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Climate neutrality of the French energy system: overview and impacts of sustainable aviation fuel production

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CO₂ emission reduction of sectors such as aviation, maritime shipping, road haulage, and chemical production is challenging but necessary. Although these sectors will most likely continue to rely on carbonaceous energy carriers, they are expected to gradually shift away from fossil fuels. In order to do so, the prominent option is to utilize alternative carbon sources—like biomass and CO₂ originating from carbon capture—for the production of non-fossil carbonaceous vectors (biofuels and e-fuels). However, the limited availability of biomass and the varying nature of other carbon sources necessitate a comprehensive evaluation of trade-offs between potential carbon uses and existing sources. Then, it is primordial to understand the origin of carbon used in sustainable aviation fuel (SAF) to understand the implications of defossilizing aviation for the energy system. Moreover, the production of SAF implies deep changes to the energy system that are quantified in this work. This study utilizes the linear programming cost optimization tool EnergyScope TD to analyze the holistic French energy system, encompassing transport, industry, electricity, and heat sectors while ensuring net greenhouse gas neutrality. A novel method to model and quantify carbon flows within the system is introduced, enabling a comprehensive assessment of greenhouse gas neutrality. This study highlights the significance of fulfilling clean energy requirements and implementing carbon dioxide removal measures as crucial steps toward achieving climate neutrality. Indeed, to reach climate neutrality, a production of 1,046 TWh of electricity by non-fossil sources is needed. Furthermore, the findings underscore the critical role of efficient carbon and energy valorization from biomass, providing evidence that producing fuels by combining biomass and hydrogen is optimal. The study also offers valuable insights into the future cost and impact of SAF production for air travel originating from France. That is, the European law ReFuelEU would

Abbreviations: BtL, biomass to liquid; BEV, battery electric vehicle; CCGT, combined cycle gas turbine; CDR, carbon dioxide removal; DAC, direct air capture; DHN, district heating network; EUD, end-use demand; FT, Fischer-Tropsch; GHGs, greenhouse gases; HT, high temperature; HVCs, high-value chemicals; SAF, sustainable aviation fuel; PBtL, power and biomass to liquid; PtL, power to liquid; PV, photovoltaic; TD, typical day.

increase the price of plane tickets by +33% and would require 126 TWh of hydrogen and 50 TWh of biomass to produce the necessary 91 TWh of jet fuel. Finally, the implications of the assumption behind the production of SAF are discussed.

KEYWORDS

sustainable aviation fuel, carbon flows, e-bio-fuel, carbon neutrality, Fischer–Tropsch, energy system model

1 Introduction

1.1 General context

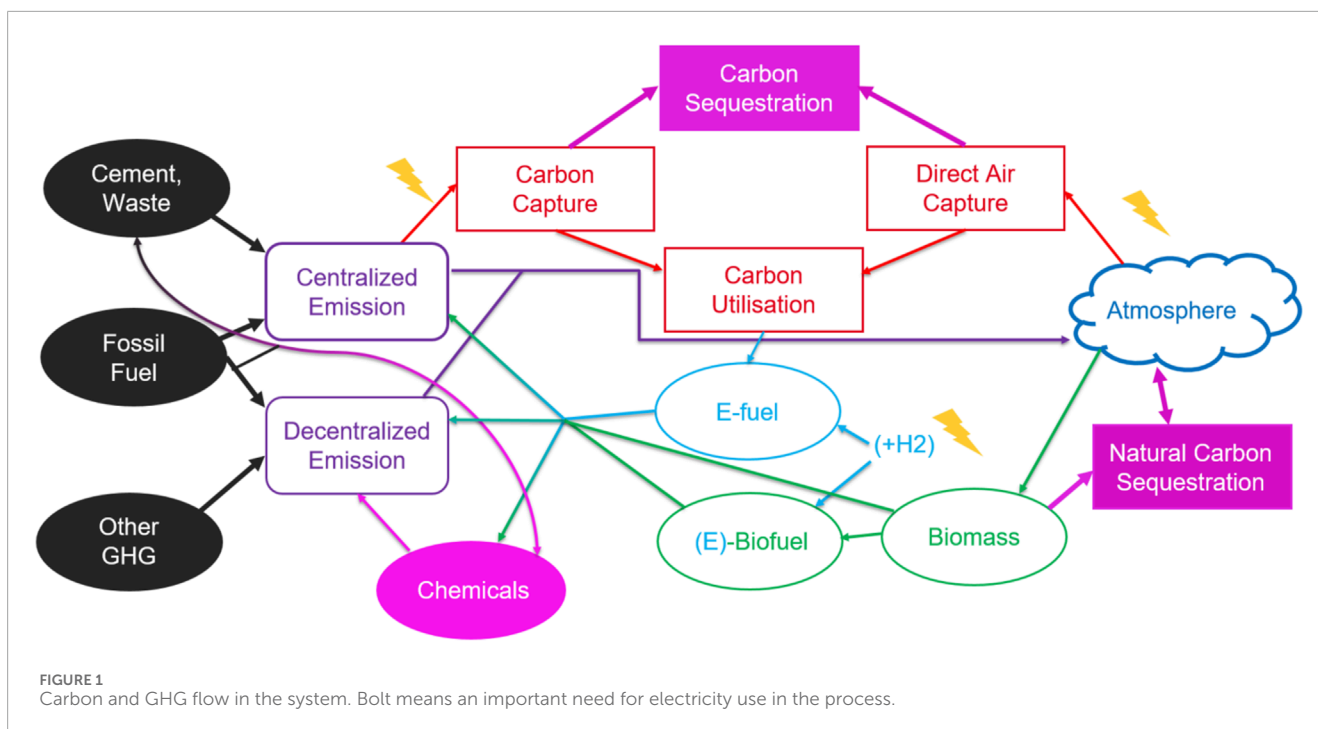
Humans affect Earth's climate by the release of greenhouse gases (GHGs) in the atmosphere (P.R. Shukla et al., 2022). In 2015, 195 countries signed the Paris Agreement, which aimed at “holding the increase in the global average temperature to well below 2°C above pre-industrial levels” (UNFCCC (2015)). As a consequence, France pledged to reach climate neutrality in 2050 and, in this goal, started a strategy released by the *Ministère de la transition écologique et solidaire* (2020) (*French Environment minister*). This strategy relies significantly on biomass and does not take into account GHG emissions and energy needs from international transport (maritime and aviation). This raises two problems; the first is the hard-to-quantify availability and environmental impacts of biomass. The second is that to reach global climate neutrality, international transport emissions must be reduced, and so, countries must take responsibility for these emissions and include them in their strategy. The long-range transport sector is one of the most challenging sectors to defossilize, especially because the volume and mass density requirements are such that only a carbonaceous vector (or energy carrier) can be used (Gray et al., 2021). To shift away from fossil fuel, these vectors must be synthetically produced and, so, require a source of carbon. The same goes for chemicals but with the additional parameter of end-of-life processing. To know where the carbon in an energy vector comes from, the best method is to quantify all carbon flows in the system. Carbon constitutes biomass at approximately 50% in mass, and this makes biomass an important provider of non-fossil carbon. Biomass is foreseen to be used in diverse sectors, and it is primordial then to study the trade-offs between the different possible uses of biomass and the optimal carbon flows for the production of e-bio-fuels and chemicals. Among sectors that need a carbonaceous vector, aviation is one of the most important sectors because there is currently no alternative to carbonaceous fuel and because it is an important energy consumer (5% of primary energy in France in 2019). This paper aims to answer the following questions: 1) what are the implications on the energy system of climate neutrality while considering every sector and only limited import of fossil energy? 2) What are the implications of importing renewable and fossil jet fuel and how much would the production of sustainable aviation fuel (SAF) cost? 3) How do different hypotheses concerning the share of Fischer–Tropsch (FT) impact the optimal system? The method applied uses the open-source linear programming optimization tool EnergyScope TD to model the entirety of the French energy system, and this model is enhanced with a carbon flow optimization component.

