbonizing road transport. While DecarbDemand emphasizes the extensive adoption of BEVs, DecarbSupply takes a more diversified approach by incorporating BEVs and FCEVs. The remaining decarb scenarios fall somewhere in between these two poles. Therefore, the subsequent analysis focuses on comparing the environmental performance of DecarbDemand and DecarbSupply to determine their respective strengths and weaknesses in achieving sustainable road transport solutions. When comparing the electricity mix-adjusted environmental performance of the road transport of DecarbDemand and DecarbSupply, the differences resulting from shifting from the BEV-dominated vehicle fleet of DecarbDemand to the more diversified vehicle fleet of DecarbSupply can be quantified in percentage points. The percentual differences in environmental impacts that result from switching from the DearbDeamdn to the DecarbSupply vehivle composition are shown in Figure 38. It is evident that some environmental impact categories show more significant deviations in their performance between DecarbDemand and DecarbSupply than others. There are five impact categories that exhibit differences of more than 15 percentage points (pp) between DecarbDemand and DecarbSupply.

Especially MRS and WC show a significantly better performance in DecarbSupply than in DecarbDemand.

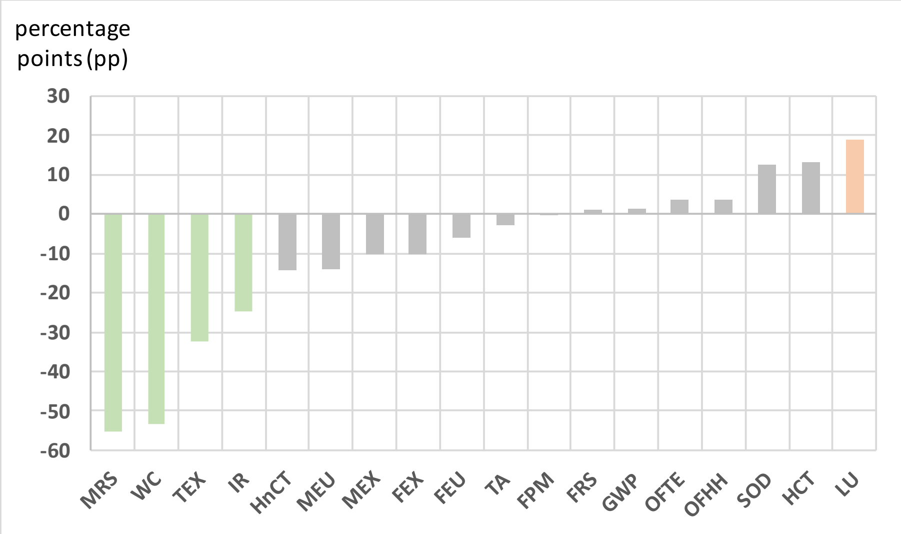

Figure 38: Implications of switching from DecarbDemand to DecarbSupply on the environmental performance of road transport.

The identified differences in the environmental performance of the two considered fleet composition suggest that, when all environmental impact categories are weighed equally a diversified road vehicle fleet as in DecarbSupply, can be considered preferable for. This preference holds true not only when all environmental impact categories are weighed equally but also when focusing solely on those categories with a difference of more than 15 percentage points between DecarbDemand and DecarbSupply.

Marine transport and navigation

Given the islands' geography, the navigation subsector holds particular importance in the overall energy system. Further, in December 2019, the European Union committed to extend the EU emissions trading system to shipping. Therefore, decisions in the navigation sector are of particular importance and must carefully be considered, while including environmental evaluation.

Depending on the policy efforts in decarbonizing marine transport and navigation, that are followed in the decarbonization scenarios, energy carriers, other than diesel may be utilized. In Figure 39 the total energy consumption and percentual contribution of the different applicable energy carriers is depicted. Even though according to the ESM, the total number of ships remains is forecasted to be the same in all scenarios, namely 109 vessels, their propulsion technologies (electric, fuel cell and internal combustion engines) vary. These differences are reflected in the scenario-specific final energy carrier mixes, as illustrated in **Fehler! Verweisquelle konnte nicht gefunden werden.**.

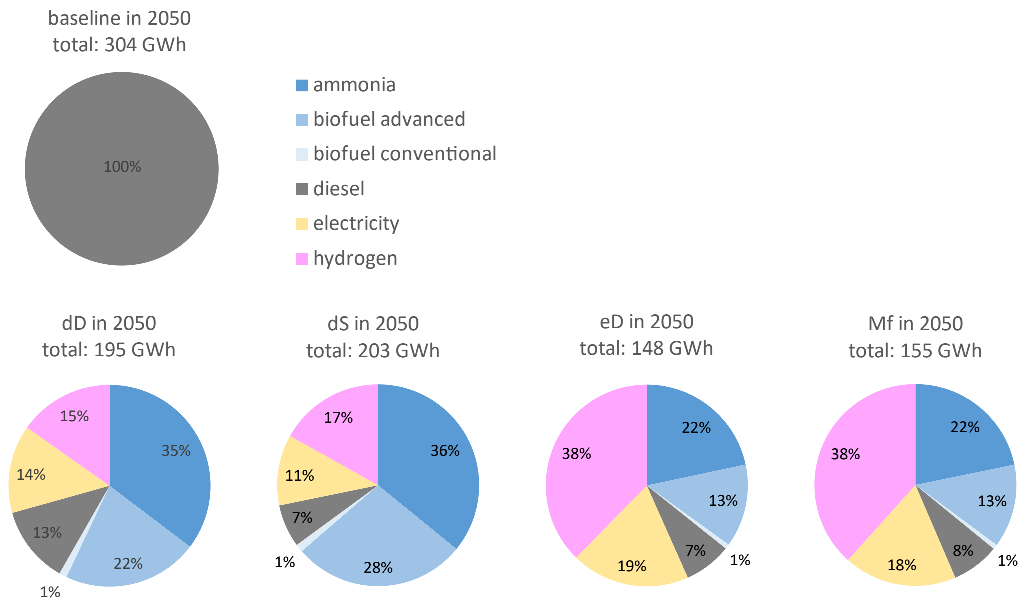

Figure 39: Scenario-specific final energy carrier demand of navigation subsector according to the ESM.

The final energy mix within the marine and navigation sector of the EarlyDecarb scenario consists of significantly more hydrogen (38%) compared to the DecarbDemand (15%) and DecarbSupply (17%) scenarios. Further, a higher percentage share of final energy is supplied directly via electricity (19% compared to 14% and 11% respectively). In contrast, less biofuel is used in the EarlyDecarb scenario (13%) compared to the DecarbDemand (22%) and DecarbSupply (28%) scenarios. The same trend applies to ammonia (22% compared to 35% each). This fuel mix additionally demonstrates a substantial reduction in the demand for final energy in absolute terms. In fact, the EarlyDecarb configuration achieves the functionality of the navigation subsector with approximately 27% less GWh of final energy compared to the DecarbSupply scenario. This disparity suggests that the end-use assets in the baseline configuration are less efficient compared to the EarlyDecarb scenario. The increased vessel efficiency in the EarlyDecarb scenario can be attributed to the use of electric and fuel cell vessels, which are more energy-efficient than IC vessels.

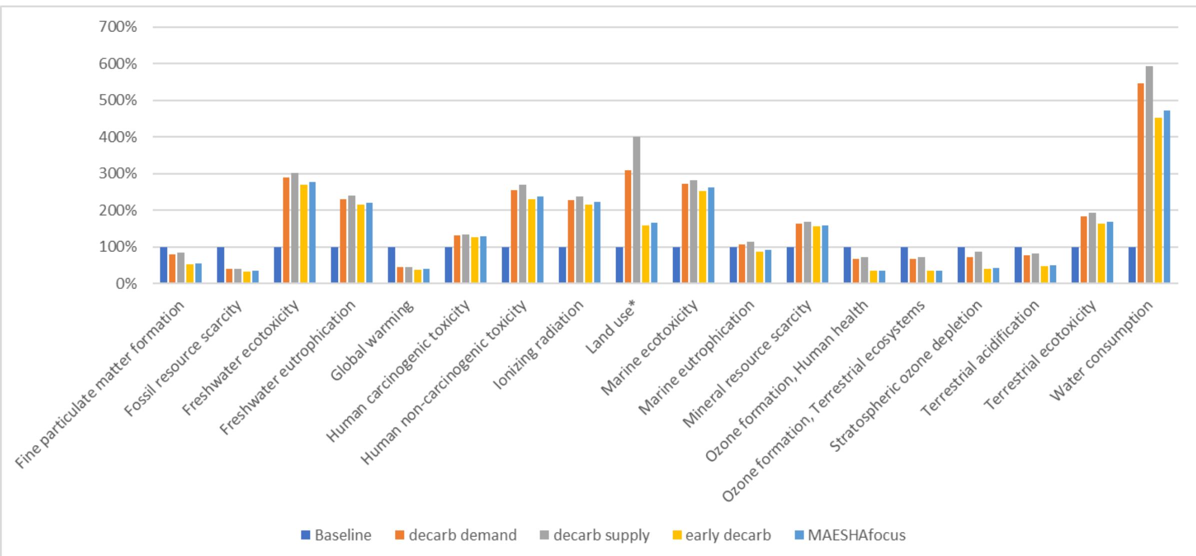

Figure 40: Environmental impact across scenarios within marine transport, with the electricity mix being harmonized to the MAESHAfocus scenario-specific mix. *Land use: impact of decarbonization scenarios divided by a factor of ten.

In accordance with the different energy carrier and propulsion technologies specified in the ESM, the environmental impact associated with the respective decarbonization measures and resulting navigation and marine transport sector varies.
As was observed, in the analysis of other sectors and subsectors, there are trade-offs to achieve GWP reductio. Essentially, 81% of the significant land use calculated as impacted within decarbonized marine sectors are caused by production of crops for biofuel. Further, decarbonizing the marine sector via hydrogen and ammonia energy carriers causes negative impact on the water consumption (68% of the total water consumption in decarbonization scenarios). On the other hand, biofuel-related water use accounts for only 10% of Decarb's water consumption. Further impacts of biofuel are ozone formation, and stratospheric ozone depletion.
The comparison of the four scenarios, tat each entail different decarbonization measures, shows that the measures taken under the EarlyDecarb scenario result in the least environmental damage across all considered impact categories. The MAESHAfocus scenarios showcases very similar results with only slightly higher impacts compared to the EarlyDecarb. The findings suggest that the direct use of hydrogen in contrast to further processing to hydrogen-derivates, and utilization in fuel cells is preferable. However, due to the long lifetime of ships and other assets in the marine sector, a decarbonization via new, net-zero ships entering the market in the future, is unlikely to deeply penetrate the market until 2050. Therefore, we suggest efforts in exploring the retrofit of existing ships with fuel cells. Early evidence in this fields suggest a relative ease of doing so. For example, Mao et al. described only “minor changes” to fuel capacity (i.e., reducing cargo-space) and operations to be required when replacing 99% of the ship-based voyages between the United States and China [97]. Related European projects have been initiated among others in Norway, France, and Belgium.

Decarbonizing the navigation sector (and aviation sector, see Subsection 4.2.2) as suggested by the ESM requires significant amounts of hydrogen and it´s derivates ammonia and synthetic liquids. With the global decarbonization proceeding, it is expected that an international market for hydrogen and derivates will establish (see e.g., [98]). In fact, by 2050 the market volume, based on energy, may reach an order comparable to today´s global natural gas markets [98]. In contrast to fossil fuels, renewable hydrogen can technically be produced anywhere in the world through water electrolysis, with the renewable energy potential and water resources as the decisive factors. Hence, countries can meet their hydrogen demand either through domestic hydrogen production or the acquisition on international markets and the import of hydrogen. While this discussion may be dominated by economic factors, such as the costs of production and transport (see [99]), and political motives, such as energy security, our analysis can contribute to the debate on sourcing hydrogen by investigating the environmental effect of importing hydrogen and it´s derivates or domestic production for the case of Mayotte. In the prior parts of this report, in accordance with the ESM, it was assumed that 50% of the needs for hydrogen, ammonia and synthetic liquids will be acquired through imports. This assumption is also is in line with other literature (e.g., [100]). This decision was further justified with the limited size and availability of renewable resources in Mayotte. To investigate the environmental impact of importing hydrogen, as opposed to producing it locally, we conducted an additional analysis, in which we varied the share of domestically and externally produced hydrogen and derivates of the total required hydrogen. In this analysis we included the comparatively small amounts of hydrogen utilized in road transport and in the electricity sector. We varied the share of imported hydrogen and its derivates in 25% intervals, ranging from 100%, which represents no local production in Mayotte, to 0%, which implies entirely domestic production in Mayotte. For the analysis the MAESHAfocus scenario was selected, as the overall most preferable decarbonization scenario.
The results presented in Figure 41 indicate that, from an environmental perspective, a higher share of domestically produced hydrogen and its derivates is favorable, as achievements in all environmental impact category can be observed. However, the environmental advantage gained can be considered limited. Even in the extreme case of 0% imports, the most significant change observed is a 5% improvement in GWP compared to an energy system relying entirely on imports of hydrogen and its

derivates. As of these comparably small differences in environmental impact, the discussion on whether to import or domestically produce hydrogen and derivates must be sophistically evaluated from other dimensions, including a social, political, and economic dimension.

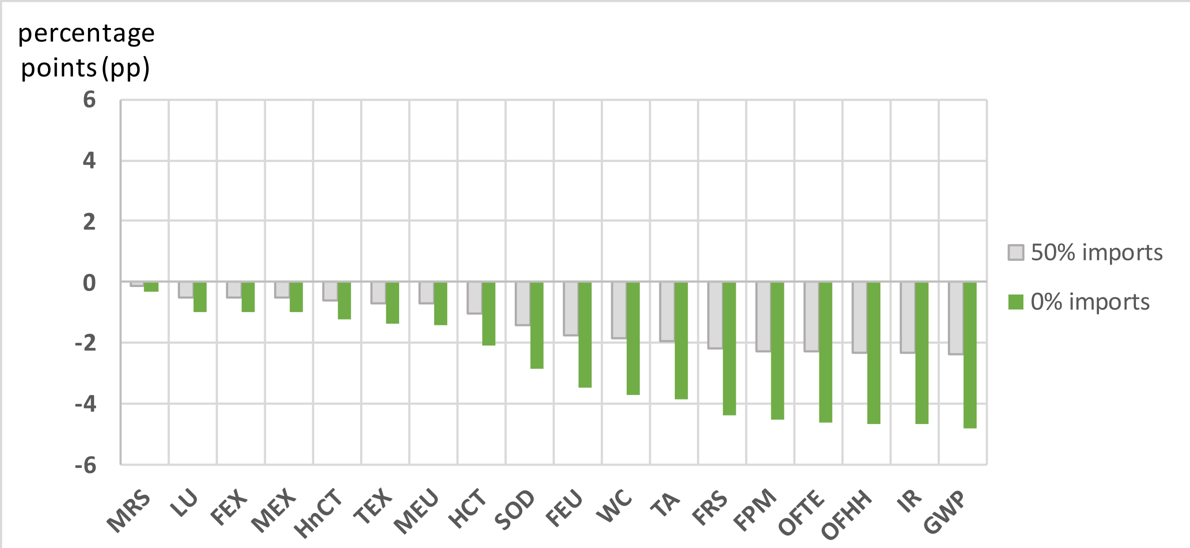

Figure 41: Relative difference in environmental impact of import shares of H_2 and derivates on the performance of MAESHAfocus compared to 100% imports

Aviation

Because the aviation industry is a minor contributor to transportation in Mayotte, the impact on the total transport sector is most likely not be as significant as on other islands, especially islands where the tourism industry is strongly developed. However, decarbonizing the aviation sector in an environmentally sound manner from a life cycle perspective is extremely challenging. Options to decarbonize aviation include advanced biofuels, and synthetic liquid, a mixture of hydrogen and carbon oxides. Under the projected economic development of Mayotte, the ESM assumes the total number of aircrafts to remain constant at 11 until 2050 across all five scenarios. The fuel mix utilized within, however, differs with the underlying assumptions. The utilized fuel mis is shown in Figure 42. When maintaining current policies in the aviation sector, solely kerosene would be used to fuel aircrafts in Mayotte by 2050. The ESM results show that policies promoting decarbonization can induce a fuel switch towards biofuel, or synthetic liquids. The resulting fuel mix across the scenarios relies on an almost equal share across all scenarios of synthetic liquids (ca. 37%), and advanced biofuels (30%), while remaining a share of kerosene (ca. 30%).

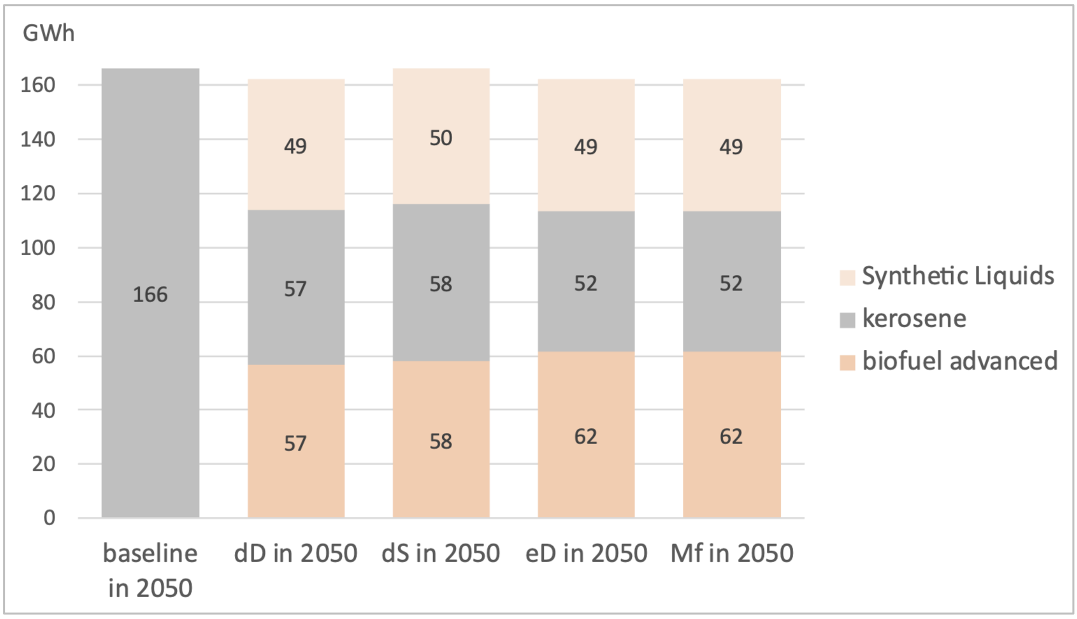

Figure 42: Scenario-specific final energy carrier demand of aviation subsector according to the ESM

The environmental impact of the aviation subsector with an adjusted electricity-mix, namely the MAESHAfocus electricity-mix, is shown in Figure 43. The environmental impacts resulting from the partial fuel switches in the decarbonization scenarios support the trends discovered within the previous transport-related sectors. In fact, the options to decarbonize the aviation sector may only improve the environmental impact of the sector to reducing GWP and fossil resource scarcity (FRS). In any other impact category, negative trade-offs are expected when reducing the share of fossil kerosene as a fuel. Notably, freshwater ecotoxicity and eutrophication, stratospheric ozone depletion and mineral resource scarcity outrank the environmental impact of the base scenario by a magnitude of ten, while the impact on land use is even multiplied by a factor of hundred. The significant impact on land-use is dominated by the use of biofuels.

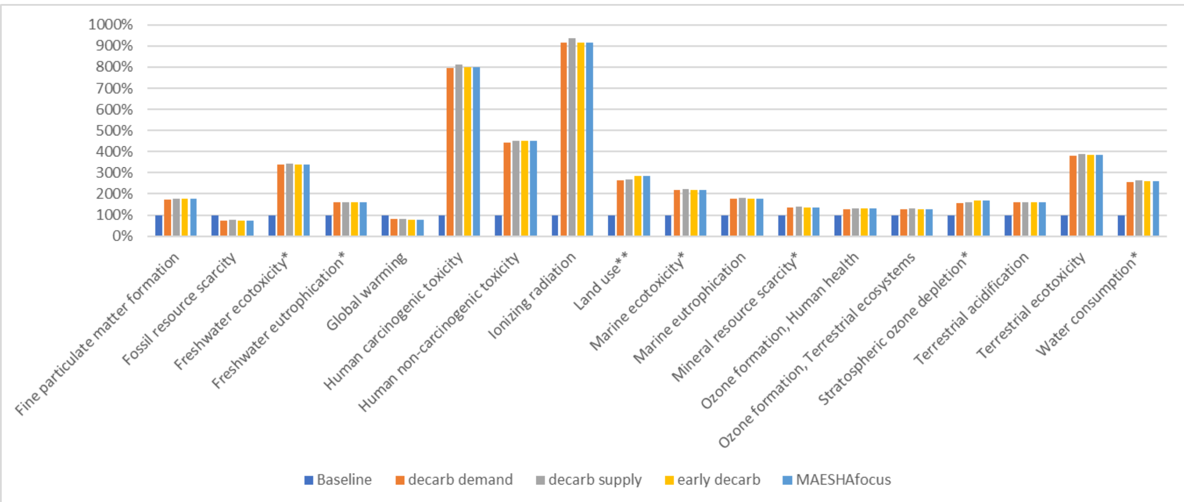

Figure 43: Environmental impact across scenarios within aviation transport, with the electricity mix being harmonized to the MAESHAfocus scenario-specific mix. *impact of the decarbonized scenarios divided by a factor of ten. ** impact of the decarbonized scenario

Conclusive remarks: We conclude on the preceded:

- On Mayotte, the transport sector dominates the environmental impact of the entire energy system by 2050. Our analysis finds robust trends that the GWP of the transport sector is reduced under any of the different policy measure proposed within the ESM scenarios. However, remarkable trade-offs to reduce GWP must be considered when promoting the use of biofuel (essentially causing land use changes) and BEVs. As both biofuels and the raw material required for BEV manufacturing must be allocated from external partners, the careful evaluation of sustainable production methods of suppliers must be considered by decision-makers in Mayotte to limit the environmental effects of decarbonizing the transport sector.
- While from techno-economic perspective the passenger transport fleet may ideally be dominated by BEVs, the LCA suggests that a more balanced utilization of BEVs and FCEVs is environmentally preferable. However, both BECs and FCEVs require large amounts of raw materials that, as of now, entail environmentally damaging production processes. Sustainable production methods and technology improvements towards low-resource technologies, should be fostered. With regard to both BECS and FCEVs emerging innovations seem promising to avoid the use of noble materials (see for example anion exchange membrane technology [101]).
- Decarbonizing the navigation and aviation sector is challenging regarding both technical challenges and market-entry challenges for net-zero solutions. Due to its high gravimetric density and storability, hydrogen and it´s derivates are seen as promising fuel options for future cost-efficient decarbonization of marine transport and aviation. Countries and regions that will utilize hydrogen as a fuel option are confronted with the decision of where to source the hydrogen. Our analysis revealed that the domestic production of hydrogen poses only minor environmental advantages compared to the import of hydrogen. Hence, other dimensions and assessments, including social, economic, and political aspects should be included in the decision-making process.