The paper is organized as follows: **Section 1** describes the state-of-the-art and the research gaps this paper aims to fill; **Section 2** presents the methodology, detailing the integration of carbon flows into the EnergyScope TD model and clarifying the data assumptions that underlie this analysis; **Section 3** presents and analyzes the results; **Section 4** is a discussion on the conclusions that can be drawn from the results. In addition, this section explains the different limitations of the study; and **Section 5** draws the general conclusion of this paper and advises on what orientation future works should take.

1.2 The carbon flows and the climate neutrality

It is not obvious why switching from a fossil carbonaceous vector to a non-fossil carbonaceous vector has a positive impact on climate. Indeed, in both cases, a carbon dioxide molecule is eventually emitted into the atmosphere on combustion, contributing to the greenhouse effect. However, fossil fuel on combustion emits carbon that was previously contained in the ground effectively, changing the concentration of CO₂ in the atmosphere, whereas for non-fossil carbonaceous fuel, the carbon contained in the fuel was previously in the atmosphere, and so, the CO₂ concentration does not change. This entails a need to quantify how much carbon dioxide enters the atmosphere and how much exits it to understand the anthropic impact on the CO₂ concentration. Thus, it is primordial to quantify carbon flows within the system. **Figure 1** shows the carbon (and other GHGs) flows in energy systems. Black ellipses stand for technologies and resources releasing carbon that was previously not in the atmospheric system. This carbon can be either captured or goes into the atmosphere. The carbon can also be directly captured in the atmosphere via direct air capture (DAC). The captured carbon can either be sequestered in geological formation underground (carbon capture and sequestration [CCS]) or used to produce fuel or chemicals (carbon capture use [CCU]). The carbon in the atmosphere can be naturally captured via biomass or finally can be sequestered through natural biogeochemical mechanisms. Climate neutrality is achieved when the flow of GHGs entering the atmosphere is exactly offset by the flow of GHGs out of the atmosphere.

Hence, the objective is to replace fossil fuels with sustainable fuels; to do so, there is a need for carbon and an energy source. Carbon and energy can come from various sources, leading to the following classification. Fuels that use biomass both as a source of energy and source of carbon are classified as biofuels, the fuels that use biomass as a carbon source and biomass and hydrogen as a source of energy are e-bio-fuels, and the fuels that use CO₂ as a



carbon source and hydrogen as a source of energy are e-fuels. As explained before, from a systemic point of view, the impact of e-fuels on climate is complex because of the question of CO₂ origins. The different types of fuel that can be produced and are considered in the model are methane, methanol, and FT liquid (which is a blend of gasoline, diesel, and jet fuel).

1.3 Energy system model climate neutrality and aviation

International transport is often a blind spot of countries; as a consequence or as a cause, many studies of energy modeling do not take into account the international transport sector in the energy system. It is then primordial to consider every sector of the energy system when studying the production of SAF because the competing use of carbon resources, such as biomass, influences the whole system. The strategies of European countries often cope with the absence of international transport by relying on massive imports of low-emission energy in their climate-neutral strategy. It is, for example, the case for France's neighbors, such as Switzerland (Office fédéral de l'énergie OFEN, 2020), Germany (Prognos AG and Wuppertal Institut, 2021), or Belgium (Gouvernement Belge, 2019). Let us assume that the import of green energy means a need for another country to be a net exporter of energy. The energy exporter can be a neighbor, but in Europe, there is no country capable and willing to export enough energy to supply for the rest of the continent. The exporter can also be a country where there is abundant potential for renewable energy (e.g., North Africa), but the import of energy from these (often developing) countries raises questions on the already reached climate neutrality of the said country and the energy justice of such partnerships (Lindner, 2023). Relying on massive imports of energy ultimately leaves the

importing country vulnerable to energy import variability and its effect on the commercial and geopolitical balance.

Many studies aim to study the future of aviation by looking at how to produce the necessary fuels. Among the research conducted on the subject, some conduct a techno-economic analysis of the process for producing SAF, and some evaluate the cost of producing SAF at the system level. All these techno-economic studies have diverse focuses. Ueckerdt et al. (2021) investigated the general challenges in e-fuel production. Habermeyer et al. (2023) examined the future cost of the power-and-biomass-to-liquid (PbTL) process. Huang et al. (2021) looked at the cost of diverse sustainably produced carbon molecules. This type of paper does not consider the impact on the system of producing the fuels. They do not put into perspective the emission reduction achieved within a fuel with the related objective at the scale of the system but focus more on the economic and process analysis. To explore these two aspects, studies use energy system models to optimize the system at the whole country's energy system scale.

Among them, some focus on subjects that are related to the production of SAF. For example, Blanco et al. (2018) studied the production of hydrogen in Europe and its relationship with the production of e-fuel. Rixhon et al. (2022) investigated the impact of non-energy demand and chemical production on the system. Korberg et al. (2021) evaluated the role of biomass gasification in the energy system and found that e-bio-fuel plays a major role in the future energy system. Li et al. (2020) studied the feasibility of reaching carbon neutrality for Switzerland while taking into account international transport but without considering the impact of the production of biomass on GHG emissions. Sacchi et al. (2023) showed the impact of reaching a climate-neutral aviation sector considering e-fuel and direct air capture with carbon sequestration (DACCS) to offset the direct impact of aviation on climate.

The FT process produces a blend of different fuels, and some studies do not consider this and take into account a 100% share of jet fuel produced. For example, Dray et al. (2022) and Bergero et al. (2023) studied the future of aviation considering the evolution of the demand, with different technological improvements and sustainable fuel penetration, but they take into account 100% of jet fuel at the output of the FT process, whereas Sacchi et al. (2023) took only an 18% share of jet fuel at the output of the process. Furthermore, no studies consider the impact of the co-product on the system and investigate the impact of changing the share of jet fuel at the output of the FT process.

1.4 Research gap

The reviewed literature showed that to model carbon neutrality, a model must take into account every emitter sector of society and the couplings between these sectors. Some sectors are often not considered by energy system optimization, and this is especially the case for the international transport and non-energy sector. These sectors are deeply coupled with carbon resources because fuels and chemicals contain carbon. Biomass is an important carbon resource but is also considered to produce heat and electricity and to store carbon geologically or biologically, leading to an important competition between all uses of biomass and carbon resources in general. Optimization often relies on carbon dioxide removal (CDR) technologies to balance emissions even though the availability of such technologies is not granted (Carton et al., 2020). Finally, the import of GHG-neutral fuel is often a way for the model to attain balance without the consideration of the import implications. Other non-thoroughly discussed aspects of aviation in the literature include the impact on the system of the non-CO₂ effect on climate neutrality and the share of jet fuel at the output of the FT process.

This paper utilizes a classic multi-energy sector optimization model to quantify the requirements for achieving climate neutrality, with a particular focus on aviation. The study novelty lies in exploring diverse pathways toward aviation climate neutrality, including the integration of e-bio-fuels. Additionally, the introduction of carbon flow modeling to the EnergyScope TD framework enhances the understanding of carbon utilization across sectors and enables the implicit assessment of the e-fuel climate impact. Notably, this study marks the first comprehensive analysis, to the best of our knowledge, of the system-level impact of the share of jet fuel produced through the FT process. By incorporating these advancements, our research aims to provide valuable insights into the challenges of climate neutrality at the scale of the energy system and associated with the transition to a fossil-free aviation.