4.2.3. Household Sector

In energy transition efforts the household sector receives particular attention as it directly interacts with the population and therefore poses a sensitive environment. Decarbonization measures and other environmental protection efforts must therefore be carefully evaluated. However, the interchange with the population and community-inclusive approaches can be effective drivers for environmental protection. When successfully communicating the benefits of the energy transition to the population and when decarbonization efforts in the daily routines of households are embedded in the population, the household sector poses a significant potential for the decarbonization of the energy sector and environmental protection in general. Many studies have focused on environmental protection on a household level, with an overwhelming dominance rooted in the households' active participation in the transformation of the electricity sector. In the energy transformation movement, consensus exists, that when adjusting time or mode of electricity consuming activities in a manner that supports the real-time operation of the power grid, the integration of renewable energies in the electricity mix can cost-efficiently be promoted, thus contributing to a reduction of the direct emissions within the power sector. Accordingly, to a varying degree, the ESM scenarios include measures directed to the household level. Especially the citizen-focused DecarbDemand and MAESHAfocus scenarios assume the development of user-based flexibility services that are integrated in the electricity system infrastructure. The flexibility measures on a household level include demand-response and storage, energy efficiency measures, small-scale rooftop PV, and increased uptake of BEVs. While the ESM has identified such measures to be cost-efficient (see Deliverable D2.3) we contribute to the discussion by evaluating the environmental impact that is associated with such measures by comparing the environmental impact of the MAESHAfocus scenario, which entails the citizen activation measures in accordance with the MAESHA KPIs, with the baseline scenario, in which the currently applicable policies are maintained. Compared to other islands, in Mayotte the household sector plays an especially important role in the transformation of the energy system, because of the comparatively small development of the industry sector in Mayotte and the accompanying high percentual contribution of the household sector to the overall environmental impact. Regarding environmental impacts, in Mayotte, the household sector constitutes the second most important sector and is therefore a significant driver of environmental impact (see Subsection 4.2.2).

The analysis we conducted suggests that the impacts from the household sector vary significantly between the different scenarios. In fact, not only GWP but any other environmental impact could be reduced with increased decarbonization measures in the household sector. The analysis shows that the MAESHAfocus scenario consistently outperforming all other scenario-specific household configurations across all 18 environmental impact categories. To allow for an in-depth analysis, **Fehler! Verweisquelle konnte nicht gefunden werden.** disaggregates the environmental impact of technologies within the household sector, comparing the MAESHAfocus scenario and baseline scenario.

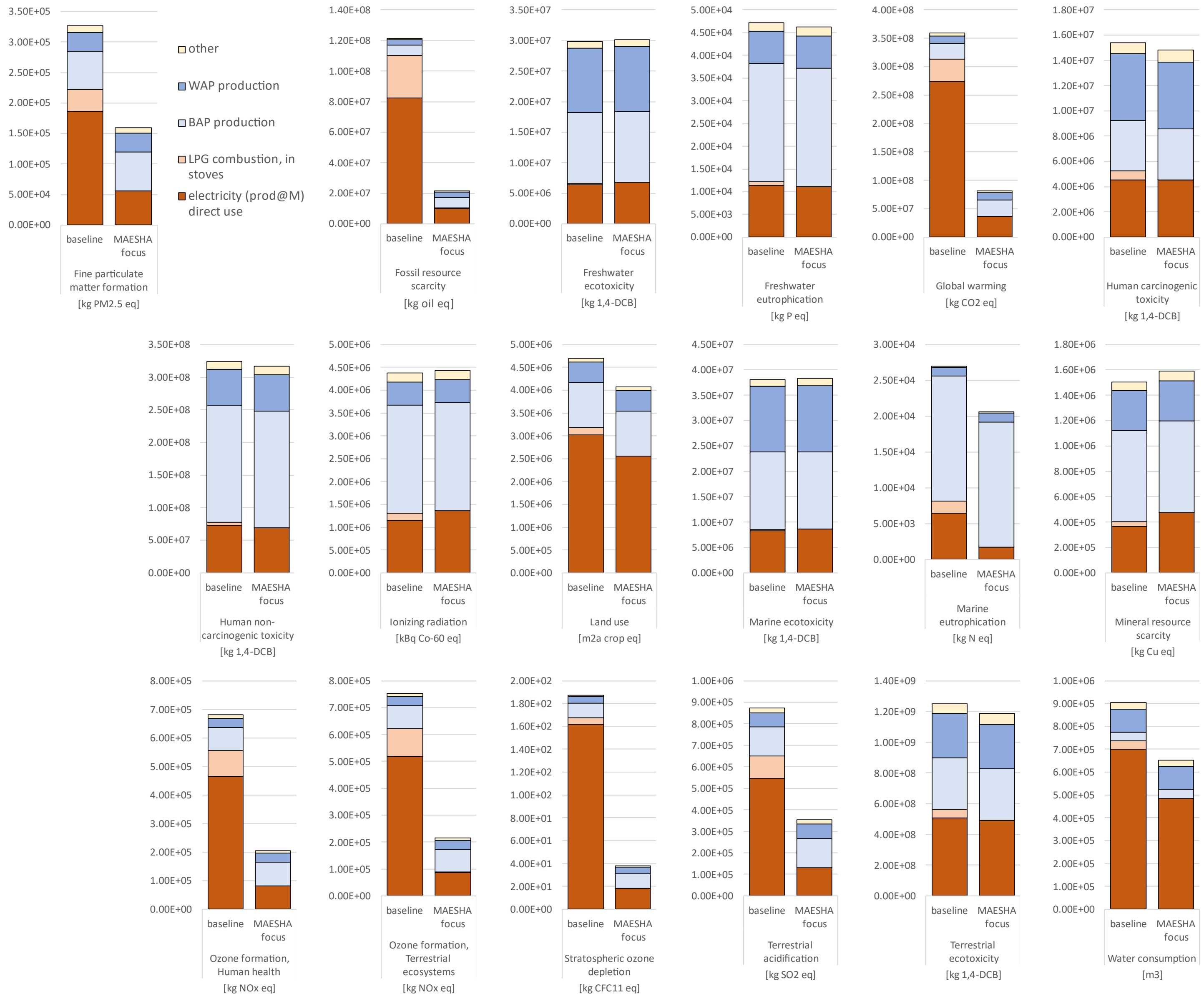

Figure 44: Technological drivers of the household sector's environmental performance in 2050

Figure 44 shows the contribution of the individual processes to the overall environmental impact across the 18 impact categories for the baseline and the MAESHAfocus scenarios. The figure suggests that i) electricity production for direct use, ii) LPG combustion, iii) white appliance (WAP) and iv) black appliances (BAP) are most significant driver of environmental impact in the household sector. While the primary drivers are the same, the total contribution differs across the different impact categories. In the following the stated drivers of environmental impact in the household sector are separately elaborated on.

Electricity: In the baseline scenario, which assumes a continuation of current policies, the production of electricity is significantly more dependent on fossil fuels, which is why the absolute environmental impact caused due to electricity production is significantly higher in related categories, including GWP, MRS, FMP. Further, under current policies the absence of energy efficiency measures in the household sector induces a higher final energy consumption in the sector – hence, increased electricity production dedicated to households. An overview of the consumption of final energy carriers in the household sector is provided in **Fehler! Verweisquelle konnte nicht gefunden werden.**.

Table 13: Scenario-specific demand of final energy carriers in the household sector according to the ESM.

demand of final energy carriers [GWh]	baseline in 2050	dD in 2050	dS in 2050	eD in 2050	Mf in 2050
Electricity	375.6	345.1	400.8	345.8	344.5
LPG	75.0	0.1	0.1	0.1	0.1
Paraffin Oil	2.9	0.0	0.0	0.0	0.0
Solar	30.4	46.5	47.7	46.2	46.9
total	**483.9**	**391.7**	**448.6**	**392.1**	**391.4**

LPG: The second driver of environmental impact in the household sector is the use of LPG. LPG represents 16% of the final energy demand in households in the baseline scenario by 2050. The lifecycle of LPG utilization is linked to a number of environmental impacts, especially in the production phase and the use phase, which in the case of LPG is its combustion. While the production of LPG impacts the fossil resource availability and is water and energy intense, the combustion of LPG releases CO_2 and NO_x, results in an increased GWP. Further, the N_2O that is emitted is contributing to stratospheric ozone depletion. The combustion of LPG results in terrestrial acidification due to emissions of SO_2, NO_x, and ammonia during the combustion. The substitution of LPG with electricity in the MAESHAfocus scenario leads to reduced environmental impacts in the associated impact categories including GWP, FPM, FRS.

White and black appliances: While environmental impacts associated with the production of fossil fuels and their usage can be successfully reduced via decarbonization efforts, the assets used in the household sector are associated with significant environmental impacts. The environmental impacts of the assets in the baseline scenario and in the decarbonization scenarios are of the same order. **Fehler! Verweisquelle konnte nicht gefunden werden.** summarizes the utilized end-use assets within the different scenarios according to the ESM.

Table 14: Scenario-specific demand of end-use assets in the household sector according to the ESM

demand of assets [items]	baseline in 2050	dD in 2050	dS in 2050	eD in 2050	Mf in 2050
WAP	452,576	452,576	452,575	452,576	452,577
BAP	176,867	176,867	176,867	176,867	176,868
other	331,391	268,118	267,766	266,597	266,930
total	**960,834**	**897,561**	**897,208**	**896,040**	**896,375**

All five scenarios exhibit an equal demand for black and white appliances in the household sector. The total number of deployed assets is lower in the decarbonization scenarios than in the baseline. This difference stems primarily from fewer installed stoves in the decarb scenarios compared to the baseline. The higher number of stoves in the baseline scenario can be attributed to a phenomenon known as "cookstove stacking," which is commonly observed as cooking practices evolve in developing countries with increased income. Instead of completely switching from one stove type to another, households tend to use multiple stove combinations concurrently [102]. The decarbonization scenarios assume having effectively addressed this issue by adopting cleaner stoves and fuels, while simultaneously driving the discontinuation of traditional stove use. These efforts align with the recommendations put forth by scholars who advocate for reducing or eliminating traditional stove use [103]. As a result, the decarb scenarios have achieved a decreased total number of installed stoves.

Conclusive remarks: We conclude on the environmental impact associated with the household sector:

- Our study reveals that there is significant potential for minimizing environmental impacts across all considered impact categories, when increasing decarbonization on a household level, for example via enhanced demand response, energy efficiency measures, and fuel switch towards electrified cooking services. Introducing environmental protection measures on a household level is important to the energy transition and other environmental strivings, as the direct interaction with daily routines of household members will determine their active engagement and their perception of the transformation process. Public opinion and social engagement are fundamental for a societal reorientation and can be an important vehicle for the acceleration of institutional change. For his reason measures on a household level should be carefully evaluated and selected.
- While environmental impacts associated with the production or use phase of fossil fuels can effectively be reduced in the household sector through decarbonization measures, the assets (including BAP, WAP) in the sector threaten to deteriorate the environmental impact across multiple categories. While the number of assets in a household should be reduced where possible (notably, the assets determine the available services and thereby activities of users and therefore pose a sensitive issue), sustainable production, lifetime extension and end-of-life treatment of assets need to be fostered.

4.2.4. Production and End-of-Life of Assets

From the previous sections we observe a trend that decarbonization measures targeting the energy sector may improve the environmental performance especially due to avoiding the production and use of fossil fuels. However, we also observe that the assets within decarbonized energy systems, especially the assets that are introduced specifically to further the decarbonization measures, imply negative trade-offs or reduce the total potential of environmental protection respectively. To confirm this hypothesis, we conduct an additional analysis and quantify the environmental impact associated with the production and EoL of assets. We subdivide EoL assets into vehicles and 'other end uses' incorporating household, services, industry, and agricultural assets. Figure 45 shows a visual representation of the respective share of the three contributor categories to environmental impact across the 18 impact categories considered.

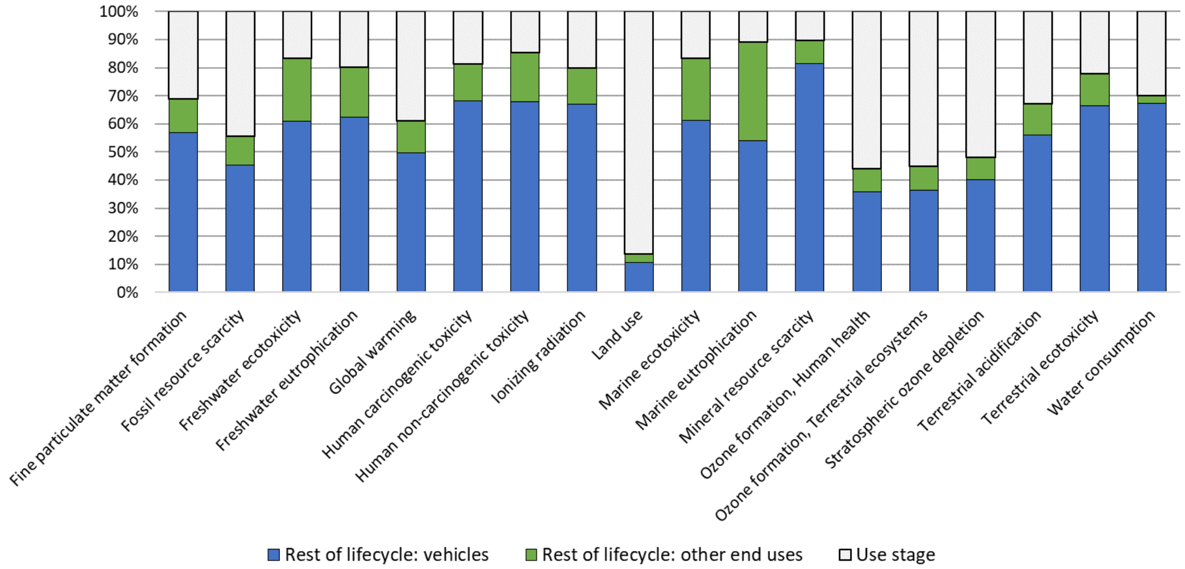

Figure 45: Influence of end-use assets on the environmental impact categories

It is striking that 14 out of 18 environmental impact categories are dominated (>50%) by end-use asset-induced impacts. About 90% of the entire system's mineral resource scarcity can be traced back to the production and EoL of end-use assets. Especially, the vehicle fleet assumed in the MAESHAfocus scenario and associated assets (i.e., BEVs) induce a deterioration of the environmental impact accordingly. Hence, measures to reduce the number of vehicles in Mayotte, i.e., public transport, shared vehicles etc., may have high potential to reduce the overall environmental impact of the energy and transport system. Technical progress in sustainable production and recycling of assets may be fostered. In addition, soft-measures to increase the lifetime of assets without substantial resource input may be an alternative to reduce the asset-induced environmental impacts. We conduct a sensitivity analysis of the lifetime of assets based on commercial values. The results of the sensitivity analysis are shown in see Figure 46. The results suggest that an extended lifetime of assets by only 20% may offer significant potential to reducing the environmental impact caused. For example, with an increase in lifetime of vehicles and other end use assets of 20%, mineral resource scarcity (MRS) and marine eutrophication (MEU) could be reduced by 15%, while a reduction of lifetime in the same magnitude would manifold the environmental impact up to 22%. Impact on Global warming (GWP) is significant: 10% reduction of the GWP could be unlocked by increasing the lifetime of assets by 20%, while a reduction of the lifetime threatens to increase the GWP by 15%.

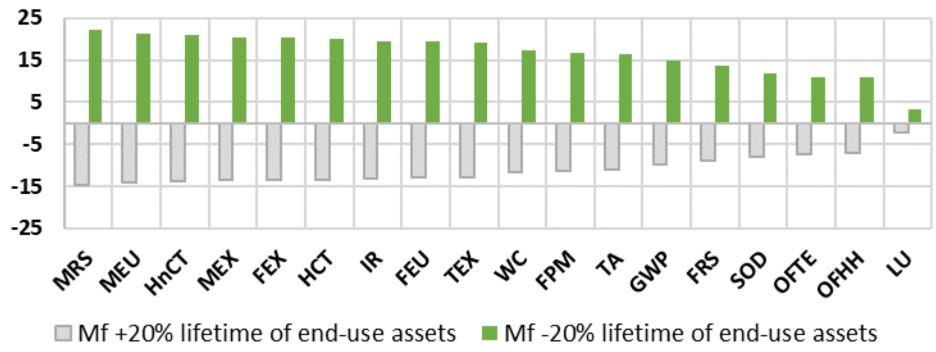

Figure 46: Impact of ±20% lifetime of end-use assets on the environmental performance of the entire system.

Conclusive remarks: we conclude:

- Assets pose a severe risk to bear trade-offs or incumbent technologies to further improve the environmental performance of energy systems when switching from a fossil-fuel based systems towards RES. The production as well as EoL of assets, including BEVs or end-use appliance, induces environmental impact across may categories. Thus, sustainable production methods as well as circular economy principles, and educating consumers on sustainable choices should be fostered.
- As the lifetime of assets shows significant impact on their environmental footprint, repair and maintenance, and educating consumers to promote longer lifetimes should be explored as a potential lever to reduce the environmental footprint in decarbonized energy systems.

4.3. Policy Implications

Based on the findings of the comprehensive analysis and the conclusions drawn under the preceding sections, we derive implications for politicians and decision makers in the energy transition. We first formulate generalized high-level considerations related to the environmental footprint of decarbonizing energy systems of European islands. Second, we specify precise actions recommended for the energy sector policies in Mayotte.

4.3.1. Generalized High-Level Considerations

The consequences of climate change are especially severe in sensitive island environments. The European islands and their inhabitant are experiencing the effects of climate change firsthand, and simultaneously are in a pivotal role of advancing mitigation measures. European islands have accelerated efforts to mitigate climate change and proactively protect their environment and economies, but uncertainties regarding the optimal transformation pathways remain high. Because the energy sector is a major driver of GHG emissions and in extension climate change, mitigation efforts have focused on the decarbonizing the energy sector. The decarbonization of the energy sector of islands poses a fundamental infrastructural shift especially in islands, where fossil fuel-based energy systems dominate. Many European islands are technically in an outstanding position to decarbonize their energy systems, as they often have vast renewable resources, such as wind or PV. The deployment of renewable energies inevitably plays a key role in reducing local GHG emissions. Climate change is a global crisis and while islands are in a advantageous position to reduce local emissions, mitigating the risks of climate change requires global efforts to reduce emissions.

While the operation of renewable energies may not entail any emissions, the sourcing of raw materials, the transportation of materials and parts and the production of RES assets entails energy intensive processes. In a globalized world these processes take place in different parts of the world and without a full decarbonization of all upstream process, the production of an RES inevitably results in GHG emissions. These 'indirect' emissions of the energy sector must be considered underline the complexity of the decarbonization efforts. True decarbonization of the energy sector not only required the mitigation of direct emissions, that result from the operation of the energy sector, but also the consideration of indirect emissions, that result from upstream processes. Naturally, in energy system, in which fossil fuel-based processes are increasingly phased out, the percentage share of indirect emissions will increase. For a detailed description and quantification of direct and indirect emission in the energy system represented by five scenarios in this report, we refer to Section 4.2. It is of essential importance to take the indirect emissions of decarbonized energy systems into account to enable informed and sustainable decision making. In addition, European islands must take responsibility and action beyond their geographical scope. While renewable energy sources are often abundant, most European islands showcase a scarcity in other resources, such as land and water resources, but also resources that are required for the production of renewable energy assets and the extended energy infrastructure. With limited water and land available the production of renewable fuels, such as biofuels, has practical limitations. This inevitably results in the islands relying on global partnerships with suppliers of technologies, or renewable fuels. The European islands' choice of suppliers for technologies and renewable fuels determines the indirect emissions and all other external environmental impacts that are associated with the islands' energy system. These additional emissions and environmental impact are especially relevant when the underlying motivation of utilizing renewables energy assets and renewable fuels is the decarbonization of the energy system. The underlying rationale of selection suppliers of renewable energy assets and renewable fuels has two levels. Decision makers need to carefully choose suppliers and assesses the sustainability of production methods to limit the environmental impact both at the point of production, concerning environmental impacts that primarily result in local damages, and environmental impact, such as GHG emissions, that inflict damages on a global scale. It is important to point out that politicians and governmental bodies do not make all decisions regarding supply options in the energy system, but instead many product streams are predominantly influenced by the private sector and the consumption behavior of the civic population. Especially in the private sector it is not feasible to assume that supply decisions are based on comprehensive sustainability analyses. It is the responsibility of the governing body to come up with guidelines and regulations. To ensure a minimum standard with regard to sustainability consideration in supply options, processes related to indirect emissions, such as mining of resources, industrial construction processes, and transportation, are integrated in the EU emission trading scheme and similar governing mechanisms. Further, additional standards be universally adopted that enforce detailed descriptions of environmental costs that are associated with products and processes.

In consideration of the indirect environmental impacts associated with the mining of resources and limitations in essential resources that are required to renewable energy assets, a sustainable end-of-life management of assets becomes increasingly important. The concept of the circular economy, or "closed loop" is promoted by scholars and policymakers alike. The closed loop concept aims at mitigating waste and establishing dematerialization. At its core, the concept makes provision for the replacement of the end-of-life stage of products with restoration. The reusing of products avoids additional extraction of natural resources and production processes, minimizing the environmental footprint of products. Under joint efforts, EU countries promote the circular economy to escape the dependency on raw material imports and the unresolved waste problem. For example, as part of the Circular Economy Package, the European Commission proposed to ensure that, by 2030, the amount of municipal waste put into landfills will be reduced by 90 %. The limitations in the availability of resources on European islands and the, in many cases, limited potentials for waste treatment further underline the fundamental importance of further investigating the opportunities of the circular economy principles for European islands. In addition to environmental benefits, there are economic opportunities arising from the circular economy model. For example, new business opportunities for innovative companies may be built. New job opportunities and enhanced skills may accelerate economy and leave social benefits, like increased knowledge and capacity building. Hence, taking a front row in developing circular economy strategies may offer great potential for European islands and their citizens to propel their sustainable development.

While our study has shown that the decarbonization of the energy sector in Mayotte does in fact reduce the energy sector related GHG emissions, we have discovered the significance of indirect emissions and the underlying environmental trade-offs that need to be considered by decision makers. These trade-offs have shown to depend on specific technologies or fuels used as a decarbonization measure. For example, we found an impact on land-use to significantly increase when promoting the uptake of biofuels. As determined by the Paris agreement, it is important to further measures to mitigate GHG and in extension the associated GWP. However, transformation analyses need to go further to include an in-depth investigation of context-dependent compromises that allow for informed and balanced decision-making. This study shows that inevitably compromises are to be made when, in addition to GWP reduction, other environmental impact categories are considered. The impacts can result in severe local and global damages and need to be carefully weighted. For example, switching from diesel to biofuel is a very effective measure to reduce direct GHG emissions in the transport sector, but it leads to significant land change and ozone depletion. The severe environmental consequences of large-scale biodiesel utilization were highlighted in this study and alternative renewable fuel sources, such as hydrogen and derivates should be considered. Hydrogen production is associated with different environmental costs, as its production requires significant amounts of water, which may be a stressor in regions with insufficient sustainable water resources, as is the case in Mayotte. Further, the use of hydrogen or any other fuel may conflict with other applications and sectors interrelated with the transport or energy sector. A context-embedded evaluation of the possible trade-offs and finally conclusive compromise must be made.

4.3.2. Mayotte-specific considerations

While the previous paragraph elaborated the context-dependency of decisions to take in energy planning considering environmental impacts, we will now summarize some recommendations to be drawn for the specific context of Mayotte that have resulted from our analysis.

The cost-efficient decarbonizing of the energy sector of Mayotte, lea to energy system topologies in 2050, in which the transport sector is a major driver of environmental impact across many categories. In Mayotte passenger car transport and maritime transport dominate over the aviation sector. In the passenger sector, the results of the LCA suggest that BEVs as a cost-efficient pathway to decarbonize the local emissions may pose the risk of enhanced environmental impacts across other categories. The mining associated with the resources required for the battery manufacturing processes can be associated with high environmental impact. While policymakers in Mayotte may not have direct control over the design and manufacturing processes of these assets, they can consider mineral resource intensity when contracting asset manufacturers to deploy assets in Mayotte. By considering suppliers that strive for less mineral resource-intensive manufacturing processes, policymakers can contribute to mitigating the impact on mineral resource scarcity. Further, measures to reduce the absolute number of vehicles may be explored on the island. Amongst these, social innovations like car sharing may be effective, alongside with technical infrastructure modifications, including public transport. The latter offers additional potential to widen the technology mix in the road transport and reduce the stress caused by singular strategies. For example, FCEVs could be an alternative option to be explored for public transport vehicles. While our study suggested a more balanced technology mix in the transport sector from environmental perspective (see Section 4.2.2.) diversifying the technologies may as well reduce the stress on interrelated infrastructures, including the power grid. Decoupling the electricity consumption required to produce hydrogen fuel from the charging of BEVs may have positive effects on the power system operation and related infrastructures.