2 Materials and methods

2.1 Model

2.1.1 Modeling framework

The model used is based on EnergyScope TD, which was developed consecutively by Moret (2017), Limpens et al. (2019), and Rixhon et al. (2022). EnergyScope TD is a linear

programming tool that optimizes both investment (i.e., installed capacity) and operation at the same time. This tool allows an hourly resolution and solving in 1 min on a personal computer using the typical days (TD) method. The main objective of the model is to minimize the total cost of the system while constrained by a maximum of GHG emissions and the end use demand (EUD), which corresponds to the energy needs of a country. To do so, the model can install energy production and transformation technologies (TECH), which consume and transform resources (RES). GHGs and CO₂ molecules can be in different states: captured, in the atmosphere, or emitted. These possible states are called GHG categories (GHG_{CAT}). The different energy vectors, possible states of GHGs, and EUD are called layers ($L = RES \cup EUD \cup GHG_{CAT}$). The solving is made for every hour of a year, and these hours are called periods (PERIODS). Every period is associated with one of the 12 TDs, and TDs are computed from the time series of demand and production. EUD, TECH, RES, L, and PERIODS are mathematically equivalent to set.

2.1.2 Economic modeling

The objective function of the model is to minimize the total cost of the system (Eq. 1), with τ being the actualization factor, lifetime (j) being the lifetime of the technology j , and i_{rate} being the interest rate. The total cost is composed of annualized CAPEX (Eq. 2), the annualized cost of equipment maintenance (Eq. 3), and the cost of importing resources (Eq. 4). $F(j)$ is the installed capacity of technology j (usually expressed in GW), and $c_{inv}(j)$ and $c_{maint}(j)$ and $c_{imp}(i)$ are the cost of investment (MEUR/GW) and maintenance (MEUR/GW/year) of technology j and the cost of importing the resource i (MEUR/GWh), respectively. Economic values in this study are given in EUR₂₀₁₉.

$$\min C_{tot} = \min \sum_{j \in \text{TECH}} (\tau(j) C_{inv}(j) + C_{maint}(j)) + \sum_{i \in \text{RES}} C_{imp}(i), \quad (1)$$

$$\text{with } \tau(j) = \frac{i_{rate}(i_{rate} + 1)^{\text{lifetime}(j)}}{(i_{rate} + 1)^{\text{lifetime}(j)} - 1} \quad \forall j \in \text{TECH},$$

$$C_{inv}(j) = c_{inv}(j) F(j) \quad \forall j \in \text{TECH}, \quad (2)$$

$$C_{maint}(j) = c_{maint}(j) F(j) \quad \forall j \in \text{TECH}, \quad (3)$$

$$C_{imp}(i) = \sum_{t \in \text{PERIODS}} c_{imp}(i) F_t(i, t) \quad \forall i \in \text{RES}. \quad (4)$$

2.1.3 End use demand and energy modeling

Each EUD can correspond to the industry, the transport, the households, or the service sectors. The EUD for households and services is separated into electricity and heat, where electricity is separated into a base load and a variable curve to take into account the demand variation over time. Heating is separated into space heating and hot water requirements, where space heating also varies over time. Heating requirements can be met using district heating or decentralized heating. The variations in electricity and heating are generated by the TD algorithm based on electricity and heating time series. The industry uses electricity, low-temperature heat, and high-temperature heat as a base load. All the previous EUD

requirements are expressed as energy requirements in GWh. For passenger transport, which encompasses the public (train, bus, and trolley), private mobility (cars), and aviation, the EUD requirements are expressed in millions of passenger kilometers (M.pax.km), and $f(i, l)$ is converted into energy requirement for each technology. For the haulage sector with trucks, trains, and maritime transport, EUD is expressed in millions of tons kilometers (M.t.km). The non-energy EUD is divided into high-value chemicals (HVCs), methanol, and ammonia, and the requirement is expressed in GWh.

Equation 5 represents the constraint that at any given moment, demand must be balanced by supply. With $f(i, l)$ being the coefficient of the layer l used (if negative) or produced (if positive) by the technology or resource i , for example, the battery electric vehicle (BEV) technology uses 0.173 GWh of electricity to move people on 1 M.pax.km, so $f(\text{CAR_BEV}, \text{ELECTRICITY}) = -0.173$ (expressed in GWh because the layer *ELECTRICITY* is in GWh) and $f(\text{CAR_BEV}, \text{MOB_PRIVATE}) = 1$ (expressed in M.pax.km, the unit of the layer *MOB_PRIVATE*). $\text{Sto}_{\text{in}}(j, l, t)$ and $\text{Sto}_{\text{out}}(j, l, t)$ are the quantity of the layer l that go in and out of the storage technology j , respectively, at the period t . $\text{EndUses}(l, t)$ is the quantity of the layer l that must be matched at periods t .

$$\sum_{i \in \text{RES} \cup \text{TECH} \setminus \text{STO}} f(i, l) \mathbf{F}_t(i, t) + \sum_{j \in \text{STO}} (\text{Sto}_{\text{out}}(j, l, t) - \text{Sto}_{\text{in}}(j, l, t)) - \text{EndUses}(l, t) = 0, \quad \forall l \in L \setminus \text{GHG}_{\text{CAT}}, \quad \forall t \in \text{PERIODS}. \quad (5)$$

Further details on the modelization of storage and system operation are given in the study by [Limpens et al. \(2019\)](#).

2.1.4 Carbon flow modeling

The addition of carbon flow modeling in EnergyScope TD is inspired by a previous addition of carbon flows in the monthly version of EnergyScope, given in the study by [Li et al. \(2020\)](#). It is based on the addition to the precedent version of EnergyScope TD of layers and technologies that aim to model carbon and GHG flows in the system. These layers are referred to as $\text{GHG}_{\text{CAT}} = \{\text{CO}_2 \text{ DEC}, \text{CO}_2 \text{ CEN}, \text{CO}_2 \text{ ATM}, \text{OTHER GHG}, \text{CO}_2 \text{ CAPT}\}$. Usually $f(i, l)$ is expressed in GWh but $\forall i \in \text{TECH}$ if $l \in \text{GHG}_{\text{CAT}}$ $f(i, l)$ is expressed in $\text{ktCO}_{2,\text{eq}}$.

One of the main constraints of the system is the maximum emission of GHGs (GHG_{max}) that can be released by the system (Eq. 6); $C_{\text{Atmosphere}}$ is the net quantity of GHGs emitted in the atmosphere by the system (Eq. 7). This quantity is the sum over time of the net quantity of CO_2 emitted by decentralized and centralized technologies and non- CO_2 GHGs emitted minus the CO_2 removal from the atmosphere, C_{CDR} (CDR).

$$C_{\text{Atmosphere}} \leq \text{GHG}_{\text{max}}, \quad (6)$$

$$C_{\text{Atmosphere}} = \sum_{t \in \text{PERIODS}} (C_{\text{Decentralised}}(t) + C_{\text{Net,Centralised}}(t) + C_{\text{GHG}}(t) + C_{\text{CDR}}(t)). \quad (7)$$

Indeed, some technology emits CO_2 molecules on combustion when consuming carbonaceous vectors for energy purposes. The quantity of CO_2 emitted by a technology then depends on the quantity of the carbonaceous vector consumed by this technology and is given in Eq. 8. The emission factor (expressed in ktCO_2/GWh)

for each vector is computed from the quantity of carbon in one mole of the vector n_{C} , the energy content E_{LHV} , and the molecular mass M of the vector and CO_2 . This equation is implicitly computed in the data.