The geographic boundaries of islands in many cases lead to more developed community identities among its inhabitants. A strong community identity may fuel coherent social engagement and community movements that can democratize and accelerate the energy transition. Previous deliverables (i.e., Deliverable 3.1) and scientific publications [48] of the MAESHA project have identified a strong sense for communal action in the energy transition, promoting citizen-focused energy interventions on Mayotte. Citizen-led energy transformation offers a great potential for a cost-efficient, and sustainable energy transition. For many of the decentralized solutions, the approval and the active participation of citizens in the energy transitions is of essential importance. This includes the adoption of BEVs, decentralized shared PV, and behavioral and energy-efficiency measures in the household sector. Because of the significant environmental impacts resulting from the household sector, this sector was analyzed in detail in this report (see Section 4.2). The findings of this analysis show different a variety of measures than have the potential to efficiently contribute to a reduction in environmental impact. Measure that should be considered by policy makers include energy efficiency measures, a cooking fuel switch to electric cooking, and reduction of assets used as beneficial to reduce the environmental impact of the household sector.

Interventions to promote the reduction of energy use in the household sector should be explored, with manifold options having been reported in the literature. For example, introducing instruments to support new businesses for renovation of existing buildings has proven to significantly reduce the heating demand in Norway [104]. While no space heating loads are relevant in Mayotte, cooling via electric air conditioning is a major driver of household electricity demand in Mayotte – which likewise may be able to reduce via renovation of buildings. While other anecdotal evidence of case studies is abundant, the unconditional effectiveness of measure improving energy efficiency on a household level remain challenging. While potentially having private (cost savings) and public benefits (GHG emission reduction), households invest less in energy efficiency than what may appear economically rational, and some other energy efficiency investments do not seem economically worthwhile – a phenomenon known as the energy efficiency gap or energy efficiency paradox [105]. A comprehensive overview of reasons causing energy efficiency gap is given in [106], including (i) market failures, (ii) behavioural failures and (iii) other factors. Different policies and instruments how to prevent or reduce the gap and promote appropriate behavioural changes to successfully nudge consumers towards more energy-efficient decisions is given in [111]. Essentially, these include energy standards and codes, economic incentives, feedback information and energy labelling, among others. Del Mar Solà et al. [105] compile empirical evidence on energy efficiency policies and discuss their effectiveness. Reflecting on evidence from various contexts, the authors find command and control instruments (including code and standards) to be effective in reaching set minimum standard, but often imply legislative or normative measures (e.g., the renovation of a building) leading to high costs. Price instruments, including subsidies and taxes lack in effectiveness while rebates showed mixed results. Informational policies, including certificates or labels, informational feedback or audits may be the cheapest and easiest way of providing consumers with energy efficiency related information, but their effectiveness is highly context dependent. Here, a sophisticated assessment and approach how to establish awareness campaigns, education programs, and incentives that motivate households should be conducted first.

Our study suggests significant environmental benefits to be unlocked from phasing out LPG cooking fuel and use electric cooking instead. The use of LPG as a cooking fuel, however, is known to be highly user convenient, while the uptake of electric cooking in regions with unstable grid connection is reluctant. LPG cooking via combustion meets the criteria of ease of use during utilization, which is a combination of direct ignition, systematic heat regulation, systematic fuel use, allowance for partial fuel refill, non-smoking clear flame/heat, and fuel level detection [107]. Notably, the ease-of-use criterion is recognized as the second most important factor affecting the choice of cooking fuel some contexts [107]. Switching towards electric alternatives will thus only be feasible when not jeopardizing the comfort and current convenience of users. From previous related studies we know that crucial success factors to induce the adoption of e-cooking are i) the reliability of the power supply without voltage drops or black-outs, ii) cost reduction of e-cooking appliances and, iii) widespread awareness of the benefits and practicalities of e-cooking appliances for everyday meals [108]. Hence, policies and energy sector related actions must foster the stable operation of the grid, especially in the low voltage sections (address i)), evaluate measures reducing the upfront costs of e-cooking appliances including subsidies, if relevant (addressing ii)) and support awareness-raising campaigns including workshops in with communities and distribution via public media (addressing iii)).

As a more recent alternative to e-cooking and LPG, hydrogen has been proposed as a clean cooking fuel, substituting polluting fuels including LPG, see for example [109]. With having similar physical properties as LPG, the utilization of hydrogen is feasible in infrastructure similar to LPG, with only marginal differences to be expected in the use behaviour. In fact, hydrogen can be blended into existing LPG infrastructures to a certain extent, depending on the end-use appliances used. When considering the local production of hydrogen via PV-fed water electrolysis, the environmental impact could be significantly reduced compared to it´s fossil counterpart, LPG. To this end we rely on a first study by Schmidt Rivera et al. [94], who performed a LCA of PV-fed hydrogen production and it´s utilization as gaseous cooking fuel in a rural village in Jamaica deployed under the ACP Science and Technology Programme [110]. The system considers a polymer membrane electrolysis and gaseous storage tanks (retrofitted from LPG tanks). Similar to this study´s LCA approach, the authors follow the guidelines of the ISO 14040/44 at a cradle-to-grave scope. Hydrogen fuel is compared to other cooking fuels including LPG, firewood, and charcoal. Interpretation of the results show the PV system to dominate the environmental impacts of the entire hydrogen cooking system by far in every considered impact category. Similar to our study, the authors see the environmental damage caused by PV to stem from it´s production and EoL-phase (see Section 4.2.4) and propose recycling of material and PV efficiency improvements to be fostered. Comparing hydrogen in its combustion to the other fuels, the study of Schmidt Rivera et al. finds the hydrogen system to be the best option for avoiding fossil fuel depletion, climate change, ozone depletion, and summer smog (the last, jointly with LPG). Specifically, hydrogenwould reduce the climate-change impact to 0.04 kg CO_2 eq./MJ compared to firewood (0.10 kg CO2 eq./MJ) and LPG (0.57 kg CO2 eq./MJ). Additionally, considering the point-of-use, local health and environmental benefits could be significantly improved when using hydrogen as cooking fuel, compared to traditional fuels. However, analogous to our study, trade-offs in the depletion of metals, freshwater eutrophication and freshwater and marine ecotoxicity are to be considered. These are, however, mainly associated with the lifecycle of PV panel.

5. Summary and Conclusion

This deliverable delves into the European Union's ambition to shift its energy paradigm from fossil-based sources to renewable energies, with a particular emphasis on the unique vulnerabilities faced by European islands and their communities. The overarching motivation is the reduction of environmental impact and the commitment to limiting global temperature increases to less than 1.5°C. In parallel, European islands are regarded as fertile grounds for innovation due to their high energy costs and strong sense of community action.

To achieve a successful transition towards sustainable energy, it is imperative to transform the energy sector's composition and incorporate innovative technologies that cater to growing energy demands while maintaining system stability. In the realm of energy system planning, Energy System Modeling has emerged as a potent tool for exploring cost-effective technical routes. Nevertheless, it is crucial to integrate environmental considerations into this approach, going beyond direct emissions and considering secondary emissions associated with the entire life cycle of energy systems. For this purpose, Life Cycle Assessment was applied in this study to assess the environmental impact of energy systems across all stages of their existence, encompassing factors beyond greenhouse gas emissions.

This study established a link between ESM and LCA to evaluate the environmental impact of a cost-optimal, decarbonized energy system for geographically isolated European islands, with Mayotte as a case study. It answered pertinent research questions concerning the environmental impact, optimal scenarios, influential sectors and technologies, trade-offs between emissions reduction and other environmental concerns, and the role of policy interventions. The findings offer essential guidance for policymakers, focusing on sectors, processes, and technologies for effective and efficient energy system decarbonization, while shedding light on potential hotspots and environmental consequences of energy policies.

The conducted study followed the ISO 14040/14044 LCA framework. The open-source LCA modeling tool, OpenLCA v1.9, was selected, because it offers flexibility, scenario simulation, and a simple integration of LCA databases. This study included an in-depth environmental evaluation of five scenarios each representing a distinct composition of Mayotte's energy system in 2050, covering all energy-consuming sectors, the energy supply side, and the energy demand side. The five scenarios and the accompanying energy system topologies were generated through comprehensive and sophisticated ESM in a previous stage of the MAESHA project and include all relevant energy-sectors in Mayotte, namely households, services, agriculture, industry, and transport. The LCA utilized the ESM scenarios and expanded the analysis beyond direct GHG emissions, providing insights into environmental impacts on multiple levels. In addition to the ESM results, the ecoinvent database and literature sources, were utilized in the inventory analysis. The conducted assessment is based on 18 environmental impact categories, predetermined by the applied ReCiPe evaluation method. Comparative analysis was carried out, with a focus on how the four different decarbonization scenarios perform compared the baseline scenario, which represents a continuation of current policy trends. The LCA results show that there is no single optimal scenario across all environmental impact categories.

The LCA results affirm the effectiveness of decarbonization measures regarding reducing the GWP, when considering the entire life cycle. However, we find that that reducing emissions in the energy sector may result in trade-offs in other environmental categories. Our study further analyzed identified hotspot, specifically the electricity sector, transportation sector, households and the lifetime of assets deployed.

Electricity sector: In the fossil fuel-based electricity systems in the baseline scenario, the environmental impacts are dominated by operational processes, such as the diesel combustion. In contrast, in the decarbonized electricity systems, the environmental footprint results from upstream processes and the construction of energy system assets. This underscores the importance of promoting sustainable production methods and exploring alternative resources to address the depletion of minerals in these systems. In addition, shifting from conventional diesel to biodiesel for electricity sector usage lowers the GWP but simultaneously introduces various trade-offs, particularly related to land use. We conclude that policies advocating for a transition to biodiesel should be approached with caution, and alternatives should be investigated.

Transportation sector: The transportation sector stands out, as the associated environmental impacts are especially difficult to mitigate. All four decarbonization scenarios are dominated by the utilization of BEVs. We identifed environmental trade-offs associated with the large-scale deployment of BEVs. A more balanced use of BEVs and FCEVs is environmentally preferable, although both require raw materials with environmentally damaging production processes. Decarbonizing the subsector navigation and aviation poses challenges, and hydrogen is considered a promising fuel option. When considering hydrogen sourcing, domestic production offers only minor environmental advantages compared to importing, and decision-making should encompass social, economic, and political factors.

Households: We find that decarbonization measures in the household sector can lead to significant reductions in environmental impacts across different categories. The MAESHAfocus scenario consistently outperforms others in all 18 environmental impact categories. Household-level decarbonization measures, like demand response, energy efficiency improvements, and transitioning to electric cooking, have the potential to reduce environmental impacts across several categories. These measures are crucial for engaging the population in the transition process and should be investigated by policy makers.

Lifetime of assets: Assets, especially those introduced to advance decarbonization, required trade-offs with regard to the environmental performance of energy systems transitioning from fossil fuels to renewable energy sources. Sustainable production methods, circular economy principles, and consumer education on sustainable choices should be promoted. Extending the lifetime of assets, focusing on repair and maintenance, and educating consumers to make sustainable choices can be effective strategies for reducing the environmental footprint in decarbonized energy systems and should be reinforced by policy makers.

Our study reveals that the decarbonization of Mayotte's energy sector effectively reduces GHG emissions. However, it also highlights the importance of considering indirect emissions and environmental trade-offs associated with the choice of specific technologies or fuels for decarbonization. This underscores the need for informed decision-making by policymakers, to which comprehensive LCA studies can contribute to.

APPENDIX

Appendix A1: LCI of Supply Processes

Table A1.1: LCI of Local Electricity Production in Mayotte.

electricity production@M							
Inputs				**Outputs**			**Based on...**
flow name	**amount**	**unit**	**provider**	**flow name**	**amount**	**unit**	
electricity net_commercialPV	generatedEL_commercialPV	GWh	*electricity production, commercial solar PV*	**electricity@M**	**generatedEL_sum*(1-(lossrate_Hvgrid + lossrate_MLVgrid))**	**GWh**	data from E3-Modeling
electricity net_geothermal	generatedEL_geothermal	GWh	*electricity production, geothermal plant*				
electricity net_open cycle IC	generatedEL_opencycle_IC	GWh	*electricity production, open cycle IC plant*				
electricity net_rooftopPV	generatedEL_rooftopPV	GWh	*electricity production, rooftop solar PV*				
electricity net_wind offshore	generatedEL_windoff	GWh	*electricity production, wind offshore*				
electricity net_wind onshore	generatedEL_windon	GWh	*electricity production, wind onshore*				
battery cell, Li-ion, NMC111	batteries_installed	kg	*market for battery cell, Li-ion, NMC111 | battery cell, Li-ion, NMC111 | Cutoff, U - GLO*				ecoinvent process "market for battery cell, Li-ion, NMC111 | battery cell, Li-ion, NMC111 | Cutoff, U - GLO"; https://www.saurenergy.com/solar-energy-news/the-top-5-largest-battery-energy-storage-systems-worldwide
distribution network, electricity, low voltage	548000.0/40.8	m	*market for distribution network, electricity, low voltage | distribution network, electricity, low voltage | Cutoff, U - GLO*				Schöne et al. (2022); CRE (2020); Shiomi et al. (2019)
transmission network, electricity, high voltage	16000.0/40.8	m	*market for transmission network, electricity, high voltage | transmission network, electricity, high voltage | Cutoff, U - GLO*				
transmission network, electricity, medium voltage	422000.0/40.8	m	*market for transmission network, electricity, medium voltage | transmission network, electricity, medium voltage | Cutoff, U - GLO*				

Table A1.2: LCI of Electricity Production from RES plants in Mayotte.

electricity production, commercial solar PV							
Inputs				**Outputs**			**Based on...**
flow name	**amount**	**unit**	**provider**	**flow name**	**amount**	**unit**	
photovoltaic plant, 570kWp, multi-Si, on open ground	1.0*1000/570*Pinst_commercialPV	Item(s)	*photovoltaic plant construction, 570kWp, multi-Si, on open ground | photovoltaic plant, 570kWp, multi-Si, on open ground | Cutoff, U - GLO*	**electricity net_commercialPV**	**generatedEL_commercialPV**	**GWh**	ecoinvent process "photovoltaic plant construction, 570kWp, multi-Si, on open ground | photovoltaic plant, 570kWp, multi-Si, on open ground | Cutoff, U"

electricity production, geothermal plant							
Inputs				**Outputs**			**Based on...**
flow name	**amount**	**unit**	**provider**	**flow name**	**amount**	**unit**	
geothermal power plant, 5.5MWel	1.0/5.5*Pinst_geothermal	Item(s)	*market for geothermal power plant, 5.5MWel | geothermal power plant, 5.5MWel | Cutoff, U - GLO*	**electricity net_geothermal**	**generatedEL_geothermal**	**GWh**	ecoinvent process "market for geothermal power plant, 5.5MWel | geothermal power plant, 5.5MWel | Cutoff, U"

electricity production, rooftop solar PV							
Inputs				**Outputs**			**Based on...**
flow name	**amount**	**unit**	**provider**	**flow name**	**amount**	**unit**	
photovoltaic flat-roof installation, 3kWp, multi-Si, on roof	1.0*1000/3*Pinst_rooftopPV	Item(s)	*photovoltaic flat-roof installation, 3kWp, multi-Si, on roof | photovoltaic flat-roof installation, 3kWp, multi-Si, on roof | Cutoff, U - RoW*	**electricity net_rooftopPV**	**generatedEL_rooftopPV**	**GWh**	ecoinvent process "photovoltaic flat-roof installation, 3kWp, multi-Si, on roof | photovoltaic flat-roof installation, 3kWp, multi-Si, on roof | Cutoff, U"

electricity production, wind onshore							
Inputs				**Outputs**			**Based on...**
flow name	**amount**	**unit**	**provider**	**flow name**	**amount**	**unit**	
wind turbine, 4.5MW, onshore	1.0/4.5*Pinst_windon	Item(s)	*market for wind turbine, 4.5MW, onshore | wind turbine, 4.5MW, onshore | Cutoff, U - GLO*	**electricity net_wind onshore**	**generatedEL_windon**	**GWh**	ecoinvent process "market for wind turbine, 4.5MW, onshore | wind turbine, 4.5MW, onshore | Cutoff, U - GLO"

electricity production, wind offshore						
Inputs				**Outputs**		
flow name	**amount**	**unit**	**provider**	**flow name**	**amount**	**unit**
wind offshore plant, 2MW	1.0/2*Pinst_windoff	Item(s)	*wind offshore plant construction, 2MW*	**electricity net_wind offshore**	**generatedEL_windoff**	**GWh**

wind offshore plant construction, 2MW							
Inputs				**Outputs**			**Based on...**
flow name	**amount**	**unit**	**provider**	**flow name**	**amount**	**unit**	
wind power plant, 2MW, offshore, fixed parts	1	Item(s)	*market for wind power plant, 2MW, offshore, fixed parts | wind power plant, 2MW, offshore, fixed parts | Cutoff, U - GLO*	**wind offshore plant, 2MW**	1	**Item(s)**	ecoinvent process "electricity production, wind, 1-3MW turbine, offshore | electricity, high voltage | Cutoff, U"
wind power plant, 2MW, offshore, moving parts	1	Item(s)	*market for wind power plant, 2MW, offshore, moving parts | wind power plant, 2MW, offshore, moving parts | Cutoff, U - GLO*				

Table A1.3: LCI of Electricity Production from open cycle IC plants in Mayotte.

electricity production, open cycle IC plant						
Inputs				Outputs		
flow name	**amount**	**unit**	**provider**	**flow name**	**amount**	**unit**
burned diesel, in open cycle IC plant	burneddiesel_opencycle_IC	GWh	*diesel combustion, in open cycle IC plant*	**electricity net_open cycle IC**	**generatedEL_opencycle_IC**	**GWh**
open cycle IC plant, 200kW	Pinst_opencycle_IC*1000/200	Item(s)	*open cycle IC plant construction, 1MW*			

open cycle IC plant construction, 1MW						
Inputs				Outputs		
flow name	**amount**	**unit**	**provider**	**flow name**	**amount**	**unit**
heat and power co-generation unit, 200kW electrical, diesel SCR, common components for heat+electricity	1	Item(s)	*market for heat and power co-generation unit, 200kW electrical, diesel SCR, common components for heat+electricity | heat and power co-generation unit, 200kW electrical, diesel SCR, common components for heat+electricity | Cutoff, U - GLO*	**open cycle IC plant, 200kW**	**1**	**Item(s)**
heat and power co-generation unit, 200kW electrical, diesel SCR, components for electricity only	1	Item(s)	*market for heat and power co-generation unit, 200kW electrical, diesel SCR, components for electricity only | heat and power co-generation unit, 200kW electrical, diesel SCR, components for electricity only | Cutoff, U - GLO*			

Based on...
ecoinvent process "heat and power co-generation, diesel, 200kW electrical, SCR-NOx reduction | electricity, high voltage | Cutoff, U - RoW"

diesel combustion, in open cycle IC plant							Based on...
Inputs				Outputs			
flow name	amount	unit	provider	flow name	amount	unit	
diesel, imported	0.18342668	kg	*diesel, import - YT*	**burned diesel, in open cycle IC plant**	**0.18342668*42.5**	**MJ**	ecoinvent process "heat and power co-generation, diesel, 200kW electrical, SCR-NOx reduction | electricity, high voltage | Cutoff, U - RoW"
lubricating oil	0.000525196	kg	*market for lubricating oil | lubricating oil | Cutoff, U - RoW*	Ammonia	7.83875E-06	kg	
urea	0.006788403	kg	market for urea | urea | Cutoff, U - RoW	Carbon dioxide, fossil	0.577715655	kg	
urea	0.000858542	kg	market for urea | urea | Cutoff, U - RNA	Carbon monoxide, fossil	0.001175812	kg	
urea	0.005796814	kg	market for urea | urea | Cutoff, U - CN	Dinitrogen monoxide	3.91937E-05	kg	
				Methane, fossil	9.4065E-05	kg	
				Nitrogen oxides	0.000548712	kg	
				NMVOC, non-methane volatile organic compounds	0.000391937	kg	
				Particulate Matter, < 2.5 um	7.83875E-06	kg	
				Platinum	5.48712E-11	kg	
				Sulfur dioxide	0.000391937	kg	
				waste mineral oil (market for waste mineral oil | waste mineral oil | Cutoff, U - RoW)	0.000380048	kg	
				waste mineral oil (market for waste mineral oil | waste mineral oil | Cutoff, U - Europe without Switzerland)	0.000145148	kg	

Table A1.4: LCI of Steam Production in Mayotte.

steam production@M							
Inputs				**Outputs**			**Based on…**
flow name	**amount**	**unit**	**provider**	**flow name**	**amount**	**unit**	
burned diesel, in boiler	burneddiesel_STEAM	GWh	*diesel combustion, in boiler*	**steam@M**	**generated_ STEAM**	**GWh**	
burned diesel, in boiler	burnedbiodiesel_STEAM	GWh	*biodiesel combustion, in boiler*				"diesel combustion, in boiler" with the following changes: 1. zero CO2 emissions to avoid double counting of biogenic carbon dioxide from biomass 2. -50% of CO and hydrocarbons (methane, ethane, propane, buthane, penthane, hexane, heptane, octane, benzene, toluene, xylene, formaldehyde) according to Thangavelu et al., 2015. 3. input flow changed to "biofuel advanced, imported"
oil boiler, 100kW	pinst_STEAM *1000/100	Item(s)	market for oil boiler, 100kW | oil boiler, 100kW | Cutoff, U - GLO				

Appendix A2: LCI of Partly Locally and Partly Externally Produced and Imported Final Energy Carriers

Table A2.1: LCI of Local Hydrogen Production in Mayotte.