$$f(i, m) = \sum_{l \in \text{RES}} f(i, l) \text{Em}_{\text{CO}_2}(l) \quad \forall i \in \text{TECH}, \quad \forall m \in \{\text{CO}_2 \text{ CEN}, \text{CO}_2 \text{ DEC}\}, \quad (8)$$

with $\text{Em}_{\text{CO}_2}(l) = \frac{n_{\text{C}}(l) M(\text{CO}_2)}{E_{\text{LHV}} M(l)} \quad \forall l \in \text{RES}.$

The combustion of the molecule can be either centralized, i.e., a consequent quantity of carbon is emitted in a single point that does not move (for example, in a coal power plant or a cement production plant), or it can be decentralized, i.e., the production of CO_2 is too low or moves (for example, a plane or a wood boiler in a house). This is the distinction between decentralized technologies (TECH_{DEC}) and centralized technologies (TECH_{CEN}); the main final difference is that the carbon at the output of a centralized technology can be captured. Emissions of centralized and decentralized technologies are expressed in Eqs 9, 10, respectively. The carbon capture technology considered in this model is based on methyldiethanolamine (MDEA) chemical looping, yielding a post-combustion carbon capture efficiency of 90% ([Cormos et al., 2020](#)).

$$C_{\text{Net,Centralised}}(t) = \sum_{i \in \text{TECH}_{\text{CEN}}} f(i, \text{CO}_2 \text{ CEN}) \mathbf{F}_t(i, t) - f(i, \text{CO}_2 \text{ CEN}) \mathbf{F}_t(\text{Carbon Capture}, t) \quad \forall t \in \text{PERIODS}, \quad (9)$$

$$C_{\text{Decentralised}}(t) = \sum_{i \in \text{TECH}_{\text{DEC}}} f(i, \text{CO}_2 \text{ DEC}) \mathbf{F}_t(i, t) \quad \forall t \in \text{PERIODS}. \quad (10)$$

The biogeochemical carbon cycle is a very complex system that is influenced by plenty of parameters, but it can be simplified as a net carbon removal because of the sequestration of CO_2 by ecosystems such as oceans, swamps, forests, or meadows. There is also a net flow of CO_2 from the atmosphere to the biomass through photosynthesis. Humans aim to remove CO_2 from the atmosphere by using DAC; all the processes that remove CO_2 are defined as CDR technologies (TECH_{CDR}). The removal of carbon from the atmosphere is defined in Eq. 11 ($f(i, l)$ is negative for CDR technologies, explaining the positive sign of Eq. 7).

$$C_{\text{CDR}}(t) = \sum_{i \in \text{TECH}_{\text{CDR}}} f(i, \text{CO}_2 \text{ ATM}) \mathbf{F}_t(i, t) \quad \forall t \in \text{PERIODS}. \quad (11)$$

Every technology on installation emits GHGs because of the materials required to produce it; the emission from these technologies is taken into account for electricity and heat production technologies, assuming that emission to produce cars, for example, is already taken into account by the industry sector. In addition, some sectors emit non- CO_2 GHGs, it is, for example, the case for the agricultural sector, which is a net emitter of methane from cattle farming and N_2O from fertilizer use, or aviation with contrail cirrus and NO_x emissions but also GHGs from biomass harvest. Emissions of GHGs other than CO_2 are expressed in Eq. 12 (because fossil fuel on production releases CH_4 , resources are taken into account

to model this flow). Concerning aviation, the global warming potential of aviation is converted into a GHG equivalent (because contrail cirrus affects climate with a mechanism other than the greenhouse effect).

$$C_{\text{GHG}}(t) = \sum_{i \in \text{TECHURES}} f(i, \text{OTHER GHG}) F_t(i, t) \quad \forall t \in \text{PERIODS}. \quad (12)$$

The captured CO₂ can be used in a process or definitely sequestered; the CO₂ comes either from DAC or from carbon capture from centralized emission. The quantity of carbon captured and used or sequestered must be at any time balanced as expressed in Eq. 13.

$$\sum_{i \in \text{TECH}} f(i, \text{CO}_2 \text{ CAPT}) F_t(i, t) = 0 \quad \forall t \in \text{PERIODS}. \quad (13)$$

The non-energy demand sector uses carbonaceous vectors as material for the production of chemicals, and it is assumed that the carbon in these vectors is sequestered. The final use of the molecule can be a definite use, in which case the carbon is definitely stored, or a use that results in the molecule being in waste. The waste treatment is such that if the molecule is recycled, then carbon is not emitted; if it ends in a landfill, carbon is stored (not taking into account other environmental impacts of the landfill); and if it is burned to produce energy, then the CO₂ emission of waste is already taken into account by the waste resource.

2.1.5 Data and assumptions

Many assumptions are made when hypothesizing the future of an energy system, especially on a long-term basis. Most of the data on technology cost and yields can be found online on the EnergyScope documentation website. Details on the source of data for French-specific EUDs are given in [Supplementary Table S1](#). Specific technology additions to the EnergyScope TD model for this study are given in [Supplementary Material Section 1.2](#). In this model, the possibility of using energy crops as a biomass source is not considered because of the concurrence between energy and food production and the non-negligible impact of the process on GHG emissions. The system is built from Greenfield with the assumption of no previously made investment. The Greenfield assumption is not very impactful in this study because the focus is on the sustainable fuel production system, which is a system with no previously existing infrastructure. The system studied in this paper is the global energy system of metropolitan France with the constraint of climate neutrality, i.e., net-zero emission of GHGs. The following major assumptions are made for every result in the paper.

- The interest rate is set at 5.0% (conservative derived from [OECD \(2024\)](#)).
- The time series of the electricity, heating, and renewable energy production factors are taken from 2019.
- The EUDs are taken from 2019.
- The costs and yields of technology are taken from 2019.
- A maximum capacity of 60 GW of nuclear power, 210 GW of photovoltaic (PV), 75 GW of onshore wind, 60 GW of offshore wind, 22 GW of river hydroelectricity, and 5.5 GW of pump hydro storage (PHS) are

assumed (values taken to be consistent with [RTE - Réseau de Transport d'Electricité \(2022\)](#)).

- It is expected that 85,000 GWh of waste will be available as an energy source in France every year by 2050. In addition, 400 TWh/year of biomass can be expected to be produced in France in 2050, of which 34% is wet biomass, and the remaining is lignocellulosic biomass ([Ministère de la transition écologique et solidaire, 2020](#)).
- The maximum share of heat delivered by district heating networks (DHNs) is set at 15% of the total heat needed for services and households ([Leurent, 2019](#)).
- The maximum share of transport delivered by public transport is set at 25% of the total transport needed for passengers and 25% for freight ([Bigo, 2020](#)).
- The non-CO₂ effect of aviation is set to contribute 0.7 times the effect of CO₂ to global warming potential (GWP) over 100 years (GWP₁₀₀), mainly because of NO_x and the impact of contrail effects on climate ([Lee et al., 2021](#)). This value is subject to high uncertainty and may change in the future because of changes in plane efficiency, fuel composition, air traffic management, etc.
- GHGs from agriculture and natural carbon sequestration values are taken from SNBC [Ministère de la transition écologique et solidaire \(2020\)](#). GHG emissions from biomass harvest are taken from the [European Parliament \(2018\)](#) database (forest wood residues).
- Non-energy demand is divided into methanol, ammonia, HVCs, and refinery products, and the proportional energy content of these vectors is 5%, 25%, 41%, and 28%, respectively. In this study, refinery products are not taken into account because they are mainly a stock of carbon ([Daioglou et al., 2014](#)).
- Maximum yearly geological sequestration of CO₂ is set at 24 MtCO₂/year ([ADEME, 2020](#)).