hydrogen production@M							
Inputs				**Outputs**			**Based on…**
flow name	**amount**	**unit**	**provider**	**flow name**	**amount**	**unit**	
air compressor, screw-type compressor, 300kW	3.68E-07	Item(s)	market for air compressor, screw-type compressor, 300kW | air compressor, screw-type compressor, 300kW | Cutoff, U - GLO	**hydrogen_prod@M**	**1**	**kg**	Terlouw et al. 2022; E3 data
electricity@M	45.74149	kWh	electricity production@M				E3 data
electrolyzer, PEM	3.68E-07	Item(s)	electrolyzer, PEM, production - YT				Bareiß et al. 2019; (Terlouw et al. 2022); E3 data
hydrogen storage vessel	2.6E-07	Item(s)	hydrogen storage vessel, production - YT				Palmer et al. 2021; (Terlouw et al. 2022); E3 data
Water, cooling, unspecified natural origin, RoW	0.018	m3	elementary flow				https://hydrogentechworld.com/water-treatment-for-green-hydrogen-what-you-need-to-know
water, ultrapure	9	kg	water production, ultrapure | water, ultrapure | Cutoff, U - RoW				Terlouw et al. 2022; https://hydrogentechworld.com/water-treatment-for-green-hydrogen-what-you-need-to-know

hydrogen, green (electrolysis), external production							
Inputs				**Outputs**			**Based on...**
flow name	**amount**	**unit**	**provider**	**flow name**	**amount**	**unit**	
air compressor, screw-type compressor, 300kW	3.68476E-07	Item(s)	market for air compressor, screw-type compressor, 300kW | air compressor, screw-type compressor, 300kW | Cutoff, U - GLO	**hydrogen_green**	1	**kg**	Terlouw et al. 2022; E3 data
electricity@M	45.74148995	kWh	pelectricity production@M				E3M data
electrolyzer, PEM	3.68476E-07	Item(s)	electrolyzer, PEM, production - YT				Bareiß et al. 2019, (Terlouw et al. 2022); E3 data
hydrogen storage vessel	2.59936E-07	Item(s)	hydrogen storage vessel, production - YT				Palmer et al. 2021, (Terlouw et al. 2022); E3 data
Water, cooling, unspecified natural origin, RoW	0.018	m3	elementary flow				https://hydrogentechworld.com/water-treatment-for-green-hydrogen-what-you-need-to-know
water, ultrapure	9	kg	water production, ultrapure | water, ultrapure | Cutoff, U - RoW				Terlouw et al. 2022; https://hydrogentechworld.com/water-treatment-for-green-hydrogen-what-you-need-to-know

hydrogen storage vessel, production							
Inputs				**Outputs**			**Based on...**
flow name	**amount**	**unit**	**provider**	**flow name**	**amount**	**unit**	
Occupation, industrial area	960	m2*a	elementary flow	**hydrogen storage vessel**	1	**Item(s)**	Palmer et al. 2021; (Terlouw et al. 2022); E3 data
scrap steel	-81900	kg	elementary flow				
steel, chromium steel 18/8, hot rolled	126000	kg	steel production, chromium steel 18/8, hot rolled | steel, chromium steel 18/8, hot rolled | Cutoff, U - RER				
Transformation, from grassland, natural (non-use)	48	m2	elementary flow				
Transformation, to industrial area	48	m2	elementary flow				
waste reinforcement steel	-44100	kg	elementary flow				

electrolyzer, PEM, production							
Inputs				**Outputs**			**Based on...**
flow name	**amount**	**unit**	**provider**	**flow name**	**amount**	**unit**	
electrolyzer, PEM, Balance of Plant	0.35	Item(s)	electrolyzer, PEM, Balance of Plant, production - YT	**electrolyzer, PEM**	1	**Item(s)**	Bareiß et al. 2019; (Terlouw et al. 2022); E3 data
electrolyzer, PEM, Stack	1	Item(s)	electrolyzer, PEM, Stack, production - YT				

electrolyzer, PEM, Balance of Plant, production							Based on...
Inputs				**Outputs**			
flow name	**amount**	**unit**	**provider**	**flow name**	**amount**	**unit**	
aluminium, wrought alloy	100	kg	market for aluminium, wrought alloy | aluminium, wrought alloy | Cutoff, U - GLO	**electrolyzer, PEM, Balance of Plant**	1	**Item(s)**	Bareiß et al. 2019; (Terlouw et al. 2022)
chemical, organic	200	kg	market for chemical, organic | chemical, organic | Cutoff, U - GLO				
concrete, normal strength	2.3	m3	market for concrete, normal strength | concrete, normal strength | Cutoff, U - RoW				
copper, anode	100	kg	market for copper, anode | copper, anode | Cutoff, U - GLO				
electronics, for control units	1100	kg	market for electronics, for control units | electronics, for control units | Cutoff, U - GLO				
Occupation, industrial area	297	m2*a	elementary flow				
polypropylene, granulate	300	kg	market for polypropylene, granulate | polypropylene, granulate | Cutoff, U - GLO				
steel, chromium steel 18/8	1900	kg	market for steel, chromium steel 18/8 | steel, chromium steel 18/8 | Cutoff, U - GLO				
steel, low-alloyed	4800	kg	market for steel, low-alloyed | steel, low-alloyed | Cutoff, U - GLO				
Transformation, from grassland, natural (non-use)	14.9	m2	elementary flow				
Transformation, to industrial area	14.9	m2	elementary flow				

electrolyzer, PEM, Stack, production							Based on...
Inputs				**Outputs**			
flow name	**amount**	**unit**	**provider**	**flow name**	**amount**	**unit**	
activated carbon, granular	9	kg	market for activated carbon, granular | activated carbon, granular | Cutoff, U - GLO	**electrolyzer, PEM, Stack**	1	**Item(s)**	Bareiß et al. 2019; (Terlouw et al. 2022)
aluminium, wrought alloy	27	kg	market for aluminium, wrought alloy | aluminium, wrought alloy | Cutoff, U - GLO				
copper, anode	4.5	kg	market for copper, anode | copper, anode | Cutoff, U - GLO				
Iridium	0.75	kg	elementary flow				
platinum	0.075	kg	market for platinum | platinum | Cutoff, U - GLO				
steel, chromium steel 18/8, hot rolled	100	kg	market for steel, chromium steel 18/8, hot rolled | steel, chromium steel 18/8, hot rolled | Cutoff, U - GLO				
sulfuric acid	2.8	kg	market for sulfuric acid | sulfuric acid | Cutoff, U - RoW				
tetrafluoroethylene	13.2	kg	market for tetrafluoroethylene | tetrafluoroethylene | Cutoff, U - GLO				
titanium	528	kg	market for titanium | titanium | Cutoff, U - GLO				

scenario	hydrogen production in Mayotte in 2050 according to E3M: electricity input for H2 prod [kWh]	H2 produced [GWh]	plant capacity (scaled down to 1 year via lifetime) [MW]	assuming the LHVs of the study: **H2 produced in 2050 [kg]**	**kWh electricity/ kg H2 produced**	**MW plant capacity/ kg H2**
baseline	-	-	-	-	-	-
decarb demand	42,941,912	31.293	0.345924	938,796	45.7415	3.685E-07
decarb supply	122,855,091	89.584	0.908659	2,687,521	45.7132	3.381E-07
early decarb	121,978,477	88.857	1.054515	2,665,712	45.7583	3.956E-07
MAESHAfocus	128,881,157	93.817	0.885498	2,814,520	45.7915	3.146E-07

scenario	**1 MW electrolyzer** (LCI modeled according to Bareiß et al. 2019)	**300kW compressor** (ecoinvent flow)	**527kg hydrogen storage vessel** (LCI modeled according to Palmer et al. 2021)				
	flow: electrolyzer, PEM **provider**: electrolyzer, PEM, production **unit**: Item(s)	**flow**: air compressor, screw-type compressor, 300kW **provider**: market for air compressor, screw-type compressor, 300kW **unit**: Item(s)	daily H2 production [kg H2/day]	amount of tanks to store 1 daily production	amount of tanks (lifetime discounted)	amount of tanks (lifetime discounted) / kg H2 produced	**flow**: hydrogen storage vessel **provider**: hydrogen storage vessel, production **unit**: Item(s)
baseline	-	-	-	-	-	-	-
decarb demand	**3.68E-07**	**3.68E-07**	2,572.04	4.88	0.24	2.60E-07	**2.60E-07**
decarb supply	**3.38E-07**	**3.38E-07**	7,363.07	13.97	0.70	2.60E-07	**2.60E-07**
early decarb	**3.96E-07**	**3.96E-07**	7,303.32	13.86	0.69	2.60E-07	**2.60E-07**
MAESHAfocus	**3.15E-07**	**3.15E-07**	7,711.01	14.63	0.73	2.60E-07	**2.60E-07**

underlying assumptions:

H2 capacity of tank	[kg H2/ tank]	527	Palmer et al. 2021
lifetime of tank	[years]	20	Palmer et al. 2021

Table A2.2: Derivation of Input Quantities to Model the Electricity Demand and Infrastructure Assets of a Hydrogen Plant

scenario	ammonia production in Mayotte in 2050 according to E3M: electricity input for NH3 prod (incl. H2 prod) [kWh]	NH3 produced [GWh]	plant capacity (scaled down to 1 year via lifetime) [MW]	assuming the LHVs of the study: **NH3 produced in 2050 [kg]**	**kWh electricity/ kg NH3 produced (incl. H2 prod)**	5.75% of the comprehensive elc demand (Verleysen et al. 2020): **kWh electricity/ kg NH3 (excl. H2 prod)**	**MW plant capacity/ kg NH3**
baseline	-	-	-	-	-	-	-
decarb demand	61,868,313	34.519	0.84009215	6,645,404	9.3099	0.5353	1.2642E-07
decarb supply	65,223,635	36.408	0.88505391	7,009,034	9.3057	0.5351	1.2627E-07
early decarb	28,762,960	16.023	0.48880293	3,084,701	9.3244	0.5362	1.5846E-07
MAESHAfocus	30,153,880	16.821	0.45201567	3,238,359	9.3115	0.5354	1.3958E-07

scenario	**proxy for ammonia synthesis reactor, condensor and compressors** (according to MW plant capacity / kg NH3)		**proxy for ammonia storage vessel**				
	flow: electrolyzer, PEM **provider**: electrolyzer, PEM, production **unit**: Item(s)	**flow**: air compressor, screw-type compressor, 300kW **provider**: market for air compressor, screw-type compressor, 300kW **unit**: Item(s)	daily NH3 production [kg NH3/day]	amount of tanks to store 1 daily production	amount of tanks (lifetime discounted)	amount of tanks (lifetime discounted) / kg NH3 produced	**flow**: hydrogen storage vessel **provider**: hydrogen storage vessel, production **unit**: Item(s)
baseline	-	-	-	-	-	-	-
decarb demand	**1.26E-07**	**1.26E-07**	18,206.59	0.33	0.02	2.45E-09	**2.45E-09**
decarb supply	**1.26E-07**	**1.26E-07**	19,202.83	0.34	0.02	2.45E-09	**2.45E-09**
early decarb	**1.58E-07**	**1.58E-07**	8,451.24	0.15	0.01	2.45E-09	**2.45E-09**
MAESHAfocus	**1.40E-07**	**1.40E-07**	8,872.22	0.16	0.01	2.45E-09	**2.45E-09**

underlying assumptions:

ammonia density	[kg/m^3]	682.6	https://www.aqua-calc.com/page/density-table/substance/liquid-blank-ammonia
tank volume	[m^3]	82	Palmer et al. 2021
NH3 capacity of tank	[kg NH3/ tank]	55973.2	calculated
lifetime of tank	[years]	20	Palmer et al. 2021

Table A2.3: Derivation of Input Quantities to Model the Electricity Demand and Infrastructure Assets of a HB Ammonia Plant

ammonia, green external production							
Inputs				**Outputs**			**Based on...**
flow name	**amount**	**unit**	**provider**	**flow name**	**amount**	**unit**	
air compressor, screw-type compressor, 300kW	1.26E-07	Item(s)	market for air compressor, screw-type compressor, 300kW | air compressor, screw-type compressor, 300kW | Cutoff, U - GLO	**ammonia_green**	**1**	**kg**	Terlouw et al. 2022; IAMM; E3 data
electrolyzer, PEM	1.26E-07	Item(s)	electrolyzer, PEM, production - YT				Bareiß et al. 2019, (Terlouw et al. 2022)
hydrogen storage vessel	2.45E-09	Item(s)	hydrogen storage vessel, production - YT				Palmer et al. 2021, (Terlouw et al. 2022)
hydrogen_green	0.177	kg	hydrogen, green (electrolysis), external production				Singh et al. 2018
nitrogen, liquid	0.823	kg	air separation, cryogenic | nitrogen, liquid | Cutoff, U - RoW				Singh et al. 2018
electricity@M	0.535322	kWh	electricity production@M				Verleysen et al. 2020; E3 data
Heat, waste	0.75	kWh					Smith et al. 2020
Water, cooling, unspecified natural origin, RoW	0.00245	m3					Ghavam et al. 2021

ammonia mix, transported to port							
Inputs				**Outputs**			**Based on...**
flow name	**amount**	**unit**	**provider**	**flow name**	**amount**	**unit**	
ammonia_green	share_greenH2_ externalNH3	kg	ammonia, green external production from green H2	**ammonia_mix**	**1**	**kg**	-
ammonia_grey	1-share_greenH2_ externalNH3	kg	ammonia external production, steam reforming - RoW				ecoinvent process „*ammonia production, steam reforming, liquid | ammonia, anhydrous, liquid | Cutoff, U - RoW*“ Note, that the demanded quantity of grey NH3 is zero as per the demand parameter
transport, freight train	0.2756	t*km	market for transport, freight train | transport, freight train | Cutoff, U - RoW				ecoinvent process "*market for ammonia, anhydrous, liquid - RoW* "
transport, freight, inland waterways, barge	0.0466	t*km	market for transport, freight, inland waterways, barge | transport, freight, inland waterways, barge | Cutoff, U - RoW				
transport, freight, lorry, unspecified	0.1485	t*km	market for transport, freight, lorry, unspecified | transport, freight, lorry, unspecified | Cutoff, U - RoW				

shipping NH3 as H2 carrier to M							
Inputs				**Outputs**			**Based on...**
flow name	**amount**	**unit**	**provider**	**flow name**	**amount**	**unit**	
ammonia_mix	1	kg	ammonia mix, transport to port - YT	**ammonia_mix**	**1**	**kg**	-
electricity@M	0.0675	kWh	electricity production@M				Boero et al. 2021
transport, freight, sea, tanker for liquid goods o	6	t*km	transport, freight, sea, tanker for liquid goods other than petroleum and liquefied natural gas | transport, freight, sea, tanker for liquid goods other than petroleum and liquefied natural gas | Cutoff, U - GLO				-

ammonia, import							Based on...
Inputs				Outputs			
flow name	amount	unit	provider	flow name	amount	unit	
ammonia_mix	1	kg	ammonia mix, transport to port - YT	ammonia, imported	1	kg	-
electricity@M	0.0675	kWh	electricity production@M				Boero et al. 2021
transport, freight, sea, tanker for liquid goods o	6	t*km	transport, freight, sea, tanker for liquid goods other than petroleum and liquefied natural gas | transport, freight, sea, tanker for liquid goods other than petroleum and liquefied natural gas | Cutoff, U - GLO				-

hydrogen, import							Based on...
Inputs				Outputs			
flow name	amount	unit	provider	flow name	amount	unit	
ammonia_mix	0.745734	kg	shipping NH3 as H2 carrier to M	hydrogen_imported	1	kg	Giddey et al. 2017
ammonia_mix	1.737992	kg	shipping NH3 as H2 carrier to M				
ammonia_mix	6.409615	kg	shipping NH3 as H2 carrier to M				

Table A2.4: LCI of Hydrogen/ Ammonia Imports to Mayotte.

***Note that both the import of H2 and NH3 use the first two processes, whereas "ammonia, import" constitutes the third and final process to conclude the import pathway of ammonia. The processes "shipping NH3 as H2 carrier to M" and "hydrogen, import" constitute the third and fourth processes to conclude the import pathway of hydrogen to Mayotte.**

ammonia, production@M							Based on...
Inputs				Outputs			
flow name	amount	unit	provider	flow name	amount	unit	
air compressor, screw-type compressor, 300kW	1.26E-07	Item(s)	market for air compressor, screw-type compressor, 300kW | air compressor, screw-type compressor, 300kW | Cutoff, U - GLO	ammonia, prod@M	1	kg	Terlouw et al. 2022; IAMM; E3 data
electrolyzer, PEM	1.26E-07	Item(s)	electrolyzer, PEM, production - YT				Bareiß et al. 2019, (Terlouw et al. 2022)
hydrogen storage vessel	2.45E-09	Item(s)	hydrogen storage vessel, production - YT				Palmer et al. 2021, (Terlouw et al. 2022)
hydrogen_prod@M	0.177	kg	hydrogen production@M - YT				Singh et al. 2018
nitrogen, liquid	0.823	kg	air separation@M				Singh et al. 2018
electricity@M	0.535322	kWh	electricity production@M				Verleysen et al. 2020; E3 data
Heat, waste	0.75	kWh	elementary flow				Smith et al. 2020
Water, cooling, unspecified natural origin, RoW	0.00245	m3	elementary flow				Ghavam et al. 2021

air separation@M							Based on...
Inputs				Outputs			
flow name	amount	unit	provider	flow name	amount	unit	
air separation facility	4.43E-10	Item(s)	market for air separation facility | air separation facility | Cutoff, U - GLO	**nitrogen, liquid**	**1**	**kg**	ecoinvent process "air separation, cryogenic | nitrogen, liquid | Cutoff, U"
Argon-40	0.009849	kg	elementary flow	Water	0.008285	m3	
electricity@M	0.562816	kWh	electricity production@M	Water	0.013095	m3	
Nitrogen	0.531158	kg	elementary flow				
Oxygen	0.162513	kg	elementary flow				
Water, cooling, unspecified natural origin	0.02138	m3	elementary flow				

Table A2.5: LCI of Local Ammonia Production in Mayotte.

carbon dioxide production, direct air capturing							Based on...
Inputs				Outputs			
flow name	amount	unit	provider	flow name	amount	unit	
electricity@M	0.7	kWh	*electricity production@M*	**carbon dioxide, from direct air capturing**	**1**	**kg**	Deutz and Bardow, 2021
electricity@M	16.6 - 3.444	MJ	*electricity production@M*				
synthetic liquids, import							**Based on...**
Inputs				Outputs			
flow name	amount	unit	provider	flow name	amount	unit	
carbon dioxide, from direct air capturing	22.85	kg	*carbon dioxide production, direct air capturing*	**synthetic liquids, imported**	**5.47**	**kg**	König et al., 2015
chemical factory, organics	3.53E-10	Item(s)	*market for chemical factory, organics | chemical factory, organics | Cutoff, U - GLO*				
electricity@M	10.944	MJ	*electricity production@M*				
hydrogen_green	3.01*greenH2share	kg	*hydrogen, green (electrolysis), external production*				
hydrogen_grey	3.01*(1-greenH2share)	kg	*hydrogen, grey (SMR), external production*				
transport, freight, sea, tanker for petroleum	6	t*km	*market for transport, freight, sea, tanker for petroleum | transport, freight, sea, tanker for petroleum | Cutoff, U - GLO*				
carbon dioxide production, direct air capturing @M							**Based on...**
Inputs				Outputs			
flow name	amount	unit	provider	flow name	amount	unit	
electricity@M	0.7	kWh	*electricity production@M*	**carbon dioxide, from direct air capturing**	**1**	**kg**	Deutz and Bardow, 2021
electricity@M *	16.6 - 3.444	MJ	*electricity production@M*				

*assuming an electric boiler for steam production with an efficiency of 99%

synthetic liquids, production @M							
Inputs				**Outputs**			**Based on...**
flow name	**amount**	**unit**	**provider**	**flow name**	**amount**	**unit**	
carbon dioxide, from direct air capturing	22.85	kg	*carbon dioxide production, direct air capturing @M*	synthetic liquids, imported	5.47	kg	König et al., 2015
chemical factory, organics	3.53E-10	Item(s)	*market for chemical factory, organics | chemical factory, organics | Cutoff, U - GLO*				
electricity@M	10.944	MJ	*electricity production@M*				
hydrogen, imported	3.01*(1-H2share_producedinM)	kg	*hydrogen import*				
hydrogen_prod@M	3.01*H2share_producedinM	kg	hydrogen production@M - YT				

Table A2.6: LCI of external and local Synthetic Liquids Production

carbon dioxide production, direct air capturing							
Inputs				**Outputs**			**Based on...**
flow name	**amount**	**unit**	**provider**	**flow name**	**amount**	**unit**	
electricity@M	0.7	kWh	*electricity production@M*	carbon dioxide, from direct air capturing	1	kg	Deutz and Bardow, 2021
electricity@M	16.6 - 3.444	MJ	*electricity production@M*				

synthetic liquids, import							
Inputs				**Outputs**			**Based on...**
flow name	**amount**	**unit**	**provider**	**flow name**	**amount**	**unit**	
carbon dioxide, from direct air capturing	22.85	kg	*carbon dioxide production, direct air capturing*	synthetic liquids, imported	5.47	kg	König et al., 2015
chemical factory, organics	3.53E-10	Item(s)	*market for chemical factory, organics | chemical factory, organics | Cutoff, U - GLO*				
electricity@M	10.944	MJ	*electricity production@M*				
hydrogen_green	3.01*greenH2share	kg	*hydrogen, green (electrolysis), external production*				
hydrogen_grey	3.01*(1-greenH2share)	kg	*hydrogen, grey (SMR), external production*				
transport, freight, sea, tanker for petroleum	6	t*km	*market for transport, freight, sea, tanker for petroleum | transport, freight, sea, tanker for petroleum | Cutoff, U - GLO*				

carbon dioxide production, direct air capturing @M							
Inputs				**Outputs**			**Based on...**
flow name	**amount**	**unit**	**provider**	**flow name**	**amount**	**unit**	
electricity@M	0.7	kWh	*electricity production@M*	carbon dioxide, from direct air capturing	1	kg	Deutz and Bardow, 2021
electricity@M *	16.6 - 3.444	MJ	*electricity production@M*				

*assuming an electric boiler for steam production with an efficiency of 99%

synthetic liquids, production @M							
Inputs				Outputs			**Based on...**
flow name	**amount**	**unit**	**provider**	**flow name**	**amount**	**unit**	
carbon dioxide, from direct air capturing	22.85	kg	*carbon dioxide production, direct air capturing @M*	**synthetic liquids, imported**	**5.47**	**kg**	König et al., 2015
chemical factory, organics	3.53E-10	Item(s)	*market for chemical factory, organics | chemical factory, organics | Cutoff, U - GLO*				
electricity@M	10.944	MJ	*electricity production@M*				
hydrogen, imported	3.01*(1-H2share_producedinM)	kg	*hydrogen import*				
hydrogen_prod@M	3.01*H2share_producedinM	kg	hydrogen production@M - YT				

Table A2.7: LCI of external and local Synthetic Liquids Production

Appendix A3: LCI of Exclusively Externally Produced and Imported Final Energy Carriers

Table A3.1: Underlying Assumptions to Model Supply of Solely Externally Produced Final Energy Carriers

Modeling of external production & subsequent import for final energy carriers that are solely produced externally					
final energy carrier	**external production process** based on ecoinvent process	**additional input flow to account for subsequent import**		**newly created overarching import process in openLCA** (consolidating both external production and transportation to facilitate the import)	
		assumed average import distance [km]	**means of transport**	**process name**	**reference product**
diesel	*diesel production, low-sulfur, petroleum refinery operation | diesel, low-sulfur | Cutoff, U - RoW*	6,000	transport, freight, sea, tanker for petroleum	*diesel, import*	diesel, imported
LPG	*liquefied petroleum gas production, petroleum refinery operation | liquefied petroleum gas | Cutoff, U - RoW*	6,000	transport, freight, sea, tanker for liquefied natural gas	LPG, import	LPG, imported
gasoline	*petrol production, low-sulfur | petrol, low-sulfur | Cutoff, U - RoW*	6,000	transport, freight, sea, tanker for petroleum	gasoline, import	gasoline, imported
biofuel conventional	1. edible energy crops from ecoinvent process *"market for ethanol, without water, in 95% solution state, from fermentation | ethanol, without water, in 95% solution state, from fermentation | Cutoff, U"* *2. dewatering of ethanol from biomass, from 95% to 99.7% solution state | ethanol, without water, in 99.7% solution state, from fermentation | Cutoff, U*	6,000	transport, freight, sea, tanker for petroleum	biofuel conventional, import	biofuel conventional, imported
biofuel advanced	1. lignocellulosic energy crops from ecoinvent process *"market for ethanol, without water, in 95% solution state, from fermentation | ethanol, without water, in 95% solution state, from fermentation | Cutoff, U"* *2. dewatering of ethanol from biomass, from 95% to 99.7% solution state | ethanol, without water, in 99.7% solution state, from fermentation | Cutoff, U*	6,000	transport, freight, sea, tanker for petroleum	biofuel advanced, import	biofuel advanced, imported
paraffin oil	*paraffin production | paraffin | Cutoff, U - RoW*	6,000	transport, freight, sea, tanker for petroleum	paraffin oil, import	paraffin oil, imported
kerosene	*kerosene production, petroleum refinery operation | kerosene | Cutoff, U - RoW*	6,000	transport, freight, sea, tanker for petroleum	kerosene, import	kerosene, imported

Table A3.2: LCI of Imports of Diesel, LPG, Gasoline, Paraffin oil and Kerosene to Mayotte.

diesel, import						
Inputs				Outputs		
flow name	amount	unit	provider	flow name	amount	unit
diesel, low-sulfur	1	kg	diesel production, low-sulfur, petroleum refinery operation | diesel, low-sulfur | Cutoff, U - RoW	diesel, imported	1	kg
transport, freight, sea, tanker for petroleum	6	t*km	market for transport, freight, sea, tanker for petroleum | transport, freight, sea, tanker for petroleum | Cutoff, U - GLO			