The following assumptions are only made for the base case. The composition of the blend coming out of the FT refinery can be adjusted to boost the production of one of the three vectors, namely, gasoline, diesel, and jet fuel, but this production reaches a maximum ratio because of chemical constraints. The maximum share of fuel that can be reached at the output is 37% for gasoline, 63% for diesel, and 50% for jet fuel. It is assumed that it is possible to import 30% of jet fuel demand; this fuel is fossil and, so, is associated with non-CO₂ emissions (see [Supplementary Material Section 1.3](#)). It is hypothesized that other energy vectors cannot be imported. This hypothesis is coherent with the French national strategy, which set, as an objective, the “energy independence” of France. The base case corresponds to the scenario RF-EU, described in the following section.

2.2 Scenarization

According to the law named ReFuelEU passed by the [European Parliament \(2023\)](#), European aviation should be powered at a minimum of 70% by SAF in 2050, of which a minimum of 35% of the total demand is by e-SAF. This legislation places an

important constraint on the system and massive requirements for the production of SAF. It is then important to not only quantify the differences between different policy configurations but also the impact of adding aviation on a climate-neutral system and the requirement behind the production of SAF. Different scenarios are defined to study how requirements on jet fuel production influence relevant parameters. The scenarios are described as follows.

1. 0-AV: No demand for aviation.
2. 100-FO: Possible import of fossil jet fuel at 100% of demand.
3. 100-OP: 100% of demand from optimal processes according to the system.
4. 70-OP: 30% of demand from fossil fuel and 70% of demand from optimal processes.
5. 70-BI: 30% of demand from fossil fuel and 70% of demand from biofuel processes.
6. 70-EF: 30% of demand from fossil fuel and 70% of demand from e-fuel processes.
7. RF-EU: 30% of demand from fossil fuel and a minimum of 35% of demand from e-fuel processes.

2.3 Variation in the cost of import

Previously, in the RF-EU scenario, there was an assumption that 30% of the demand for jet fuel was met by the import of energy. When there is no import, the system produces each vector with a price implicitly calculated, and this price is the sum of the cost of every technology used to produce this vector divided by the quantity produced. When the import is available, the only parameters the modeler controls are the quantity of import available and the cost at which the system will import a vector. So, if the system can import a vector at a cost inferior to the system production cost, it will be optimal for the system to import this vector. Then, by running the model within a range of costs of import for the same vector, it is possible to compute the production cost of this vector. The production cost is the integral of the quantity imported over the variation in the cost of import.

To be produced sustainably, the carbon used in a fuel must come from a renewable source. If 100% of the carbon contained in fuel comes from a renewable source, then the carbon offsets its CO₂ impact on the climate. However, it does not offset the total impact on the climate, which is 1.7 times higher than the only CO₂ effect. Then, to analyze the cost of climate-neutral aviation, it is necessary to take into account these non-CO₂ effects.

To study this, the import of jet fuel is set to be possible at 100% of demand. EnergyScope TD is run for different costs of import of jet fuel varying between 50 EUR/MWh and 350 EUR/MWh, with a step of 5 EUR/MWh. This is done for different values of reduction in the emission of jet fuel relative to the CO₂ emission of jet fuel. The reduction in emission associated with the import of jet fuel ranged between +10% (jet fuel coming from fossil sources with methane-associated emissions) and -170% (complete offset of the impact of aviation), with -100% being an offset of CO₂ emissions of aviation solely due to the combustion of jet fuel. This yields a total of 610 configurations, and the results for these configurations are given in Section 3.3. An analysis is done of the evolution of the

import quantity of jet fuel with the cost of the vector to compute the production cost of jet fuel.

2.4 Share of jet fuel produced from Fischer–Tropsch technology

The FT technology produces a blend of molecules with different lengths of carbonaceous chains. The most common way to forecast the composition of the fuel produced by the FT process is based on the Anderson–Schulz–Flory distribution. This distribution yields a maximum ratio of production of jet fuel of 42%. However, this can be changed by using different catalysts, adjusting the process to recycle longer carbon chains, and reforming shorter ones. This is what was considered in this study, giving a maximum ratio of 50%. In Section 3.4, the effect on the system of the share of jet fuel at the output of the FT process is investigated.

3 Results

3.1 Climate neutrality of the French energy system

3.1.1 Energy and carbon flows in the system

The results given in this section refer to the base case described in Section 2.1.5. In Figure 2, the annual energy and carbon flows of the energy systems are represented with Sankey diagrams. In these diagrams, the width of the arrows is proportional to the energy and carbon flows. Energy content is quantified in TWh, and the content of carbon is quantified in MtCO_{2,eq} (the equivalent is relevant only concerning GHGs other than CO₂). In the energy Sankey diagram, the sum of flows out of a node is smaller than the sum of flows entering a node; this is because at each step of a process, energy is lost (except for heat pumps because of the coefficient of performance greater than 1). In the carbon Sankey diagram, every flow out of a node (except for technologies producing GHGs) is the same as the entry because flows are a quantification of a physical molecule. There are no energy flows of uranium in the energy diagram to simplify the representation. The total cost of the optimal system is 236,956 MEUR/year, and the distribution of this cost is given in Supplementary Figure S5. A yearly cost of the system has to be put in regard to the gross domestic product (GDP), and the GDP of France in 2019 was 2,425,000 MEUR, so the energy system cost in this scenario is 9.7% of the GDP. This is increased related to the usual characterizations of the energy sector weight in GDP because it also considers the cost of investment for cars, trucks, factories, etc.

The results show that the main energy carrier is electricity produced from diverse low-carbon sources of energy, reaching a total production of 1,081 TWh. Nuclear, PV, hydroelectricity, and onshore wind reach their maximum capacity potential. An important part of electricity is stored during the peak of production of PV panels and is used during the night. This energy is stored mainly using the electric private car battery (127 TWh), specifically using the vehicle-to-grid (V2G) technology and for 1 TWh part using Pumped-Hydro storage (PHS). In addition, 25 TWh of gas is used in a combined cycle gas turbine (CCGT) for the production of

15 TWh of electricity during cold winter days with low production from PV and wind (see [Section 3.1.2](#)). A consequent part of electricity is used to produce 240 TWh of hydrogen, the third most important energy carrier. This production is made at 83% using alkaline electrolysis and 17% by high-temperature (HT) electrolysis. The hydrogen is a way to store energy (see [Supplementary Figure S4](#)) and is used to produce ammonia, which is a non-energy EUD. Hydrogen is also used in e-bio-fuel and e-fuel processes producing FT and methanol. Methanol is a non-energy EUD and used also as a precursor for the production of HVCs, and methanol is produced with carbon coming only from biomass. Gas is produced with wet biomass using bio-hydrolysis. Gas use is separated into maritime shipping, electricity production, and buses.

Half of the FT fuel is produced using hydrogen and biomass, and the other half is produced using CO₂ and hydrogen; FT fuel is then converted into jet fuel, gasoline, and diesel. The results show that it is optimal to produce a maximum of jet fuel from the FT fuel. [Figure 2](#) shows that the optimal choice is to produce the maximum amount of jet fuel possible. The diesel produced is used for long-range mobility (trucks and buses), and the gasoline is used to produce HVCs.

The results also show that in the base case, decentralized heat is produced in totality using heat pumps. DHNs are powered with heat pumps and, for a part, through integration with the hydrogen and fuel industrial sectors and by a cogeneration process (approximately 19%); part of the DHN heat is stored during summer to be used in winter. High-temperature heat for the industry is provided by industrial wood boilers (52%), waste boilers (33%), and direct electric industrial heating (15%). This production of high-temperature heat consumes all the available waste.

Concerning mobility, the maximum share of public transport is reached (for passenger transport and freight). Private mobility is filled only by BEVs and public transport from a share of trains, trolleys, and hydrogen buses. Road haulage uses a majority of hydrogen trucks (75%) with a share of diesel trucks (25%). Maritime shipping is powered only by gas. Carbon capture from a point source consumes 48 TWh of heat.

The carbon Sankey diagram shows that under climate neutrality, there remains 205 MtCO_{2,eq} of gross emissions coming mainly from other GHGs (74 MtCO_{2,eq}), decentralized emissions (77 MtCO_{2,eq}), the construction of technologies (15 MtCO_{2,eq}, distribution of these emissions are given in [Supplementary Figure S5](#)), and finally, not captured centralized emissions (35 MtCO_{2,eq} and 4.5 MtCO_{2,eq} due to the loss of carbon capture). These emissions are offset by CDR, with natural sequestration removing 55 MtCO_{2,eq} and biomass growth removing 151 MtCO_{2,eq}.

Other GHGs are made up of emissions from planes (23%), agriculture (65%), and biomass harvest (12%). A majority of centralized emissions (56%) are captured. The captured carbon is used in part to produce FT fuel and in part is sequestered, reaching the maximum availability of sequestration. Furthermore, 67% (53.5 MtCO₂) of centralized emissions have a biogenic origin. A significant part of biomass is not used and is used as a carbon sink definitely (59 TWh, which is equivalent to 22 MtCO_{2,eq}). The production of biogas from wet biomass is the main contributor to decentralized CO₂ emissions (45%) before aviation (31%) and buses (13%). HVCs are produced using biomass (for a part with methanol [50%] and naphtha [21%] as intermediaries); hence, HVCs sequester 15.2 MtCO_{2,eq} and methanol 2 MtCO_{2,eq}.

3.1.2 Electricity production and consumption balance

[Figure 3](#) shows the hourly evolution of the production and consumption of electricity during each of the 12 typical days. The differences between the 12 typical days are due to different meteorological conditions associated with each typical day. Some days can be characterized as summer days (TDs 6, 7, 8, and 9) because during these days, there is a low demand for heat and high production by PV panels. TDs 4, 5, 10, and 11 can be classified as mid-season (medium heat demand, medium PV, and wind production), and TDs 1, 2, 3, and 12 can be classified as winter days (high heat demand, low PV production, and variable wind production). There is a consequent load variation due to the PV production peak at the intra-day time scale. BEVs are loaded during the peak of PV production, and additionally, BEVs provide a way to store energy. An important power generation is dedicated to hydrogen production during the typical days corresponding to summer days, and this stored hydrogen is used during winter. This hydrogen production also varies within the day because of the hourly variation in PV production. The overall load factor of electrolyzers is 47.7%. Gas is used in the CCGT to produce electricity during winter days, especially days with low production by intermittent renewables. A more detailed explanation about energy storage and the use of non-electricity energy carriers during different TDs is given in [Supplementary Figures S1–S3](#).

3.2 Analysis of different strategies for the production of jet fuel

The assumptions behind the different strategies are described in [Section 2.2](#). The results for these strategies are summarized in [Table 1](#). The additional demand for aviation is associated with an important increase in the cost of the system, electricity production, and biomass sequestration. The increase in production due to a decrease in the import of fossil jet fuel leads to the same pattern. SAF in the 70-OP scenario is produced at 100.0% by PbtL processes. In the 100-OP scenario, 100.0% of SAF is produced via PbtL processes. In the RF-EU scenario, as expected, half of the SAF is produced via power-to-liquid (PtL) processes (as required) and the other half with PbtL processes. It is important to note that in the 70-BI scenario, 64 TWh of gas is permanently stored, which corresponds to a carbon content of 12.8 MtCO₂. This gas is stored to remove carbon out of the system to offset the low availability of biomass for biomass sequestration.

3.3 Import price of renewable and fossil fuel

[Figure 4](#) shows the evolution of several key parameters of the system upon the variation in jet fuel import price and emission reduction of this jet fuel. The import price and emission reduction associated with it have primarily an impact on the quantity of jet fuel imported. As expected, an increase in the cost of imported jet fuel leads to a decrease in the quantity imported. Under a certain cost, all the jet fuel used in the system is imported, and over a certain cost, no jet fuel is imported by the system. The values for these two

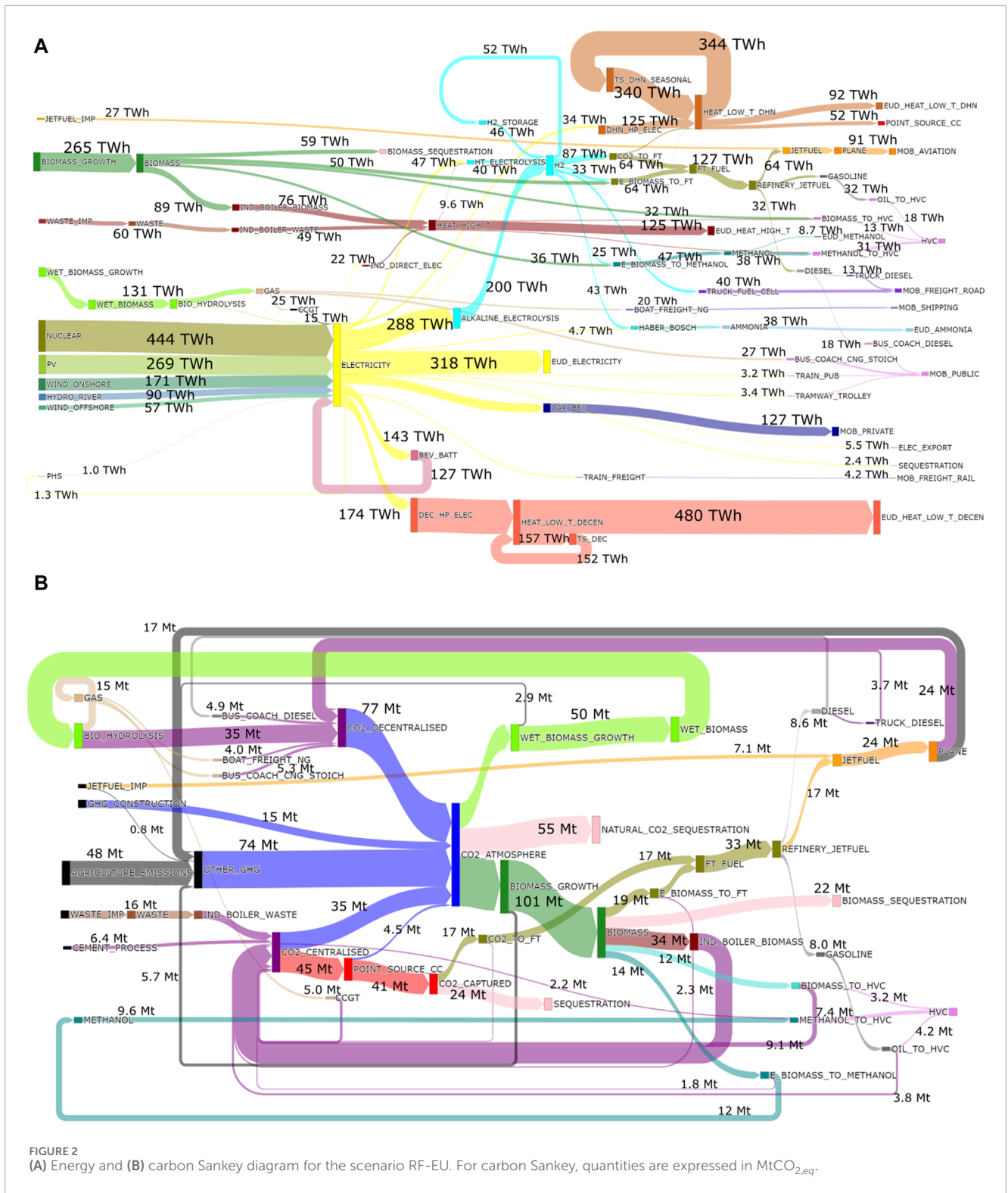


FIGURE 2 (A) Energy and (B) carbon Sankey diagram for the scenario RF-EU. For carbon Sankey, quantities are expressed in MtCO_{2,eq}.