LPG, import						
Inputs				Outputs		
flow name	amount	unit	provider	flow name	amount	unit
liquefied petroleum gas	1	kg	liquefied petroleum gas production, petroleum refinery operation | liquefied petroleum gas | Cutoff, U - RoW	LPG, imported	1	kg
transport, freight, sea, tanker for liquefied natural gas	6	t*km	market for transport, freight, sea, tanker for liquefied natural gas | transport, freight, sea, tanker for liquefied natural gas | Cutoff, U - GLO			

gasoline, import						
Inputs				Outputs		
flow name	amount	unit	provider	flow name	amount	unit
petrol, low-sulfur	1	kg	petrol production, low-sulfur | petrol, low-sulfur | Cutoff, U - RoW	gasoline, imported	1	kg
transport, freight, sea, tanker for petroleum	6	t*km	market for transport, freight, sea, tanker for petroleum | transport, freight, sea, tanker for petroleum | Cutoff, U - GLO			

paraffin oil, import						
Inputs				Outputs		
flow name	amount	unit	provider	flow name	amount	unit
paraffin	1	kg	paraffin production | paraffin | Cutoff, U - RoW	paraffin oil, imported	1	kg
transport, freight, sea, tanker for petroleum	6	t*km	market for transport, freight, sea, tanker for petroleum | transport, freight, sea, tanker for petroleum | Cutoff, U - GLO			

kerosene, import						
Inputs				Outputs		
flow name	amount	unit	provider	flow name	amount	unit
kerosene	1	kg	kerosene production, petroleum refinery operation | kerosene | Cutoff, U - RoW	kerosene, imported	1	kg
transport, freight, sea, tanker for petroleum	6	t*km	market for transport, freight, sea, tanker for petroleum | transport, freight, sea, tanker for petroleum | Cutoff, U - GLO			

Table A3.3: LCI of Conventional and Advanced Biofuel Imports to Mayotte.

bioethanol conventional, fermentation to 95% solution state							
Inputs				**Outputs**			**Based on...**
flow name	**amount**	**unit**	**provider**	**flow name**	**amount**	**unit**	
ethanol, without water, in 95% solution state, from fermentation	0.06626	kg	*ethanol production from maize | ethanol, without water, in 95% solution state, from fermentation | Cutoff, U - RoW*	**bioethanol conventional, 95%**	**0.94341**	**kg**	ecoinvent process "market for ethanol, without water, in 95% solution state, from fermentation | ethanol, without water, in 95% solution state, from fermentation | Cutoff, U"
ethanol, without water, in 95% solution state, from fermentation	0.00093	kg	*ethanol production from sweet sorghum | ethanol, without water, in 95% solution state, from fermentation | Cutoff, U - RoW*				
ethanol, without water, in 95% solution state, from fermentation	0.01602	kg	*ethanol production from sugar beet | ethanol, without water, in 95% solution state, from fermentation | Cutoff, U - RoW*				
ethanol, without water, in 95% solution state, from fermentation	0.00065	kg	*ethanol production from rye | ethanol, without water, in 95% solution state, from fermentation | Cutoff, U - RoW*				
ethanol, without water, in 95% solution state, from fermentation	0.00029	kg	*ethanol production from whey | ethanol, without water, in 95% solution state, from fermentation | Cutoff, U - RoW*				
ethanol, without water, in 95% solution state, from fermentation	0.00098	kg	*ethanol production from potatoes | ethanol, without water, in 95% solution state, from fermentation | Cutoff, U - RoW*				
ethanol, without water, in 95% solution state, from fermentation	0.01270	kg	*ethanol production from sugar beet molasses | ethanol, without water, in 95% solution state, from fermentation | Cutoff, U - RoW*				
ethanol, without water, in 95% solution state, from fermentation	0.84559	kg	*sugarcane processing, traditional annexed plant | ethanol, without water, in 95% solution state, from fermentation | Cutoff, U - RoW*				

biofuel conventional, import								
Inputs				**Outputs**				**Based on...**
flow name	**amount**	**unit**	**provider**	**flow name**	**amount**	**unit**	**provider**	
bioethanol conventional, 95%	1	kg	*bioethanol conventional, fermentation to 95% solution state*	**biofuel, conventional, imported**	**1**	**kg**		ecoinvent process "dewatering of ethanol from biomass, from 95% to 99.7% solution state | ethanol, without water, in 99.7% solution state, from fermentation | Cutoff, U"
electricity, medium voltage	0.005005	kWh	*market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U - GLO*	wastewater, average	9.8255E-08	m3	*market for wastewater, average | wastewater, average | Cutoff, U - CA-QC*	
ethanol fermentation plant	2.96E-11	Item(s)	*market for ethanol fermentation plant | ethanol fermentation plant | Cutoff, U - GLO*	wastewater, average	2.7597E-05	m3	*market for wastewater, average | wastewater, average | Cutoff, U - RoW*	
heat, district or industrial, natural gas	0.552795	MJ	*market for heat, district or industrial, natural gas | heat, district or industrial, natural gas | Cutoff, U - RoW*					
heat, district or industrial, natural gas	0.009084	MJ	*market for heat, district or industrial, natural gas | heat, district or industrial, natural gas | Cutoff, U - CA-QC*					
transport, freight, sea, tanker for petroleum	6	t*km	*market for transport, freight, sea, tanker for petroleum | transport, freight, sea, tanker for petroleum | Cutoff, U - GLO*					assumption of 6,000 km average import distance

bioethanol advanced, fermentation to 95% solution state							Based on...
Inputs				Outputs			
flow name	amount	unit	provider	flow name	amount	unit	
ethanol, without water, in 95% solution state, from fermentation	0.05540	kg	*ethanol production from wood | ethanol, without water, in 95% solution state, from fermentation | Cutoff, U - RoW*	**bioethanol advanced, 95%**	**0.05654**	**kg**	ecoinvent process "market for ethanol, without water, in 95% solution state, from fermentation | ethanol, without water, in 95% solution state, from fermentation | Cutoff, U"
ethanol, without water, in 95% solution state, from fermentation	0.00003	kg	*ethanol production from wood | ethanol, without water, in 95% solution state, from fermentation | Cutoff, U - CH*				
ethanol, without water, in 95% solution state, from fermentation	0.00030	kg	*ethanol production from wood | ethanol, without water, in 95% solution state, from fermentation | Cutoff, U - SE*				
ethanol, without water, in 95% solution state, from fermentation	0.00080	kg	*ethanol production from grass | ethanol, without water, in 95% solution state, from fermentation | Cutoff, U - CH*				

biofuel advanced, import								Based on...
Inputs				Outputs				
flow name	amount	unit	provider	flow name	amount	unit	provider	
bioethanol advanced, 95%	1	kg	*bioethanol advanced, fermentation to 95% solution state*	**biofuel, advanced, imported**	**1**	**kg**		ecoinvent process "dewatering of ethanol from biomass, from 95% to 99.7% solution state | ethanol, without water, in 99.7% solution state, from fermentation | Cutoff, U"
electricity, medium voltage	0.005005	kWh	*market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U - GLO*	wastewater, average	9.8255E-08	m3	*market for wastewater, average | wastewater, average | Cutoff, U - CA-QC*	
ethanol fermentation plant	2.96E-11	Item(s)	*market for ethanol fermentation plant | ethanol fermentation plant | Cutoff, U - GLO*	wastewater, average	2.7597E-05	m3	*market for wastewater, average | wastewater, average | Cutoff, U - RoW*	
heat, district or industrial, natural gas	0.552795	MJ	*market for heat, district or industrial, natural gas | heat, district or industrial, natural gas | Cutoff, U - RoW*					
heat, district or industrial, natural gas	0.009084	MJ	*market for heat, district or industrial, natural gas | heat, district or industrial, natural gas | Cutoff, U - CA-QC*					
transport, freight, sea, tanker for petroleum	6	t*km	*market for transport, freight, sea, tanker for petroleum | transport, freight, sea, tanker for petroleum | Cutoff, U - GLO*					assumption of 6,000 km average import distance

APPENDIX A4: LCI OF LEVEL1 DEMAND PROCESSES

				in % of net weight according to Bauer et al., 2015						disaggregated parts to model the total vehicle																						ecoinvent flow to model 1 vehicle				self-modeled **process** to model 1 vehicle	
Technology type		**net weight of vehicle [kg]**		**glider, tank, trans-mission, engine**	**battery**	**(el.) motor/ genera-tor**	**glider, transmission, (el.) motor/ generator**	**Hydro gen tank**	**Fuel cell**	**glider, tank, transmission, engine**			**battery**			**(electric) motor/generator**			**glider, transmission, (electric) motor/generator**			**Hydrogen tank**					**Fuel cell**					**name**	**unit**	**amount**	**provider uuid**	all diaggregated parts aggregated in one newly created process, called…	**reference flow [Item(s)]**
ICE	passenger car	1450	average of ICEV-g (2012 & 2030) and ICEV-d (2012 & 2030)*																													passenger car, petrol/ natural gas	kg	1450	0a2d6d36-cefe-3a6b-b53e-1266bd74311b	passenger car production, ICE	passenger car, ICE
	light duty vehicle	2500	assumption																													passenger car, petrol/ natural gas	kg	2500	0a2d6d36-cefe-3a6b-b53e-1266bd74311b	light duty vehicle production, ICE	light duty vehicle, ICE
	heavy duty vehicle	10000	assumption																													lorry, 28 metric ton	Item(s)	1	2b237244-dc82-3277-95e1-5705040fc44d		
	public bus	11000	net weight of ecoinvent "bus"																													bus	Item(s)	1	54d68af5-d3d4-35de-a6d2-2889199058b7		
PHEV	passenger car	1550	average of HEV-g (2012 & 2030) and HEV-d (2012 & 2030)*	92%	4%	4%				passenger car, petrol/ natural gas	kg	1428	battery cell, Li-ion, NMC111	kg	60	powertrain, for electric passenger car	kg	61																		passenger car production, PHEV	passenger car, PHEV
	light duty vehicle	2500	assumption							passenger car, petrol/ natural gas	kg	2304	battery cell, Li-ion, NMC111	kg	97	powertrain, for electric passenger car	kg	98																		light duty vehicle production, PHEV	light duty vehicle, PHEV
BEV	passenger car	1800	average of BEV (2012 & 2030)*		21%		79%						battery cell, Li-ion, NMC111	kg	383				passenger car, electric, without battery	kg	1417															passenger car production, BEV	passenger car, BEV
	light duty vehicle	2500	assumption										battery cell, Li-ion, NMC111	kg	532				passenger car, electric, without battery	kg	1968															light duty vehicle production, BEV	light duty vehicle, BEV
	heavy duty vehicle	10000	assumption										battery cell, Li-ion, NMC111	kg	2128				passenger car, electric, without battery	kg	7872															heavy duty vehicle production, BEV	heavy duty vehicle, BEV
	public bus	11000	net weight of ecoinvent "bus"										battery cell, Li-ion, NMC111	kg	2341				passenger car, electric, without battery	kg	8660															public bus production, BEV	public bus, BEV
FCEV	passenger car	1750	average of FCEV (2012 & 2030)*		4%		81%	7%	9%				battery cell, Li-ion, NMC111	kg	68				passenger car, electric, without battery	kg	1411	hydrogen storage vessel	kg	116	**Item(s)**	**9.17E-04**	fuel cell, 1 kW PEMFC	kg	156	**Item(s)**	**45**					passenger car production, FCEV	passenger car, FCEV
	light duty vehicle	2500	assumption										battery cell, Li-ion, NMC111	kg	97				passenger car, electric, without battery	kg	2016	hydrogen storage vessel	kg	165	**Item(s)**	**1.31E-03**	fuel cell, 1 kW PEMFC	kg	223	**Item(s)**	**64**					light duty vehicle production, FCEV	light duty vehicle, FCEV
	heavy duty vehicle	10000	assumption										battery cell, Li-ion, NMC111	kg	387				passenger car, electric, without battery	kg	8064	hydrogen storage vessel	kg	660	**Item(s)**	**5.24E-03**	fuel cell, 1 kW PEMFC	kg	894	**Item(s)**	**257**					heavy duty vehicle production, FCEV	heavy duty vehicle, FCEV
	public bus	11000	net weight of ecoinvent "bus"										battery cell, Li-ion, NMC111	kg	426				passenger car, electric, without battery	kg	8871	hydrogen storage vessel	kg	726	**Item(s)**	**5.76E-03**	fuel cell, 1 kW PEMFC	kg	983	**Item(s)**	**283**					public bus production, FCEV	public bus, FCEV
Aviation: helicopters																																helicopter	1	Item(s)	1933385c-a369-34e8-a3bb-d9013c0f307f		
2 wheelers - ICE																																motor scooter, 50 cubic cm engine	1	Item(s)	bcf64adf-4881-3423-abf3-6430ae06c37f		
2 wheelers - electric													battery cell, Li-ion, NMC111	kg	20				electric scooter, without battery	kg	90															electric scooter production	electric scooter
Inland freight navigation (due to lack of LCI data, all drive types are modeled via a conventional ICE barge)																																barge	1	Item(s)	46f18bfe-d97b-3871-91f8-23cda5de6c8a		
Inland passenger navigation (due to lack of LCI data, all drive types are modeled via a conventional ICE ferry)																																ferry	1	Item(s)	6e4b3916-3be4-3f25-baad-3b22af89178b		

Table A4.1: Modeling vehicle assets in OpenLCA (based on Bauer et al., 2015)

passenger car production, ICE						
Inputs				Outputs		
flow name	**amount**	**unit**	**provider**	**flow name**	**amount**	**unit**
passenger car, petrol/natural gas	1450	kg	market for passenger car, petrol/natural gas | passenger car, petrol/natural gas | Cutoff, U - GLO	**passenger car, ICE**	1	**Item(s)**
light duty vehicle production, ICE						
Inputs				Outputs		
flow name	**amount**	**unit**	**provider**	**flow name**	**amount**	**unit**
passenger car, petrol/natural gas	2500	kg	market for passenger car, petrol/natural gas | passenger car, petrol/natural gas | Cutoff, U - GLO	**light duty vehicle, ICE**	1	**Item(s)**
passenger car production, PHEV						
Inputs				Outputs		
flow name	**amount**	**unit**	**provider**	**flow name**	**amount**	**unit**
battery cell, Li-ion, NMC111	60	kg	market for battery cell, Li-ion, NMC111 | battery cell, Li-ion, NMC111 | Cutoff, U - GLO	**passenger car, PHEV**	1	**Item(s)**
passenger car, petrol/natural gas	1428	kg	market for passenger car, petrol/natural gas | passenger car, petrol/natural gas | Cutoff, U - GLO			
powertrain, for electric passenger car	61	kg	market for powertrain, for electric passenger car | powertrain, for electric passenger car | Cutoff, U - GLO			
light duty vehicle production, PHEV						
Inputs				Outputs		
flow name	**amount**	**unit**	**provider**	**flow name**	**amount**	**unit**
battery cell, Li-ion, NMC111	97	kg	market for battery cell, Li-ion, NMC111 | battery cell, Li-ion, NMC111 | Cutoff, U - GLO	**light duty vehicle, PHEV**	1	**Item(s)**
passenger car, petrol/natural gas	2304	kg	market for passenger car, petrol/natural gas | passenger car, petrol/natural gas | Cutoff, U - GLO			
powertrain, for electric passenger car	98	kg	market for powertrain, for electric passenger car | powertrain, for electric passenger car | Cutoff, U - GLO			

passenger car production, BEV						
Inputs				**Outputs**		
flow name	**amount**	**unit**	**provider**	**flow name**	**amount**	**unit**
battery cell, Li-ion, NMC111	383	kg	market for battery cell, Li-ion, NMC111 | battery cell, Li-ion, NMC111 | Cutoff, U - GLO	**passenger car, BEV**	**1**	**Item(s)**
passenger car, electric, without battery	1417	kg	market for passenger car, electric, without battery | passenger car, electric, without battery | Cutoff, U - GLO			
light duty vehicle production, BEV						
Inputs				**Outputs**		
flow name	**amount**	**unit**	**provider**	**flow name**	**amount**	**unit**
battery cell, Li-ion, NMC111	532	kg	market for battery cell, Li-ion, NMC111 | battery cell, Li-ion, NMC111 | Cutoff, U - GLO	**light duty vehicle, BEV**	**1**	**Item(s)**
passenger car, electric, without battery	1968	kg	market for passenger car, electric, without battery | passenger car, electric, without battery | Cutoff, U - GLO			
heavy duty vehicle production, BEV						
Inputs				**Outputs**		
flow name	**amount**	**unit**	**provider**	**flow name**	**amount**	**unit**
battery cell, Li-ion, NMC111	2128	kg	market for battery cell, Li-ion, NMC111 | battery cell, Li-ion, NMC111 | Cutoff, U - GLO	**heavy duty vehicle, BEV**	**1**	**Item(s)**
passenger car, electric, without battery	7872	kg	market for passenger car, electric, without battery | passenger car, electric, without battery | Cutoff, U - GLO			
public bus production, BEV						
Inputs				**Outputs**		
flow name	**amount**	**unit**	**provider**	**flow name**	**amount**	**unit**
battery cell, Li-ion, NMC111	2341	kg	market for battery cell, Li-ion, NMC111 | battery cell, Li-ion, NMC111 | Cutoff, U - GLO	**public bus, BEV**	**1**	**Item(s)**
passenger car, electric, without battery	8660	kg	market for passenger car, electric, without battery | passenger car, electric, without battery | Cutoff, U - GLO			

passenger car production, FCEV						
Inputs				Outputs		
flow name	**amount**	**unit**	**provider**	**flow name**	**amount**	**unit**
battery cell, Li-ion, NMC111	68	kg	market for battery cell, Li-ion, NMC111 | battery cell, Li-ion, NMC111 | Cutoff, U - GLO	**passenger car, FCEV**	**1**	**Item(s)**
fuel cell, 1 kW PEMFC	45	Item(s)	fuel cell production, 1 kW PEMFC			
hydrogen storage vessel	9.17E-04	Item(s)	hydrogen storage vessel, production - YT			
passenger car, electric, without battery	1411	kg	market for passenger car, electric, without battery | passenger car, electric, without battery | Cutoff, U - GLO			

light duty vehicle production, FCEV						
Inputs				Outputs		
flow name	**amount**	**unit**	**provider**	**flow name**	**amount**	**unit**
battery cell, Li-ion, NMC111	97	kg	market for battery cell, Li-ion, NMC111 | battery cell, Li-ion, NMC111 | Cutoff, U - GLO	**light duty vehicle, FCEV**	**1**	**Item(s)**
fuel cell, 1 kW PEMFC	64	Item(s)	fuel cell production, 1 kW PEMFC			
hydrogen storage vessel	1.31E-03	Item(s)	hydrogen storage vessel, production - YT			
passenger car, electric, without battery	2016	kg	market for passenger car, electric, without battery | passenger car, electric, without battery | Cutoff, U - GLO			

heavy duty vehicle production, FCEV						
Inputs				Outputs		
flow name	**amount**	**unit**	**provider**	**flow name**	**amount**	**unit**
battery cell, Li-ion, NMC111	387	kg	market for battery cell, Li-ion, NMC111 | battery cell, Li-ion, NMC111 | Cutoff, U - GLO	**heavy duty vehicle, FCEV**	**1**	**Item(s)**
fuel cell, 1 kW PEMFC	257	Item(s)	fuel cell production, 1 kW PEMFC			
hydrogen storage vessel	5.24E-03	Item(s)	hydrogen storage vessel, production - YT			
passenger car, electric, without battery	8064	kg	market for passenger car, electric, without battery | passenger car, electric, without battery | Cutoff, U - GLO			

public bus production, FCEV						
Inputs				Outputs		
flow name	**amount**	**unit**	**provider**	**flow name**	**amount**	**unit**
battery cell, Li-ion, NMC111	426	kg	market for battery cell, Li-ion, NMC111 | battery cell, Li-ion, NMC111 | Cutoff, U - GLO	**public bus, FCEV**	**1**	**Item(s)**
fuel cell, 1 kW PEMFC	283	Item(s)	fuel cell production, 1 kW PEMFC			
hydrogen storage vessel	5.76E-03	Item(s)	hydrogen storage vessel, production - YT			
passenger car, electric, without battery	8871	kg	market for passenger car, electric, without battery | passenger car, electric, without battery | Cutoff, U - GLO			

electric scooter production						
Inputs				Outputs		
flow name	amount	unit	provider	flow name	amount	unit
battery cell, Li-ion, NMC111	20	kg	market for battery cell, Li-ion, NMC111 | battery cell, Li-ion, NMC111 | Cutoff, U - GLO	**electric scooter**	1	**Item(s)**
electric scooter, without battery	90	kg	market for electric scooter, without battery | electric scooter, without battery | Cutoff, U - GLO			

Table A4.2: LCIs of Vehicles

Air Conditioner production						
Inputs				Outputs		
flow name	amount	unit	provider	flow name	amount	unit
acrylonitrile-butadiene-styrene copolymer	0.022302	kg	market for acrylonitrile-butadiene-styrene copolymer | acrylonitrile-butadiene-styrene copolymer | Cutoff, U - GLO	**air conditioner, 1 kW**	1	**Item(s)**
aluminium, wrought alloy	0.659502	kg	market for aluminium, wrought alloy | aluminium, wrought alloy | Cutoff, U - GLO			
cast iron	0.757206	kg	market for cast iron | cast iron | Cutoff, U - GLO			
coating powder	0.09133	kg	market for coating powder | coating powder | Cutoff, U - RoW			
copper, anode	1.8054	kg	market for copper, anode | copper, anode | Cutoff, U - GLO			
nylon 6	0.13487	kg	market for nylon 6 | nylon 6 | Cutoff, U - RoW			
polyethylene terephthalate, granulate, amorphous	0.06372	kg	market for polyethylene terephthalate, granulate, amorphous | polyethylene terephthalate, granulate, amorphous | Cutoff, U - GLO			
polyethylene, high density, granulate	0.00743	kg	market for polyethylene, high density, granulate | polyethylene, high density, granulate | Cutoff, U - GLO			
polypropylene, granulate	0.08708	kg	market for polypropylene, granulate | polypropylene, granulate | Cutoff, U - GLO			
polystyrene foam slab	0.04142	kg	market for polystyrene foam slab | polystyrene foam slab | Cutoff, U - GLO			
polystyrene, general purpose	0.69561	kg	market for polystyrene, general purpose | polystyrene, general purpose | Cutoff, U - GLO			
polystyrene, high impact	1.71725	kg	market for polystyrene, high impact | polystyrene, high impact | Cutoff, U - GLO			
polyvinylchloride, suspension polymerised	0.42905	kg	market for polyvinylchloride, suspension polymerised | polyvinylchloride, suspension polymerised | Cutoff, U - GLO			
steel, chromium steel 18/8	0.15611	kg	market for steel, chromium steel 18/8 | steel, chromium steel 18/8 | Cutoff, U - GLO			
steel, low-alloyed	3.72868	kg	market for steel, low-alloyed | steel, low-alloyed | Cutoff, U - GLO			
synthetic rubber	0.01805	kg	market for synthetic rubber | synthetic rubber | Cutoff, U - GLO			

Table A4.3: LCI of Air Conditioner Production - based on Almutairi et al. [78]