costs depend on the emission reduction associated with the import of jet fuel. The higher the emission reduction, the higher the cost at which the system both stops to import jet fuel and stops to only import jet fuel. For example, for 90% emission reduction, the system only stops importing jet fuel at 200 EUR/MWh and stops importing jet fuel at 230 EUR/MWh. The quantity of jet fuel that is not

imported must be produced, which is why these quantities influence electricity and hydrogen production. However, it also influences the necessary sequestration of biomass. Biomass sequestration is also highly correlated with emission reduction because there is less need for sequestration when there are fewer emissions of non-CO₂ GHGs. Less biomass sequestration leaves more biomass to be used for

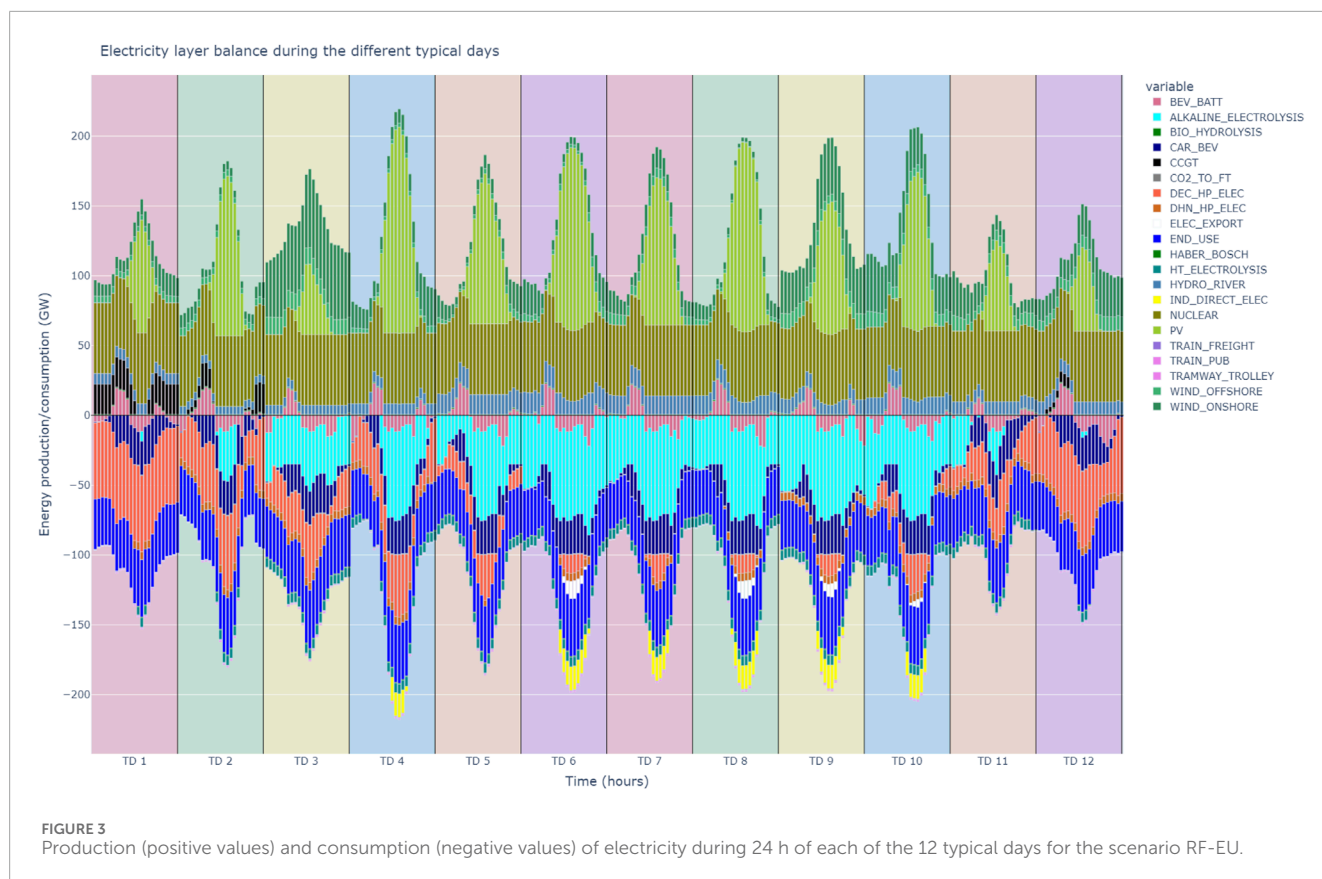


FIGURE 3 Production (positive values) and consumption (negative values) of electricity during 24 h of each of the 12 typical days for the scenario RF-EU.

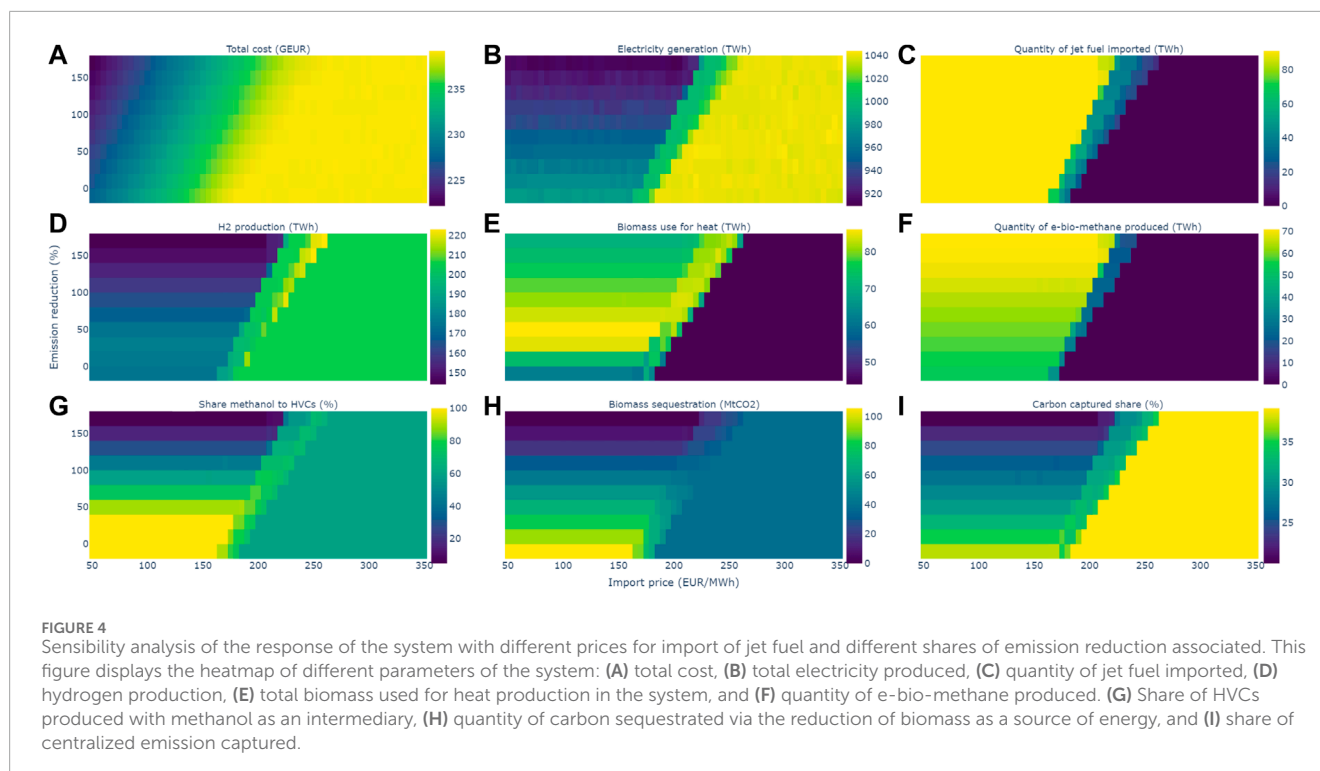
TABLE 1 Consumption of biomass, hydrogen, and CO₂ solely for the production of FT fuel in the different scenarios, and total economic and technical values of the system in different scenarios.