LED production						
Inputs				Outputs		
flow name	amount	unit	provider	flow name	amount	unit
aluminium oxide, metallurgical	0.1	g	market for aluminium oxide, metallurgical | aluminium oxide, metallurgical | Cutoff, U - RoW	LED, 19W	1	Item(s)
aluminium, cast alloy	723	g	market for aluminium, cast alloy | aluminium, cast alloy | Cutoff, U - GLO			
cable, unspecified	7	g	market for cable, unspecified | cable, unspecified | Cutoff, U - GLO			
capacitor, film type, for through-hole mounting	18	g	market for capacitor, film type, for through-hole mounting | capacitor, film type, for through-hole mounting | Cutoff, U - GLO			
chemical, organic	0.1	g	chemical production, organic | chemical, organic | Cutoff, U - GLO			
diode, glass-, for surface-mounting	0.6	g	market for diode, glass-, for surface-mounting | diode, glass-, for surface-mounting | Cutoff, U - GLO			
electric connector, peripheral type buss	5	g	market for electric connector, peripheral type buss | electric connector, peripheral type buss | Cutoff, U - GLO			
electricity, medium voltage	0.031	kWh	market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U - GLO			
electronic component, active, unspecified	0.35	g	market for electronic component, active, unspecified | electronic component, active, unspecified | Cutoff, U - GLO			
electronic component, passive, unspecified	0.35	g	market for electronic component, passive, unspecified | electronic component, passive, unspecified | Cutoff, U - GLO			
injection moulding	7	g	market for injection moulding | injection moulding | Cutoff, U - GLO			
injection moulding	26	g	market for injection moulding | injection moulding | Cutoff, U - GLO			
integrated circuit, logic type	0.1	g	market for integrated circuit, logic type | integrated circuit, logic type | Cutoff, U - GLO			
light emitting diode	28	g	market for light emitting diode | light emitting diode | Cutoff, U - GLO			
mounting, surface mount technology, Pb-free solder	0.0045	m2	market for mounting, surface mount technology, Pb-free solder | mounting, surface mount technology, Pb-free solder | Cutoff, U - GLO			
mounting, through-hole technology, Pb-free solder	0.0045	m2	market for mounting, through-hole technology, Pb-free solder | mounting, through-hole technology, Pb-free solder | Cutoff, U - GLO			
Packaging waste, paper and board	0.175	kg				
paper, woodfree, uncoated	3	g	market for paper, woodfree, uncoated | paper, woodfree, uncoated | Cutoff, U - RoW			
polyethylene, high density, granulate	130	g	market for polyethylene, high density, granulate | polyethylene, high density, granulate | Cutoff, U - GLO			
resistor, surface-mounted	2	g	market for resistor, surface-mounted | resistor, surface-mounted | Cutoff, U - GLO			
silicone product	3.74	g	market for silicone product | silicone product | Cutoff, U - RoW			
steel, low-alloyed	4	g	market for steel, low-alloyed | steel, low-alloyed | Cutoff, U - GLO			
steel, low-alloyed	17	g	market for steel, low-alloyed | steel, low-alloyed | Cutoff, U - GLO			
transformer, low voltage use	48	g	market for transformer, low voltage use | transformer, low voltage use | Cutoff, U - GLO			
transistor, surface-mounted	0.3	g	market for transistor, surface-mounted | transistor, surface-mounted | Cutoff, U - GLO			

Table A4.4: LCI of LED Production based on Tähkämö et al. [79]

solar thermal water heater production							Based on...
Inputs				Outputs			
flow name	amount	unit	provider	flow name	amount	unit	
auxiliary heating unit, electric, 5kW	1/2	Item(s)	market for auxiliary heating unit, electric, 5kW | auxiliary heating unit, electric, 5kW | Cutoff, U - GLO	solar thermal water heater, 5kW	1	Item(s)	ecoinvent process "heat production, at hot water tank, solar+electric, flat plate, multiple dwelling | heat, solar+electric, multiple-dwelling, for hot water | Cutoff, U"
solar collector system, Cu flat plate collector, one-family house, hot water	1/2	Item(s)	market for solar collector system, Cu flat plate collector, one-family house, hot water | solar collector system, Cu flat plate collector, one-family house, hot water | Cutoff, U - GLO				

Table A4.5: LCI of Solar Thermal Water Heater Production.

white appliance production						
Inputs				Outputs		
flow name	amount	unit	provider	flow name	amount	unit
dishwasher	1/3	Item(s)	market for dishwasher | dishwasher | Cutoff, U - GLO	white appliance	1	Item(s)
refrigerator	1/3	Item(s)	market for refrigerator | refrigerator | Cutoff, U - GLO			
washing machine	1/3	Item(s)	market for washing machine | washing machine | Cutoff, U - GLO			

Table 4.6: LCI of White Appliance Production.

black appliance production						
Inputs				Outputs		
flow name	amount	unit	provider	flow name	amount	unit
internet access equipment	1	Item(s)	internet access equipment production | internet access equipment | Cutoff, U - RoW	black appliance	1	Item(s)
computer, desktop, without screen	1/2	Item(s)	market for computer, desktop, without screen | computer, desktop, without screen | Cutoff, U - GLO			
display, liquid crystal, 17 inches	1/2	Item(s)	market for display, liquid crystal, 17 inches | display, liquid crystal, 17 inches | Cutoff, U - GLO			
computer, laptop	1/2	Item(s)	market for computer, laptop | computer, laptop | Cutoff, U - GLO			

Table A4.7: LCI of Black Appliance Production.

gas stove (electric oven + 4 cooking hobs)			
Weight [kg]	Installed Power [kW] according to manufacturer	Model	Source
52	10.3	BEKO FSM62320DWS Standherd (EEK A, Gaskochfeld, 72 Liter)	https://www.saturn.de/de/product/_beko-fsm62320dws-2160760.html
35	5.88	AMICA SHGG 11560 W Standherd (EEK A, Gaskochfeld, 56 Liter)	https://www.saturn.de/de/product/_amica-shgg-11560-w-1896157.html
56.507	11.8	BOSCH HXR 39 AI 50 Standherd (EEK A, Gaskochfeld, 66 Liter)	https://www.saturn.de/de/product/_bosch-hxr-39-ai-50-2464125.html
45	10.6	AMICA SHEG 914 121 E Standherd (EEK A, Gaskochfeld, 65 Liter)	https://www.saturn.de/de/product/_amica-sheg-914-121-e-2315759.html
47.13	**9.65**		

induction stove (electric oven + 4 cooking hobs)			
Weight [kg]	Installed Power [kW] according to manufacturer	Model	Source
52.8	9.6	BEKO FSM69301XCT Standherd (EEK A, Induktion, 72 Liter)	https://www.saturn.de/de/product/_beko-fsm69301xct-multifunktionsofen-mit-induktions-kochfeld-induktion-72-liter-2801185.html
44	10.1	KOENIC KFC 2311 A Standherd (EEK A, Induktionskochfeld, 65 Liter)	https://www.saturn.de/de/product/_koenic-kfc-2311-a-standherd-eek-a-induktionskochfeld-65-liter-2714578.html
52	9	AEG CIB6641BBM Standherd (EEK A, Induktionskochfeld, 73 Liter)	https://www.saturn.de/de/product/_aeg-cib6641bbm-standherd-eek-a-induktion-73-liter-2739283.html
54.28	10	EXQUISIT EHI 60-3.1 Inox Standherd (EEK A, Induktion)	https://www.saturn.de/de/product/_exquisit-ehi-60-31-inox-standherd-eek-a-induk-96629748.html
50.77	**9.68**		

Table A4.8: Manufacturer's Data on Gas and Induction Stoves.

gas stove production						
Inputs				Outputs		
flow name	**amount**	**unit**	**provider**	**flow name**	**amount**	**unit**
aluminium, wrought alloy	0.761	kg	market for aluminium, wrought alloy | aluminium, wrought alloy | Cutoff, U - GLO	**gas stove, 10 kW**	1	Item(s)
brass	0.344	kg	market for brass | brass | Cutoff, U - RoW			
ceramic tile	0.081	kg	market for ceramic tile | ceramic tile | Cutoff, U - GLO			
compressed air, 700 kPa gauge	13.0184	m3	market for compressed air, 700 kPa gauge | compressed air, 700 kPa gauge | Cutoff, U - RoW			
copper, anode	0.45	kg	market for copper, anode | copper, anode | Cutoff, U - GLO			
electricity, medium voltage	5.4437	kWh	market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U - GLO			
ethylene vinyl acetate copolymer	0.037	kg	market for ethylene vinyl acetate copolymer | ethylene vinyl acetate copolymer | Cutoff, U - RoW			
ferrite	0.335	kg	market for ferrite | ferrite | Cutoff, U - GLO			
flat glass, uncoated	7.415	kg	market for flat glass, uncoated | flat glass, uncoated | Cutoff, U - RoW			
glass fibre reinforced plastic, polyamide, injection moulded	0.648	kg	market for glass fibre reinforced plastic, polyamide, injection moulded | glass fibre reinforced plastic, polyamide, injection moulded | Cutoff, U - GLO			
glass fibre reinforced plastic, polyamide, injection moulded	0.695	kg	market for glass fibre reinforced plastic, polyamide, injection moulded | glass fibre reinforced plastic, polyamide, injection moulded | Cutoff, U - GLO			
iron-nickel-chromium alloy	0.037	kg	market for iron-nickel-chromium alloy | iron-nickel-chromium alloy | Cutoff, U - GLO			
magnesium oxide	0.143	kg	market for magnesium oxide | magnesium oxide | Cutoff, U - GLO			
natural gas, high pressure	1.7321	m3	market group for natural gas, high pressure | natural gas, high pressure | Cutoff, U - GLO			
nylon 6-6	0.365	kg	market for nylon 6-6 | nylon 6-6 | Cutoff, U - RoW			
polyethylene, high density, granulate	0.265	kg	market for polyethylene, high density, granulate | polyethylene, high density, granulate | Cutoff, U - GLO			
polyethylene, low density, granulate	0.472	kg	market for polyethylene, low density, granulate | polyethylene, low density, granulate | Cutoff, U - GLO			
polypropylene, granulate	0.081	kg	market for polypropylene, granulate | polypropylene, granulate | Cutoff, U - GLO			
polystyrene foam slab	1.433	kg	market for polystyrene foam slab | polystyrene foam slab | Cutoff, U - GLO			
steel, chromium steel 18/8	0.663	kg	market for steel, chromium steel 18/8 | steel, chromium steel 18/8 | Cutoff, U - GLO			
steel, low-alloyed	31.982	kg	market for steel, low-alloyed | steel, low-alloyed | Cutoff, U - GLO			
stone wool	2.653	kg	market for stone wool | stone wool | Cutoff, U - GLO			

Table A4.9: LCI of Gas Stove Production based on Landi et al., 2019

electric stove production						
Inputs				**Outputs**		
flow name	**amount**	**unit**	**provider**	**flow name**	**amount**	**unit**
aluminium, wrought alloy	1.685	kg	market for aluminium, wrought alloy | aluminium, wrought alloy | Cutoff, U - GLO	**electric stove, 10 kW**	**1**	**Item(s)**
ceramic tile	0.069	kg	market for ceramic tile | ceramic tile | Cutoff, U - GLO			
compressed air, 700 kPa gauge	10.2785	m3	market for compressed air, 700 kPa gauge | compressed air, 700 kPa gauge | Cutoff, U - RoW			
copper, anode	1.086	kg	market for copper, anode | copper, anode | Cutoff, U - GLO			
electricity, medium voltage	4.3102	kWh	market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U - GLO			
ferrite	0.988	kg	market for ferrite | ferrite | Cutoff, U - GLO			
flat glass, coated	2.986	kg	market for flat glass, coated | flat glass, coated | Cutoff, U - RoW			
flat glass, uncoated	6.331	kg	market for flat glass, uncoated | flat glass, uncoated | Cutoff, U - RoW			
glass fibre reinforced plastic, polyamide, injection moulded	0.593	kg	market for glass fibre reinforced plastic, polyamide, injection moulded | glass fibre reinforced plastic, polyamide, injection moulded | Cutoff, U - GLO			
glass fibre reinforced plastic, polyamide, injection moulded	0.553	kg	market for glass fibre reinforced plastic, polyamide, injection moulded | glass fibre reinforced plastic, polyamide, injection moulded | Cutoff, U - GLO			
iron-nickel-chromium alloy	0.072	kg	market for iron-nickel-chromium alloy | iron-nickel-chromium alloy | Cutoff, U - GLO			
magnesium oxide	0.272	kg	market for magnesium oxide | magnesium oxide | Cutoff, U - GLO			
natural gas, high pressure	1.4275	m3	market group for natural gas, high pressure | natural gas, high pressure | Cutoff, U - GLO			
nylon 6-6	1.344	kg	market for nylon 6-6 | nylon 6-6 | Cutoff, U - RoW			
paper, woodfree, uncoated	0.645	kg	market for paper, woodfree, uncoated | paper, woodfree, uncoated | Cutoff, U - RoW			
polyethylene, high density, granulate	1.446	kg	market for polyethylene, high density, granulate | polyethylene, high density, granulate | Cutoff, U - GLO			
polyethylene, low density, granulate	0.489	kg	market for polyethylene, low density, granulate | polyethylene, low density, granulate | Cutoff, U - GLO			
polyphenylene sulfide	0.648	kg	market for polyphenylene sulfide | polyphenylene sulfide | Cutoff, U - GLO			
polypropylene, granulate	0.021	kg	market for polypropylene, granulate | polypropylene, granulate | Cutoff, U - GLO			
polystyrene, expandable	0.467	kg	market for polystyrene, expandable | polystyrene, expandable | Cutoff, U - GLO			
polyvinylchloride, suspension polymerised	0.106	kg	market for polyvinylchloride, suspension polymerised | polyvinylchloride, suspension polymerised | Cutoff, U - GLO			
steel, chromium steel 18/8	1.426	kg	market for steel, chromium steel 18/8 | steel, chromium steel 18/8 | Cutoff, U - GLO			
steel, low-alloyed	28.981	kg	market for steel, low-alloyed | steel, low-alloyed | Cutoff, U - GLO			
stone wool	2.266	kg	market for stone wool | stone wool | Cutoff, U - GLO			

Table A4.10: LCI of Electric Stove Production based on Landi et al., 2019 & Pina et al., 2015

agricultural management system (computer 300W), production							Based on...
Inputs				Outputs			
flow name	amount	unit	provider	flow name	amount	unit	
computer, laptop	1	Item(s)	market for computer, laptop | computer, laptop | Cutoff, U - GLO	agricultural management system (computer 300W)	1	Item(s)	
display, liquid crystal, 17 inches	1	Item(s)	market for display, liquid crystal, 17 inches | display, liquid crystal, 17 inches | Cutoff, U - GLO				
internet access equipment	1	Item(s)	internet access equipment production | internet access equipment | Cutoff, U - RoW				

Table A4.11: LCI of Agricultural Management System (Computer 300W), Production

asset (50%BAP 50%WAP) production 1kW, SER_WHCR						
Inputs				Outputs		
flow name	amount	unit	provider	flow name	amount	unit
black appliance	1.0/300*500	Item(s)	black appliance production	asset (50%BAP 50%WAP) 1kW, SER_WHCR	1	Item(s)
white appliance	1.0/900*500	Item(s)	white appliance production			

Table A4.12: LCI of Asset (50% BAP 50%WAP) 1kW, SER_WHCR

asset (50%LED 50% AC) production 1kW, OTHR_ELSP						
Inputs				Outputs		
flow name	amount	unit	provider	flow name	amount	unit
air conditioner, 1 kW	1/2	Item(s)	air conditioner production	asset (50%LED 50% AC) 1kW, OTHR_ELSP	1	Item(s)
LED, 19W	1000/19/2	Item(s)	LED production			

Table A4.13: LCI of Asset (50% LED 50% AC) 1kW, OTHR_ELSP

parameter name	assumed lifetime of asset	parameter name	assumed lifetime of asset	parameter name	assumed lifetime of asset	parameter name	assumed lifetime of asset
asset_AGR_ELC	8	asset_FRLDT_GSL	12	asset_HOU_WTHR	20	asset_PSPRD_ELE	15
asset_AGR_HEATB	20	asset_FRLDT_H2	12	asset_OTHR_ELSP	11.5	asset_PSPRD_H2	15
asset_AGR_HEATE	20	asset_FRLDT_PHEVDSL	12	asset_OTHR_HT	20	asset_PSWTR_ELE	50
asset_AGR_LIGHT	15	asset_FRLDT_PHEVGSL	12	asset_OTHR_THP	20	asset_PSWTR_H2	50
asset_AGR_PMOTD	15	asset_FRWTR_ELE	50	asset_PS2WL_ELE	10	asset_PSWTR_OIL	50
asset_AGR_PMOTE	15	asset_FRWTR_H2	50	asset_PS2WL_GSL	10	asset_SER_AIRC	15
asset_FDDRTB_ELSP	11.5	asset_FRWTR_OIL	50	asset_PSAIR_KERO	25	asset_SER_ELC	9
asset_FDDRTB_HT	20	asset_HOU_AIRC	15	asset_PSCAR_DSL	12	asset_SER_LIGHT	15
asset_FDDRTB_THP	20	asset_HOU_BAP	8	asset_PSCAR_ELE	12	asset_SER_WHCE	20
asset_FRHDT_DSL	12	asset_HOU_COOKE	15	asset_PSCAR_GSL	12	asset_SER_WHCR	20
asset_FRHDT_ELE	12	asset_HOU_COOKS	15	asset_PSCAR_H2	12		
asset_FRHDT_H2	12	asset_HOU_LIGHT	15	asset_PSCAR_PHEVDSL	12		
asset_FRLDT_DSL	12	asset_HOU_WAP	10	asset_PSCAR_PHEVGSL	12		
asset_FRLDT_ELE	12	asset_HOU_WTHE	20	asset_PSPRD_DSL	15		

Table 4.14: Underlying Lifetimes of End-Use Assets

promising ecoinvent process	changes	process in openLCA to model the combustion of diesel		to represent the respective demand processes according to the ESM	
		process name	reference flow		
heat production, light fuel oil, at boiler 100kW condensing, non-modulating | heat, central or small-scale, other than natural gas | Cutoff, U - RoW	delete chimney, electricity, oil boiler and oil storage change reference flow to sum of diesel-input (convert kg to MJ according to diesel LHV of 42.5 MJ/kg)	*diesel combustion, in boiler*	burned diesel, in boiler	AGR_HEATB	Agriculture - Heating - Boilers
				FDDRTB_HT	Food, Drink & Tobacco - Horizontal energy uses - Heat uses
				OTHR_HT	Other Industries - Horizontal energy uses - Heat uses
diesel, burned in agricultural machinery | diesel, burned in agricultural machinery | Cutoff, U - GLO	delete agricultural trailer, shed tractor & all abraison soil related emissions due to tyres change reference flow to sum of diesel-input (convert kg to MJ according to diesel LHV of 42.5 MJ/kg)	*diesel combustion, in pumping and motors*	burned diesel, in pumping and motors	AGR_PMOTD	Agriculture - Pumping & motors - Diesel
				FDDRTB_THP	Food, Drink & Tobacco - Thermal processing
				OTHR_THP	Other Industries - Thermal processing
transport, freight, inland waterways, barge | transport, freight, inland waterways, barge | Cutoff, U - RoW	delete barge, canal, maintenance barge and port facilities change reference flow to sum of diesel-input (convert kg to MJ according to diesel LHV of 42.5 MJ/kg)	*diesel combustion, in navigation*	burned diesel, in navigation	PSWTR_OIL	Inland Passenger navigation - Oil
				FRWTR_OIL	Inland Freight navigation - Oil
transport, freight, lorry 16-32 metric ton, EURO6 | transport, freight, lorry 16-32 metric ton, EURO6 | Cutoff, U - RoW	delete lorry, lorry maintenance, road and road maintenance change reference flow to sum of diesel-input (convert kg to MJ according to diesel LHV of 42.5 MJ/kg)	*diesel combustion, in heavy duty vehicle*	burned diesel, in heavy duty vehicle	FRHDT_DSL	Road Freight Transport - Heavy duty vehicles - ICE - Diesel
transport, regular bus | transport, regular bus | Cutoff, U - RoW	delete bus, bus maintenance, road and road maintenance change reference flow to sum of diesel-input (convert kg to MJ according to diesel LHV of 42.5 MJ/kg)	*diesel combustion, in public bus*	burned diesel, in public bus	PSPRD_DSL	Public passenger transport - Road - ICE - Diesel
transport, passenger car, medium size, diesel, EURO 5 | transport, passenger car, medium size, diesel, EURO 5 | Cutoff, U - RoW	delete passenger car, maintenance, road and road maintenance change reference flow to sum of diesel-input (convert kg to MJ according to diesel LHV of 42.5 MJ/kg)	*diesel combustion, in passenger car or light duty vehicle*	burned diesel, in passenger car or light duty vehicle	FRLDT_DSL	Road Freight Transport - Light duty vehicles - ICE - Diesel
				FRLDT_PHEVDSL	Road Freight Transport - Light duty vehicles - Plug-in Hybrid - Diesel
				PSCAR_DSL	Private passenger transport - Private passenger cars - ICE - Diesel
				PSCAR_PHEVDSL	Private passenger transport - Private passenger cars - Plug-in Hybrid - Diesel

Table A4.15: Modeling the Combustion of Diesel – Derivation.

promising ecoinvent process	changes	process in openLCA to model the combustion of gasoline: process name	process in openLCA to model the combustion of gasoline: reference flow	to represent the respective demand processes according to the ESM	
heat production, light fuel oil, at boiler 100kW condensing, non-modulating | heat, central or small-scale, other than natural gas | Cutoff, U - RoW	change reference flow to sum of gasoline-input (convert kg to MJ according to gasoline LHV of 43.5 MJ/kg)"	*gasoline combustion, in boiler*	burned gasoline, in boiler	FDDRTB_HT	Food, Drink & Tobacco - Horizontal energy uses - Heat uses
petrol, unleaded, burned in machinery | petrol, unleaded, burned in machinery | Cutoff, U	change reference flow to sum of gasoline-input (convert kg to MJ according to gasoline LHV of 43.5 MJ/kg)	*gasoline combustion, in pumping and motors*	burned gasoline, in pumping and motors	FDDRTB_THP	Food, Drink & Tobacco - Thermal processing
				OTHR_THP	Other Industries - Thermal processing
transport, passenger, motor scooter | transport, passenger, motor scooter | Cutoff, U - RoW	delete motor scooter, maintenance, road and road maintenance change reference flow to sum of gasoline-input (convert kg to MJ according to gasoline LHV of 43.5 MJ/kg)	*gasoline combustion, in scooter*	burned gasoline, in scooter	PS2WL_GSL	Private passenger transport - 2wheelers - Gasoline
transport, passenger car, medium size, petrol, EURO 5 | transport, passenger car, medium size, petrol, EURO 5 | Cutoff, U - RoW	just retain fuel and emissions change reference flow to sum of gasoline-input (convert kg to MJ according to gasoline LHV of 43.5 MJ/kg)	*gasoline combustion, in passenger car or light duty vehicle*	burned gasoline, in passenger car or light duty vehicle	FRLDT_GSL	Road Freight Transport - Light duty vehicles - ICE - Gasoline
				FRLDT_PHEVGSL	Road Freight Transport - Light duty vehicles - Plug-in Hybrid - Gasoline
				PSCAR_GSL	Private passenger transport - Private passenger cars - ICE - Gasoline
				PSCAR_PHEVGSL	Private passenger transport - Private passenger cars - Plug-in Hybrid - Gasoline

Table A4.16: Modeling the Combustion of Gasoline – Derivation.

promising ecoinvent process	changes	process in openLCA to model the combustion of LPG: process name	process in openLCA to model the combustion of LPG: reference flow	to represent the respective demand processes according to the ESM	
heat production, light fuel oil, at boiler 100kW condensing, non-modulating | heat, central or small-scale, other than natural gas | Cutoff, U - RoW	change reference flow to sum of LPG-input (convert kg to MJ according to LPG LHV of 46.1 MJ/kg)"	*LPG combustion, in boiler*	burned LPG, in boiler	FDDRTB_HT	Food, Drink & Tobacco - Horizontal energy uses - Heat uses
				OTHR_HT	Other Industries - Horizontal energy uses - Heat uses
transport, passenger car, medium size, liquefied petroleum gas (LPG), EURO 5 | transport, passenger car, medium size, liquefied petroleum gas, EURO 5 | Cutoff, U - GLO	delete passenger car, passenger car maintenance, road, road maintenance and emissions related to tyre/break/road wear change reference flow to sum of LPG-input (convert kg to MJ according to LPG LHV of 46.1 MJ/kg)	*LPG combustion, in pumping and motors*	burned LPG, in pumping and motors	FDDRTB_THP	Food, Drink & Tobacco - Thermal processing
				OTHR_THP	Other Industries - Thermal processing
modeled based on literature: IPPC report 2006 + Weyant et al., 2019		*LPG combustion, in stove*	burned LPG, in stove	HOU_COOKS	Households - Thermal Uses - Cooking - Stoves

Table A4.17: Modeling the Combustion of LPG – Derivation.

promising ecoinvent process	changes	process in openLCA to model the combustion of synthetic liquids		to represent the respective demand processes according to the ESM	
		process name	reference flow		
transport, freight, aircraft, dedicated freight, very short haul | transport, freight, aircraft, very short haul | Cutoff, U	change reference flow to the sum of synthetic liquids-input (convert kg to MJ according to synthetic liquids LHV of 43.9 MJ/kg) adaptations based on literature: Styring et al., 2021; Treyer et al., 2021 exclusion of trace elements due to impurities present in fossil-derived fuels	*synthetic liquids combustion, in aviation*	burned synthetic liquids, in aviation	PSAIR_KERO	Aviation - Kerosene
heat production, light fuel oil, at boiler 100kW condensing, non-modulating | heat, central or small-scale, other than natural gas | Cutoff, U - RoW	change reference flow to the sum of synthetic liquids-input (convert kg to MJ according to synthetic liquids LHV of 43.9 MJ/kg) adaptations based on literature: Styring et al., 2021; Treyer et al., 2021 exclusion of trace elements due to impurities present in fossil-derived fuels	*synthetic liquids combustion, in boiler*	burned synthetic liquids, in boiler	AGR_HEATB	Agriculture - Heating - Boilers
				FDDRTB_HT	Food, Drink & Tobacco - Horizontal energy uses - Heat
				OTHR_HT	Other Industries - Horizontal energy uses - Heat uses
diesel, burned in agricultural machinery | diesel, burned in agricultural machinery | Cutoff, U - GLO	change reference flow to the sum of synthetic liquids-input (convert kg to MJ according to synthetic liquids LHV of 43.9 MJ/kg) adaptations based on literature: Styring et al., 2021; Treyer et al., 2021 exclusion of trace elements due to impurities present in fossil-derived fuels	*synthetic liquids combustion, in pumping and motors*	burned synthetic liquids, in pumping and motors	FDDRTB_THP	Food, Drink & Tobacco - Thermal processing
				OTHR_THP	Other Industries - Thermal processing

Table A4.18: Modeling the Combustion of Synthetic Liquids – Derivation.

promising ecoinvent process	changes	process in openLCA to model the combustion of conventional biofuel		to represent the respective demand processes according to the ESM	
		process name	reference flow		
transport, freight, lorry 16-32 metric ton, EURO6 | transport, freight, lorry 16-32 metric ton, EURO6 | Cutoff, U - RoW	delete lorry, lorry maintenance, road and road maintenance change reference flow to sum of biofuel-input (convert kg to MJ according to biofuel LHV of 26.8 MJ/kg) zero carbon dioxide emissions to avoid double counting of biogenic carbon dioxide from biomass -50% CO and hydrocarbons (methane, ethane, propane, buthane, penthane, hexane, heptane, octane, benzene, toluene, xylene, formaldehyde) according to Thangavelu et al., 2015	*conventional biofuel combustion, in heavy duty vehicle*	burned biofuel conventional, in heavy duty vehicle	FRHDT_DSL	Road Freight Transport - Heavy duty vehicles - ICE - Diesel
transport, regular bus | transport, regular bus | Cutoff, U - RoW	delete bus, bus maintenance, road and road maintenance change reference flow to sum of biofuel-input (convert kg to MJ according to biofuel LHV of 26.8 MJ/kg) zero carbon dioxide emissions to avoid double counting of biogenic carbon dioxide from biomass -50% CO and hydrocarbons (methane, ethane, propane, buthane, penthane, hexane, heptane, octane, benzene, toluene, xylene, formaldehyde) according to Thangavelu et al., 2015	*conventional biofuel combustion, in public bus*	burned biofuel conventional, in public bus	PSPRD_DSL	Public passenger transport - Road - ICE - Diesel
transport, passenger car, medium size, diesel, EURO 5 | transport, passenger car, medium size, diesel, EURO 5 | Cutoff, U - RoW	delete passenger car, maintenance, road and road maintenance change reference flow to sum of biofuel-input (convert kg to MJ according to biofuel LHV of 26.8 MJ/kg) zero carbon dioxide emissions to avoid double counting of biogenic carbon dioxide from biomass -50% CO and hydrocarbons (methane, ethane, propane, buthane, penthane, hexane, heptane, octane, benzene, toluene, xylene, formaldehyde) according to Thangavelu et al., 2015	*conventional biofuel combustion, in passenger car or light duty vehicle_diesel blend*	burned biofuel conventional, in passenger car or light duty vehicle_diesel blend	FRLDT_DSL	Road Freight Transport - Light duty vehicles - ICE - Diesel
				FRLDT_PHEVDSL	Road Freight Transport - Light duty vehicles - Plug-in Hybrid - Diesel
				PSCAR_DSL	Private passenger transport - Private passenger cars - ICE - Diesel
				PSCAR_PHEVDSL	Private passenger transport - Private passenger cars - Plug-in Hybrid - Diesel
transport, passenger car, medium size, petrol, EURO 5 | transport, passenger car, medium size, petrol, EURO 5 | Cutoff, U - RoW	just retain fuel and emissions change reference flow to sum of biofuel-input (convert kg to MJ according to biofuel LHV of 26.8 MJ/kg) zero carbon dioxide emissions to avoid double counting of biogenic carbon dioxide from biomass -50% CO and hydrocarbons (methane, ethane, propane, buthane, penthane, hexane, heptane, octane, benzene, toluene, xylene, formaldehyde) according to Thangavelu et al., 2015	*conventional biofuel combustion, in passenger car or light duty vehicle_gasoline blend*	burned biofuel conventional, in passenger car or light duty vehicle_gasoline blend	FRLDT_GSL	Road Freight Transport - Light duty vehicles - ICE - Gasoline
				FRLDT_PHEVGSL	Road Freight Transport - Light duty vehicles - Plug-in Hybrid - Gasoline
				PSCAR_GSL	Private passenger transport - Private passenger cars - ICE - Gasoline
				PSCAR_PHEVGSL	Private passenger transport - Private passenger cars - Plug-in Hybrid - Gasoline
transport, freight, inland waterways, barge | transport, freight, inland waterways, barge | Cutoff, U - RoW	delete barge, canal, maintenance barge and port facilities change reference flow to sum of biofuel-input (convert kg to MJ according to biofuel LHV of 26.8 MJ/kg) zero carbon dioxide emissions to avoid double counting of biogenic carbon dioxide from biomass -50% CO and hydrocarbons (methane, ethane, propane, buthane, penthane, hexane, heptane, octane, benzene, toluene, xylene, formaldehyde) according to Thangavelu et al., 2015	*conventional biofuel combustion, in navigation*	burned biofuel conventional, in navigation	FRWTR_OIL	Inland Freight navigation - Oil
				PSWTR_OIL	Inland Passenger navigation - Oil
transport, passenger, motor scooter | transport, passenger, motor scooter | Cutoff, U - RoW	delete motor scooter, maintenance, road and road maintenance change reference flow to sum of biofuel-input (convert kg to MJ according to biofuel LHV of 26.8 MJ/kg) zero carbon dioxide emissions to avoid double counting of biogenic carbon dioxide from biomass -50% CO and hydrocarbons (methane, ethane, propane, buthane, penthane, hexane, heptane, octane, benzene, toluene, xylene, formaldehyde) according to Thangavelu et al., 2015	*conventional biofuel combustion, in scooter*	burned biofuel conventional, in scooter	PS2WL_GSL	Private passenger transport - 2wheelers - Gasoline

Table A4.19: Modeling the Combustion of Conventional Biofuel – Derivation.

promising ecoinvent process	changes	process in openLCA to model the combustion of advanced biofuel		to represent the respective demand processes according to the ESM	
		process name	reference flow		
transport, freight, lorry 16-32 metric ton, EURO6 | transport, freight, lorry 16-32 metric ton, EURO6 | Cutoff, U - RoW	delete lorry, lorry maintenance, road and road maintenance change reference flow to sum of biofuel-input (convert kg to MJ according to biofuel LHV of 26.8 MJ/kg) zero carbon dioxide emissions to avoid double counting of biogenic carbon dioxide from biomass -50% CO and hydrocarbons (methane, ethane, propane, buthane, penthane, hexane, heptane, octane, benzene, toluene, xylene, formaldehyde) according to Thangavelu et al., 2015	*advanced biofuel combustion, in heavy duty vehicle*	burned biofuel advanced, in heavy duty vehicle	FRHDT_DSL	Road Freight Transport - Heavy duty vehicles - ICE - Diesel
transport, regular bus | transport, regular bus | Cutoff, U - RoW	delete bus, bus maintenance, road and road maintenance change reference flow to sum of bioduel-input (convert kg to MJ according to biofuel LHV of 26.8 MJ/kg) zero carbon dioxide emissions to avoid double counting of biogenic carbon dioxide from biomass -50% CO and hydrocarbons (methane, ethane, propane, buthane, penthane, hexane, heptane, octane, benzene, toluene, xylene, formaldehyde) according to Thangavelu et al., 2015	*advanced biofuel combustion, in public bus*	burned biofuel advanced, in public bus	PSPRD_DSL	Public passenger transport - Road - ICE - Diesel
transport, passenger car, medium size, diesel, EURO 5 | transport, passenger car, medium size, diesel, EURO 5 | Cutoff, U - RoW	delete passenger car, maintenance, road and road maintenance change reference flow to sum of biofuel-input (convert kg to MJ according to biofuel LHV of 26.8 MJ/kg) zero carbon dioxide emissions to avoid double counting of biogenic carbon dioxide from biomass -50% CO and hydrocarbons (methane, ethane, propane, buthane, penthane, hexane, heptane, octane, benzene, toluene, xylene, formaldehyde) according to Thangavelu et al., 2015	*advanced biofuel combustion, in passenger car or light duty vehicle_diesel blend*	burned biofuel advanced, in passenger car or light duty vehicle_diesel blend	FRLDT_DSL	Road Freight Transport - Light duty vehicles - ICE - Diesel
				FRLDT_PHEVDSL	Road Freight Transport - Light duty vehicles - Plug-in Hybrid - Diesel
				PSCAR_DSL	Private passenger transport - Private passenger cars - ICE - Diesel
				PSCAR_PHEVDSL	Private passenger transport - Private passenger cars - Plug-in Hybrid - Diesel
transport, passenger car, medium size, petrol, EURO 5 | transport, passenger car, medium size, petrol, EURO 5 | Cutoff, U - RoW	just retain fuel and emissions change reference flow to sum of biofuel-input (convert kg to MJ according to biofuel LHV of 26.8 MJ/kg) zero carbon dioxide emissions to avoid double counting of biogenic carbon dioxide from biomass -50% CO and hydrocarbons (methane, ethane, propane, buthane, penthane, hexane, heptane, octane, benzene, toluene, xylene, formaldehyde) according to Thangavelu et al., 2015	*advanced biofuel combustion, in passenger car or light duty vehicle_gasoline blend*	burned biofuel advanced, in passenger car or light duty vehicle_gasoline blend	FRLDT_GSL	Road Freight Transport - Light duty vehicles - ICE - Gasoline
				FRLDT_PHEVGSL	Road Freight Transport - Light duty vehicles - Plug-in Hybrid - Gasoline
				PSCAR_GSL	Private passenger transport - Private passenger cars - ICE - Gasoline
				PSCAR_PHEVGSL	Private passenger transport - Private passenger cars - Plug-in Hybrid - Gasoline
transport, freight, inland waterways, barge | transport, freight, inland waterways, barge | Cutoff, U - RoW	delete barge, canal, maintenance barge and port facilities change reference flow to sum of biofuel-input (convert kg to MJ according to biofuel LHV of 26.8 MJ/kg) zero carbon dioxide emissions to avoid double counting of biogenic carbon dioxide from biomass -50% CO and hydrocarbons (methane, ethane, propane, buthane, penthane, hexane, heptane, octane, benzene, toluene, xylene, formaldehyde) according to Thangavelu et al., 2015	*advanced biofuel combustion, in navigation*	burned biofuel advanced, in navigation	FRWTR_OIL	Inland Freight navigation - Oil
				PSWTR_OIL	Inland Passenger navigation - Oil
transport, passenger, motor scooter | transport, passenger, motor scooter | Cutoff, U - RoW	delete motor scooter, maintenance, road and road maintenance change reference flow to sum of biofuel-input (convert kg to MJ according to biofuel LHV of 26.8 MJ/kg) zero carbon dioxide emissions to avoid double counting of biogenic carbon dioxide from biomass -50% CO and hydrocarbons (methane, ethane, propane, buthane, penthane, hexane, heptane, octane, benzene, toluene, xylene, formaldehyde) according to Thangavelu et al., 2015	*advanced biofuel combustion, in scooter*	burned biofuel advanced, in scooter	PS2WL_GSL	Private passenger transport - 2wheelers - Gasoline
transport, freight, aircraft, dedicated freight, very short haul | transport, freight, aircraft, very short haul | Cutoff, U	change reference flow to sum of biofuel-input (convert kg to MJ according to biofuel LHV of 26.8 MJ/kg) zero carbon dioxide emissions to avoid double counting of biogenic carbon dioxide from biomass -50% CO and hydrocarbons (represented here by NMVOCs as a proxy) according to Thangavelu et al., 2015	*advanced biofuel combustion, in aviation*	burned biofuel advanced, in aviation	PSAIR_KERO	Aviation - Kerosene

Table A4.20: Modeling the Combustion of Advanced Biofuel – Derivation.

promising ecoinvent process	changes	process in openLCA to model the reaction of H2 in a fuel cell		to represent the respective demand processes according to the ESM	
		process name	reference flow		
modeled based on the stoiciometric equation for the redox reaction in a hydrogen fuel cell		*reaction of hydrogen, in fuel cell*	reacted hydrogen, in fuel cell	FRHDT_H2	Road Freight Transport - Heavy duty vehicles - Fuel cell
				PSPRD_H2	Public passenger transport - Road - Fuel cell
				FRLDT_H2	Road Freight Transport - Light duty vehicles - Fuel cell
				PSCAR_H2	Private passenger transport - Private passenger cars - Fuel cell
				FRWTR_H2	Inland Freight navigation - Electric - Fuel cell
				PSWTR_H2	Inland Passenger navigation - Electric - Fuel cell

Table A4.21: Modeling the Reaction of Hydrogen in a Fuel Cell – Derivation.

promising ecoinvent process	changes	process in openLCA to model the combustion of ammonia		to represent the respective demand processes according to the ESM	
		process name	reference flow		
modeled based on the stoichiometric equation for the combustion reaction of ammonia, and based on Chalaris et al., 2022		*ammonia combustion, in navigation*	burned ammonia, in navigation	FRWTR_OIL	Inland Freight navigation - Oil
				PSWTR_OIL	Inland Passenger navigation - Oil

Table A4.22: Modeling the Combustion of Ammonia – Derivation.

promising ecoinvent process	changes	process in openLCA to model the combustion of paraffin oil		to represent the respective demand processes according to the ESM	
		process name	reference flow		
modeled based on Swensson & Kjellson 2015		*paraffin oil combustion, in stove*	burned paraffin oil, in stove	HOU_COOKS	Households - Thermal Uses - Cooking - Stoves
		not modeled in openLCA due to lack of information on the associated chemical reactions		NONEN_NE	Non energy uses in industry

Table A4.23: Modeling the Combustion of Paraffin Oil – Derivation.

promising ecoinvent process	changes	process in openLCA to model the combustion of kerosne		to represent the respective demand processes according to the ESM	
		process name	reference flow		
transport, freight, aircraft, dedicated freight, very short haul | transport, freight, aircraft, very short haul | Cutoff, U	delete aircraft and airport change reference flow to sum of kerosene-input (convert kg to MJ according to kerosene LHV of 43.0 MJ/kg)	*kerosene combustion, in aviation*	burned kerosene, in aviation	PSAIR_KERO	Aviation - Kerosene

Table A4.24: Modeling the Combustion of Kerosene – Derivation.

synthetic liquids combustion, in aviation							
Inputs				**Outputs**			**Based on...**
flow name	**amount**	**unit**	**provider**	**flow name**	**amount**	**unit**	
synthetic liquids, imported	0.347*share_synliq_imported	kg	synthetic liquids, import	**burned synthetic liquids, in aviation**	**0.347*43.9**	**MJ**	
synthetic liquids, prod@M	0.347*(1-share_synliq_imported)	kg	synthetic liquids, production @M	Carbon dioxide, fossil (Emission to air/low population density)	0.00E+00	kg	
				Carbon dioxide, fossil (Emission to air/lower stratosphere + upper troposphere)	0.00E+00	kg	
				Carbon monoxide, fossil (Emission to air/low population density)	8.612E-4/2	kg	Treyer et al., 2021
				Carbon monoxide, fossil (Emission to air/lower stratosphere + upper troposphere)	0.001307/2	kg	
				Nitrogen oxides (Emission to air/low population density)	2.53E-03	kg	Treyer et al., 2021
				Nitrogen oxides (Emission to air/lower stratosphere + upper troposphere)	3.83E-03	kg	
				NMVOC, non-methane volatile organic compounds (Emission to air/low population density)	7.594E-5/2	kg	Treyer et al., 2021
				NMVOC, non-methane volatile organic compounds (Emission to air/lower stratosphere + upper troposphere)	1.152E-4/2	kg	
				Particulate Matter, < 2.5 um (Emission to air/low population density)	1.765E-5/2	kg	Treyer et al., 2021
				Particulate Matter, < 2.5 um (Emission to air/lower stratosphere + upper troposphere)	2.679E-5/2	kg	
				Sulfur dioxide (Emission to air/low population density)	1.158E-4/2	kg	Styring et al., 2021
				Sulfur dioxide (Emission to air/lower stratosphere + upper troposphere)	1.757E-4/2	kg	
				Water (Emission to air/low population density)	0.00000105	m3	*ecoinvent process "transport, freight, aircraft, dedicated freight, very short haul | transport, freight, aircraft, very short haul | Cutoff, U"*
				Water (Emission to air/lower stratosphere + upper troposphere)	0.0000016	m3	

Table A4.25: LCI of Synthetic Liquids Combustion, in Aviation

synthetic liquids combustion, in boiler							Based on...
Inputs				Outputs			
flow name	amount	unit	provider	flow name	amount	unit	
synthetic liquids, imported	0.02342*share_synliq_imported	kg	synthetic liquids, import	**burned synthetic liquids, in boiler**	**0.02342*43.9**	**MJ**	
synthetic liquids, prod@M	0.02342*(1-share_synliq_imported)	kg	synthetic liquids, production @M	Benzene	2.0E-8*0.6	kg	Treyer et al., 2021
				Butane	1.5E-7*0.6	kg	Treyer et al., 2021
				Carbon dioxide, fossil	0.00E+00	kg	
				Carbon monoxide, fossil	7.5E-6*0.6	kg	Treyer et al., 2021
				Ethane	2.0E-8*0.6	kg	Treyer et al., 2021
				Hydrocarbons, aliphatic, alkanes, unspecified	2.5E-7*0.6	kg	Treyer et al., 2021
				Hydrocarbons, aliphatic, unsaturated	2.0E-8*0.6	kg	Treyer et al., 2021
				Hydrocarbons, aromatic	2.0E-8*0.6	kg	Treyer et al., 2021
				Methane, fossil	2.0E-7*0.6	kg	Treyer et al., 2021
				Nitrogen oxides	0.0000275	kg	Treyer et al., 2021
				PAH, polycyclic aromatic hydrocarbons	4.6E-10*0.6	kg	Treyer et al., 2021
				Particulate Matter, < 2.5 um	5.0E-7*0.6	kg	Treyer et al., 2021
				Pentane	1.0E-7*0.6	kg	*Treyer et al., 2021*
				Propane	3.0E-8*0.6	kg	*Treyer et al., 2021*
				Sulfur dioxide	4.5669E-5*0.6	kg	Styring et al., 2021
				Toluene	1.0E-8*0.6	kg	Treyer et al., 2021

Table A4.26: LCI of Synthetic Liquids Combustion, in Boiler.

synthetic liquids combustion, in pumping and motors							Based on...
Inputs				Outputs			
flow name	amount	unit	provider	flow name	amount	unit	
synthetic liquids, imported	0.0222222222222*share_synliq_imported	kg	synthetic liquids, import	**burned synthetic liquids, in pumping and motors**	**0.0222222222222*43.9**	**MJ**	
synthetic liquids, prod@M	0.0222222222222*(1-share_synliq_imported)	kg	synthetic liquids, production @M	Benzene	1.62079510703E-7*0.6	kg	Treyer et al., 2021
				Carbon dioxide, fossil	0.00E+00	kg	
				Carbon monoxide, fossil	1.30479102956E-4*0.6	kg	Treyer et al., 2021
				Methane, fossil	2.86952089704E-6*0.6	kg	Treyer et al., 2021
				Nitrogen oxides	8.66E-04	kg	Treyer et al., 2021
				NMVOC, non-methane volatile organic compounds	4.76554536188E-5*0.6	kg	Treyer et al., 2021
				PAH, polycyclic aromatic hydrocarbons	7.28848114169E-8*0.6	kg	Treyer et al., 2021
				Particulate Matter, < 2.5 um	1.09072375127E-4*0.6	kg	Treyer et al., 2021
				Sulfur dioxide	2.24260958206E-5*0.6	kg	Styring et al., 2021

Table A4.27: LCI of Synthetic Liquids Combustion, in Pumping and Motors.

LPG combustion, in stove							
Inputs				**Outputs**			**Based on...**
flow name	**amount**	**unit**	**provider**	**flow name**	**amount**	**unit**	
LPG, imported	0.277777778	kg	LPG, import - YT	**burned LPG, in stove**	**1**	**kWh**	
				Carbon dioxide, fossil	2.27E-01	kg	IPCC, 2006
				Carbon monoxide, fossil	1.11E-10	kg	Weyant et al., 2019
				Elemental carbon	8.06E-11	kg	Weyant et al., 2019
				Methane, fossil	1.80E-05	kg	IPCC, 2006
				Nitrogen oxides	3.60E-07	kg	IPCC, 2006
				Organic carbon	1.42E-09	kg	Weyant et al., 2019
				Particulate Matter, < 2.5 um	2.64E-09	kg	Weyant et al., 2019

Table A4.28: LCI of LPG Combustion, in Stove.

hydrogen reaction, in fuel cell							
Inputs				**Outputs**			**Based on...**
flow name	**amount**	**unit**	**provider**	**flow name**	**amount**	**unit**	
hydrogen, imported	1.0*share_H2_imported	kg	hydrogen import	**reacted hydrogen, in fuel cell**	**120**	**MJ**	stoiciometric equation for the redox reaction in a hydrogen fuel cell
hydrogen_prod@M	1.0*(1-share_H2_imported)	kg	hydrogen, prod@M - YT	Water	0.017842	m3	

Table A4.29: LCI of Hydrogen Reaction, in Fuel Cell.

ammonia combustion, in navigation							
Inputs				**Outputs**			**Based on...**
flow name	**amount**	**unit**	**provider**	**flow name**	**amount**	**unit**	
ammonia, imported	1/18.7*share_NH3_imported	kg	ammonia import	**burned ammonia, in navigation**	**1**	**MJ**	
ammonia, prod@M	1/18.7*(1-share_NH3_imported)	kg	ammonia, production@M	Nitrogen, total	0.82237/18.7	kg	stoiciometric equation for the combustion reaction of ammonia
				Water	0.52907/18.7/1000	m3	
				Nitrogen oxides	1.61	g	Chalaris et al., 2022
				Carbon dioxide, non-fossil	4.007	g	
				Methane, non-fossil	0.0001	g	

Table A4.30: LCI of Ammonia Combustion, in Navigation.

paraffin oil combustion, in stove							**Based on...**
Inputs				**Outputs**			
flow name	**amount**	**unit**	**provider**	**flow name**	**amount**	**unit**	
paraffin oil, imported	1.0/42	kg	paraffin oil, import - YT	**burned paraffin oil, in stove**	**1**	**MJ**	Swensson & Kjellson 2015
				Carbon monoxide, fossil	3.00E-03	kg	
				Carbon dioxide, fossil	1.46E-01	kg	
				Methane, fossil	3.60E-05	kg	
				Nitrogen oxides	5.00E-05	kg	
				NMVOC, non-methane volatile organic compounds	6.60E-04	kg	
				Particulate Matter, < 2.5 um	1.50E-04	kg	
				Sulfur dioxide	1.27E-04	kg	

Table A4.31: LCI of Paraffin oil Combustion, in Stove.

$$2H_2 + O_2 \rightarrow 2H_2O$$

2 moles of H2			-->	2 moles of water		
2 moles x (1.01 g/mole)			-->	2 moles x (18.02 g/mole)		
2.02	g	H2	-->	36.04	g	H2O
1,000.00	g	H2	-->	17,841.58	g	H2O

Figure A4.1: Stoichiometric Equation for Chemical Reaction in Hydrogen Fuel Cell.

$$4\ NH_3 + 3\ O_2 \rightarrow 2\ N_2 + 6\ H_2O$$

4 moles of NH3			-->	6 moles of water			and	2 moles of N2		
4 moles x (17.03 g/mole)			-->	2 moles x (18.02 g/mole)				2 moles x (28.01 g/mole)		
68.12	g	NH3	-->	36.04	g	H2O		56.02	g	N2
1,000.00	g	NH3	-->	529.07	g	H2O		822.37	g	N2

Figure A4.2: Stoichiometric Equation for the Complete Combustion of Ammonia.

diesel combustion, in boiler							
Inputs				**Outputs**			**Based on...**
flow name	**amount**	**unit**	**provider**	**flow name**	**amount**	**unit**	
diesel, imported	0.02342	kg	*diesel, import - YT*	**burned diesel, in boiler**	**.02342*42.5**	**MJ**	ecoinvent process "diesel, burned in agricultural machinery | diesel, burned in agricultural machinery | Cutoff, U" Changes: - without the inputs: shed, tractor, trailer - without abraison/soil related emissions due to tyres - without waste heat because heat is to be generated instead of application as agricultural machinery
				Acetaldehyde	2.05E-08	kg	
				Acetone	5E-08	kg	
				Acrolein	1.15E-08	kg	
				Benzaldehyde	6E-09	kg	
				Benzene	2E-08	kg	
				Butane	1.5E-07	kg	
				Carbon dioxide, fossil	0.074	kg	
				Carbon monoxide, fossil	7.5E-06	kg	
				condensate from light oil boiler	9.84E-06	m3	
				Copper ion	4E-10	kg	
				Dinitrogen monoxide	7E-07	kg	
				Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	5.7E-17	kg	
				Ethane	2E-08	kg	
				Ethylene	5E-08	kg	
				Ethyne	1E-08	kg	
				Formaldehyde	6E-09	kg	
				hazardous waste, for incineration	4.15E-06	kg	
				Hydrocarbons, aliphatic, alkanes, unspecified	2.5E-07	kg	
				Hydrocarbons, aliphatic, unsaturated	2E-08	kg	
				Hydrocarbons, aromatic	2E-08	kg	
				Hydrogen fluoride	4.5E-09	kg	
				Mercury II	5E-10	kg	
				Methane, fossil	2E-07	kg	
				Nitrogen oxides	2.75E-05	kg	
				PAH, polycyclic aromatic hydrocarbons	4.6E-10	kg	
				Particulate Matter, <2.5 um	5E-07	kg	
				Pentane	1E-07	kg	
				Propanal	6E-09	kg	
				Propane	3E-08	kg	
				Propene	2E-08	kg	
				Sulfur dioxide	4.57E-05	kg	
				Toluene	1E-08	kg	
				Zinc II	5E-10	kg	

Table A4.32: LCI of Diesel Combustion, in Boiler.

conventional biofuel combustion, in navigation							
Inputs				**Outputs**			**Based on...**
flow name	**amount**	**unit**	**provider**	**flow name**	**amount**	**unit**	
biofuel conventional, imported	0.00939	kg	biofuel conventional, import	**burned biofuel conventional, in navigation**	**0.00939*26.8**	**MJ**	
				Ammonia	4.87E-07	kg	ecoinvent process "transport, freight, inland waterways, barge | transport, freight, inland waterways, barge | Cutoff, U - RoW"
				Benzene	1.78E-7/2	kg	Thangavelu et al., 2015
				Benzo(a)pyrene	7.24E-14	kg	ecoinvent process "transport, freight, inland waterways, barge | transport, freight, inland waterways, barge | Cutoff, U - RoW"
				Cadmium II	9.39E-11	kg	
				Carbon monoxide, from soil or biomass stock	2.54E-5/2	kg	Thangavelu et al., 2015
				Chromium III	4.70E-10	kg	ecoinvent process "transport, freight, inland waterways, barge | transport, freight, inland waterways, barge | Cutoff, U - RoW"
				Copper ion	1.60E-08	kg	
				Dinitrogen monoxide	0.00000311	kg	
				Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	5.63E-19	kg	
				Hydrochloric acid	9.95E-09	kg	
				Lead II	1.88E-10	kg	
				Mercury II	6.58E-13	kg	
				Methane	2.25E-7/2	kg	Thangavelu et al., 2015
				Nickel II	6.58E-10	kg	ecoinvent process "transport, freight, inland waterways, barge | transport, freight, inland waterways, barge | Cutoff, U - RoW"
				Nitrogen oxides	0.00047	kg	
				NMVOC, non-methane volatile organic compounds	0.00000939	kg	
				Particulate Matter, < 2.5 um	0.00000867	kg	
				Particulate Matter, > 10 um	0.000000371	kg	
				Particulate Matter, > 2.5 um and < 10um	0.000000723	kg	
				Selenium IV	9.39E-11	kg	
				Sulfur dioxide	0.00000564	kg	
				Toluene	7.52E-8/2	kg	Thangavelu et al., 2015
				Xylene	7.52E-8/2	kg	Thangavelu et al., 2015
				Zinc II	9.39E-09	kg	ecoinvent process "transport, freight, inland waterways, barge | transport, freight, inland waterways, barge | Cutoff, U - RoW"

Table A4.33: LCI of Conventional Biofuel Combustion, in Navigation.

advanced biofuel combustion, in navigation							
Inputs				**Outputs**			**Based on...**
flow name	**amount**	**unit**	**provider**	**flow name**	**amount**	**unit**	
biofuel advanced, imported	0.00939	kg	biofuel advanced, import	**burned biofuel advanced, in navigation**	**0.00939*26.8**	**MJ**	
				Ammonia	4.87E-07	kg	ecoinvent process "transport, freight, inland waterways, barge | transport, freight, inland waterways, barge | Cutoff, U - RoW"
				Benzene	1.78E-7/2	kg	Thangavelu et al., 2015
				Benzo(a)pyrene	7.24E-14	kg	ecoinvent process "transport, freight, inland waterways, barge | transport, freight, inland waterways, barge | Cutoff, U - RoW"
				Cadmium II	9.39E-11	kg	
				Carbon monoxide, from soil or biomass stock	2.54E-5/2	kg	Thangavelu et al., 2015
				Chromium III	4.70E-10	kg	ecoinvent process "transport, freight, inland waterways, barge | transport, freight, inland waterways, barge | Cutoff, U - RoW"
				Copper ion	1.60E-08	kg	
				Dinitrogen monoxide	0.00000311	kg	
				Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	5.63E-19	kg	
				Hydrochloric acid	9.95E-09	kg	
				Lead II	1.88E-10	kg	
				Mercury II	6.58E-13	kg	
				Methane	2.25E-7/2	kg	Thangavelu et al., 2015
				Nickel II	6.58E-10	kg	ecoinvent process "transport, freight, inland waterways, barge | transport, freight, inland waterways, barge | Cutoff, U - RoW"
				Nitrogen oxides	0.00047	kg	
				NMVOC, non-methane volatile organic compounds	0.00000939	kg	
				Particulate Matter, < 2.5 um	0.00000867	kg	
				Particulate Matter, > 10 um	0.000000371	kg	
				Particulate Matter, > 2.5 um and < 10um	0.000000723	kg	
				Selenium IV	9.39E-11	kg	
				Sulfur dioxide	0.00000564	kg	
				Toluene	7.52E-8/2	kg	Thangavelu et al., 2015
				Xylene	7.52E-8/2	kg	Thangavelu et al., 2015
				Zinc II	9.39E-09	kg	ecoinvent process "transport, freight, inland waterways, barge | transport, freight, inland waterways, barge | Cutoff, U - RoW"

Table A4.34: LCI of Advanced Biofuel Combustion, in Navigation.

Appendix A5: Interpretation of Results

			overall performance according to LCA		sectoral hotspots according to LCA		technological hotspots within the identified sectoral hotspot according to LCA				
environmental impact category			**LEVEL1**	**Why?**	**LEVEL2**	**Why?**	**LEVEL3**	**Why?**	**underlying causalities tied to the energy system configuration according to the ESM**	**physical impact mechanism at the core of identified hotspots**	
1	**Fine particulate matter formation**	FPM	Mf outperforms baseline in the domain FPM		because in Mf the transport-induced deterioration in FPM is compensated by the collective improvement of the remaining sectors (especially the household sector)	Which technological hotspot is the main driver for the household-induced FPM improvement of Mf?	a) no LPG-induced FPM occurs in Mf b) less elc-induced FPM occurs in Mf		a) because according to the ESM in 2050 households use close to no LPG anymore in Mf while this is not the case in baseline b1) because according to the ESM in 2050 less GWh electricity are demanded in households in Mf compared to baseline *b2) because in 2050 the electricity mix/GWh is less FPM-intensive in Mf compared to baseline - decisively because according to the ESM less diesel is combusted to produce 1 GWh of electricity than in baseline	Why is the combustion of diesel and LPG so FPM-intensive?	because the combustion of diesel and LPG releases SO_2, NO_x & PM <2.5 um which have a FPM potential
2	**Fossil resource scarcity**	FRS	Mf outperforms baseline in the domain FRS		because all 5 sectors exhibit an improvement in FRS in Mf compared to baseline (especially the household sector)	Which technological hotspot is the main driver for the household-induced FRS improvement of Mf?	a) no LPG-induced FPM occurs in Mf b) less elc-induced FPM occurs in Mf		a) because according to the ESM in 2050 households use close to no LPG anymore in Mf while this is not the case in baseline b1) because according to the ESM in 2050 less GWh electricity are demanded in households in Mf compared to baseline *b2) because in 2050 the electricity mix/GWh is less FRS-intensive in Mf compared to baseline - decisively because according to the ESM less diesel is combusted to produce 1 GWh of electricity than in baseline	Why is the production of diesel so FRS-intensive?	because the production of diesel is based on the exploitation of crude oil
3	**Freshwater ecotoxicity**	FEX	Mf performs worse than baseline in the domain FEX		because in Mf all 5 sectors exhibit a deterioration in FEX in Mf compared to baseline (especially the transport sector)	Which technological hotspot is the main driver for the transport-induced FEX deterioration of Mf?	more BEV-induced FEX occurs in Mf		because according to the ESM there are significantly more BEV deployed in Mf than in baseline (i.e., Mf relies on a more BEV-dominated vehicle fleet than baseline)	Why is the production of BEV so FEX-intensive?	because the copper production that is required for the battery cell production, and the waste treatment processes of scrap copper and used BEV gliders emit copper ions, zinc II, silver I as well as antimony ions into water sources
4	**Freshwater eutrophication**	FEU	Mf performs worse than baseline in the domain FEU		because overall, the transport-induced deterioration in FEU outweights the small FEU improvement of the household and services sectors in Mf	Which technological hotspot is the main driver for the transport-induced FEU deterioration of Mf?	more BEV-induced FEU occurs in Mf		because according to the ESM there are significantly more BEV deployed in Mf than in baseline (i.e., Mf relies on a more BEV-dominated vehicle fleet than baseline)	Why is the production of BEV so FEU-intensive?	because the treatment processes of sulfidic tailings from copper/cobalt/gold/silver mine operations emit phosphate into water sources. These treatment processes are required as part of the production and beneficiation of copper/cobalt (and to a lesser degree gold and silver) in order to produce copper collector foil, cathodes and anodes for the battery cell of a BEV.

	environmental impact category		overall performance according to LCA		sectoral hotspots according to LCA		technological hotspots within the identified sectoral hotspot according to LCA		underlying causalities tied to the energy system configuration according to the ESM	physical impact mechanism at the core of identified hotspots	
			LEVEL1	Why?	LEVEL2	Why?	LEVEL3	Why?			
5	**Global warming**	GWP	Mf outperforms baseline in the domain GWP		because all 5 sectors exhibit an improvement in SOD in Mf compared to baseline (especially the household sector)	Which technological hotspot is the main driver for the household-induced GWP improvement of Mf?	a) no LPG-induced GWP occurs in Mf b) less elc-induced GWP occurs in Mf		a) because according to the ESM in 2050 households use close to no LPG anymore in Mf while this is not the case in baseline b1) because according to the ESM in 2050 less GWh electricity are demanded in households in Mf compared to baseline *b2) because in 2050 the electricity mix/GWh is less GWP-intensive in Mf compared to baseline - decisively because according to the ESM less diesel is combusted to produce 1 GWh of electricity than in baseline	Why is the combustion of diesel and LPG so GWP-intensive?	because the combustion of diesel and LPG releases for instance CO2, and N2O which have a GWP
6	**Human carcinogenic toxicity**	HCT	Mf performs worse than baseline in the domain HCT		because overall, the transport-induced deterioration in HCT outweights the small HCT improvement of the household and services sectors in Mf	Which technological hotspot is the main driver for the transport-induced HCT deterioration of Mf?	more BEV-induced HCT occurs in Mf		because according to the ESM there are significantly more BEV deployed in Mf than in baseline (i.e., Mf relies on a more BEV-dominated vehicle fleet than baseline)	Why is the production of BEV so HCT-intensive?	because the treatment processes of electric arc furnace slag emit chromium VI (and other toxic trace elements) into water sources. These treatment processes are required as part of the production of steel in order to produce for instance the glider and electric motor of a BEV.
7	**Human non-carcinogenic toxicity**	HnCT	Mf performs worse than baseline in the domain HnCT		because overall, the transport-induced deterioration in HnCT outweights the small HnCT improvement of the household and services sectors in Mf	Which technological hotspot is the main driver for the transport-induced HnCT deterioration of Mf?	more BEV-induced HnCT occurs in Mf		because according to the ESM there are significantly more BEV deployed in Mf than in baseline (i.e., Mf relies on a more BEV-dominated vehicle fleet than baseline)	Why is the production of BEV so HnCT-intensive?	because the treatment processes of sulfidic tailings, copper slack and the smelting of copper concentrate emit arsenic, zinc II and lead II (and other toxic trace elements) into water and air. These processes are required as part of the value chain of copper production in order to produce the battery and electronics of a BEV.
8	**Ionizing radiation**	IR	Mf performs worse than baseline in the domain IR		because in Mf all 5 sectors exhibit a deterioration in FEX in Mf compared to baseline (especially the transport sector)	Which technological hotspot is the main driver for the transport-induced IR deterioration of Mf?	more BEV-induced IR occurs in Mf		because according to the ESM there are significantly more BEV deployed in Mf than in baseline (i.e., Mf relies on a more BEV-dominated vehicle fleet than baseline)	Why is the production of BEV so IR-intensive?	because the entire value chain to produce battery cells is very electricity intensive (e.g., the upstream production of cobalt). As the global electricity mix is assumed to entail a certain share of nuclear energy (consistently across all scenarios) it does in turn require the treatment of tailing from uranium milling which releases radon emissions.
9	**Land use**	LU	Mf performs worse than baseline in the domain LU		because overall, the transport-induced deterioration in LU outweights the small LU improvement of the household and services sectors in Mf	Which technological hotspot is the main driver for the transport-induced LU deterioration of Mf?	more biofuel combustion-induced LU occurs in Mf		because according to the ESM there is significantly more biofuel (advanced) used in Mf than in baseline (especially for aviation and navigation)	Why is the combustion of biofuel (advanced) so LU-intensive?	because the value chain of biofuel (advanced) production exhibits a high land occupation due to intensive forests in order to produce wood chips

			overall performance according to LCA		sectoral hotspots according to LCA		technological hotspots within the identified sectoral hotspot according to LCA				
environmental impact category			**LEVEL1**	**Why?**	**LEVEL2**	**Why?**	**LEVEL3**	**Why?**	**underlying causalities tied to the energy system configuration according to the ESM**	**physical impact mechanism at the core of identified hotspots**	
10	**Marine ecotoxicity**	MEX	Mf performs worse than baseline in the domain MEX		because all 5 sectors exhibit a deterioration in MEX in Mf compared to baseline (especially the transport sector)	Which technological hotspot is the main driver for the transport-induced MEX deterioration of Mf?	more BEV-induced MEX occurs in Mf		because according to the ESM there are significantly more BEV deployed in Mf than in baseline (i.e., Mf relies on a more BEV-dominated vehicle fleet than baseline)	Why is the production of BEV so MEX-intensive?	because most prominently the treatment processes of sulfidic tailings from copper mine operation and end of life treatment of scrap copper and used gliders emit copper ions, zinc II, silver I and antimony ions (and other toxic trace elements) into water. These processes are required as part of the value chain of copper production in order to produce the battery and electronics of a BEV.
11	**Marine eutrophication**	MEU	Mf performs worse than baseline in the domain MEU		because in Mf a transport-induced deterioration in MEU outweighs the collective improvements of the remaining sectors	Which technological hotspot is the main driver for the transport-induced MEU deterioration of Mf?	more BEV-induced MEU occurs in Mf		because according to the ESM there are significantly more BEV deployed in Mf than in baseline (i.e., Mf relies on a more BEV-dominated vehicle fleet than baseline)	Why is the production of BEV so MEU-intensive?	because rare earth mine operation and beneficiation releases wastewater rich in nitrogen, ammonium and nitrate. These operation and beneficiation processes are ,for instance, part of the value chain of lithium carbonate and cobalt production which are required in order to produce battery cells and electronics of a BEV.
12	**Mineral resource scarcity**	MRS	Mf performs worse than baseline in the domain MRS		because all 5 sectors exhibit a deterioration in MRS in Mf compared to baseline (especially the transport sector)	Which technological hotspot is the main driver for the transport-induced MRS deterioration of Mf?	more BEV-induced MEU occurs in Mf		because according to the ESM there are significantly more BEV deployed in Mf than in baseline (i.e., Mf relies on a more BEV-dominated vehicle fleet than baseline)	Why is the production of BEV so MRS-intensive?	because especially the production of battery cells and electronics of a BEV requires the exploitation of cobalt, nickel, manganese, (and moreover silicon, copper, iron, magnesium, aluminium, molybdenum etc.)
13	**Ozone formation, Human health**	OFHH	Mf outperforms baseline in the domain OFHH		because all 5 sectors exhibit an improvement in OFHH in Mf compared to baseline (especially the transport sector)	Which technological hotspot is the main driver for the transport-induced OFHH improvement of Mf?	less diesel combustion-induced OFHH occurs in Mf		because according to the ESM there is significantly less diesel combusted for transportation in Mf than in baseline	Why is the combustion of diesel so OFHH-intensive?	because the combustion of diesel releases nitrogen oxides and non-methane volatile organic compounds (NMVOC) into the air, which have an ozone formation potential
14	**Ozone formation, Terrestrial ecosystems**	OFTE	Mf outperforms baseline in the domain OFTE		because all 5 sectors exhibit an improvement in OFTE in Mf compared to baseline (especially the transport sector)	Which technological hotspot is the main driver for the transport-induced OFTE improvement of Mf?	less diesel combustion-induced OFTE occurs in Mf		because according to the ESM there is significantly less diesel combusted for transportation in Mf than in baseline	Why is the combustion of diesel so OFTE-intensive?	because the combustion of diesel releases nitrogen oxides and non-methane volatile organic compounds (NMVOC), which have an ozone formation potential

			overall performance according to LCA		sectoral hotspots according to LCA		technological hotspots within the identified sectoral hotspot according to LCA				
environmental impact category			LEVEL1	Why?	LEVEL2	Why?	LEVEL3	Why?	underlying causalities tied to the energy system configuration according to the ESM	physical impact mechanism at the core of identified hotspots	
15	**Stratospheric ozone depletion**	SOD	Mf outperforms baseline in the domain SOD		because all 5 sectors exhibit an improvement in SOD in Mf compared to baseline (especially the household sector)	Which technological hotspot is the main driver for the household-induced SOD improvement of Mf?	a) no LPG-induced FPM occurs in Mf b) less elc-induced FPM occurs in Mf		a) because according to the ESM in 2050 households use close to no LPG anymore in Mf while this is not the case in baseline b1) because according to the ESM in 2050 less GWh electricity are demanded in households in Mf compared to baseline *b2) because in 2050 the electricity mix/GWh is less SOD-intensive in Mf compared to baseline - decisively because according to the ESM less diesel is combusted to produce 1 GWh of electricity than in baseline	Why is the combustion of diesel and LPG so SOD-intensive?	because the combustion of diesel and LPG releases N2O (Nitrous Oxide/ Dinitrogen monoxide) which has a SOD potential
16	**Terrestrial acidification**	TA	Mf outperforms baseline in the domain TA		because the transport-induced deterioration in TA is outweighed by the remaining sectors (especially the household sector) of Mf	Which technological hotspot is the main driver for the household-induced TA improvement of Mf?	a) no LPG-induced TA occurs in Mf b) less elc-induced TA occurs in Mf		a) because according to the ESM in 2050 households use close to no LPG anymore in Mf while this is not the case in baseline b1) because according to the ESM in 2050 less GWh electricity are demanded in households in Mf compared to baseline *b2) because in 2050 the electricity mix/GWh is less TA-intensive in Mf compared to baseline - decisively because according to the ESM less diesel is combusted to produce 1 GWh of electricity than in baseline	Why is the combustion of diesel and LPG so TA-intensive?	because the combustion of diesel and LPG releases for instance SO2, NOX and ammonia, which have a TA potential
17	**Terrestrial ecotoxicity**	TE	Mf performs worse than baseline in the domain MRS		because in Mf a transport-induced deterioration in TE outweighs the small improvement of household and services sectors	Which technological hotspot is the main driver for the transport-induced TE deterioration of Mf?	more BEV-induced TE occurs in Mf		because according to the ESM there are significantly more BEV deployed in Mf than in baseline (i.e., Mf relies on a more BEV-dominated vehicle fleet than baseline)	Why is the production of BEV so TE-intensive?	because especially the production of xxx of a BEV requires the smelting of copper concentrate for copper anode; cobalt production, which in turn emits copper ions, nickel II, lead II, zinc II, cadmium II, arsenic ions and chromium III into the air.
18	**Water consumption**	WC	Mf performs worse than baseline in the domain MRS		because in Mf a transport-induced deterioration in WC outweighs the small improvement of household, services and industrial sectors	Which technological hotspot is the main driver for the transport-induced WC deterioration of Mf?	more BEV-induced WC occurs in Mf		because according to the ESM there are significantly more BEV deployed in Mf than in baseline (i.e., Mf relies on a more BEV-dominated vehicle fleet than baseline)	Why is the production of BEV so WC-intensive?	because especially the production of battery cells of a BEV requires the exploitation of cobalt and nickel which is both electricity and water-intensive. As the global electricity mix is assumed to entail a certain share of hydro and nuclear energy (consistently across all scenarios) it increases the water-intensity even further.

* LEVEL3 finding

Table A5.1: Analysis of environmental performance: baseline vs. MAESHAfocus

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