Parameter	0-AV	100-FO	70-BI	70-EF	70-OP	100-OP	RF-EU
Consumption of CO ₂ (Mt)	0	0	0	33.5	0.1	0.1	16.7
Consumption of hydrogen (TWh)	0	0	0	174.8	76.5	109.2	125.6
Consumption of biomass (TWh)	0	0	246.5	0	99.4	142.0	49.7
Total cost (GEUR)	217.7	232.2	252.2	238.3	236.8	239.0	237.5
Total electricity produced (TWh)	912.3	982.5	1073.0	1062.9	1035.1	1039.8	1052.2
Total biomass sequestered (MtCO ₂)	0	40.3	7.0	24.4	22.3	14.4	22.3
Total hydrogen produced (TWh)	143.8	174.8	193	250.0	213.0	205.1	240.1
Carbon capture share (%)	20.0	37.5	45.6	59.8	37.3	39.1	51.0

methane production, HVC production, or heat purposes, explaining the related results. The import of jet fuel also means a reduction in the carbon capture share of centralized carbon because less production of jet fuel means less e-fuel production. The production of jet fuel is associated with the co-production of gasoline and diesel; as explained before, gasoline is used for the production of HVCs and diesel by trucks.

The consequences of the quantity of jet fuel imported influence the total cost of the system. The curve of the quantity of jet fuel over the different prices for jet fuel import enables the calculation of a

unique average cost for the production of jet fuel by the system. This cost varies with the different emission reductions associated with the jet fuel import. For example, it is possible to compute the cost of producing a fuel with emissions of fossil fuel yielding a production cost of 177 EUR/MWh for a synthetic jet fuel with the same emissions as a fossil jet fuel. For a fuel that can be qualified as a SAF (90% reduction of CO₂ emissions), this gives a production cost of 212 EUR/MWh. Finally, a climate-neutral SAF (170% emission reduction of CO₂ emissions) is produced at a cost of 237 EUR/MWh.



3.4 Impact of Fischer–Tropsch selectivity on the system

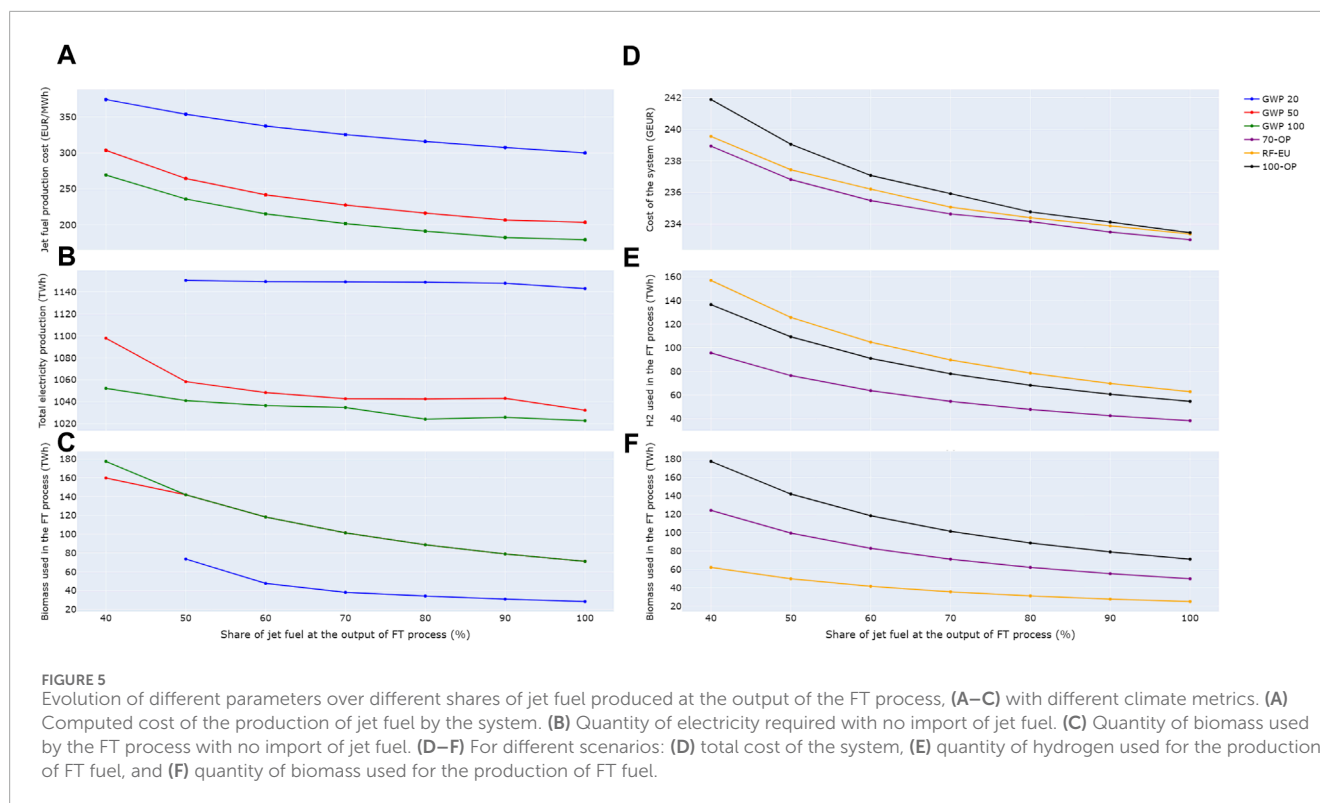
Figure 5 displays the result following the methodology described in Section 2.4. This figure shows the impact of the FT selectivity on different relevant parameters of the system for different scenarios and climate metrics (GWP over 20, 50, or 100 years). This climate metric has an impact on the non-CO₂ effect of aviation, which is 0.7 times the CO₂ effect for GWP₁₀₀, 1.3 times the CO₂ effect for GWP₅₀, and 3 times the CO₂ effect for GWP₂₀. The climate metric has an important impact on the cost of production of jet fuel, the total electricity required, and the quantity of biomass used to produce the FT fuel. The share of jet fuel in the output of the FT process has an impact on the cost of jet fuel production, the total cost of the system, and the quantity of biomass and hydrogen used for FT production. The model found no solution for GWP₂₀ with a share of jet fuel at the output of the FT process of 40%. When the metric taken is GWP₂₀, only 40% of FT production is made using the PtL process, explaining the lower requirement for biomass in this case.

4 Discussion

4.1 Climate neutrality and energy requirements

Section 3.1.1 shows that reaching climate neutrality for France is achievable even with no import of green energy and while considering every sector. However, this comes at a

very high financial and technical cost for the system. Reaching neutrality requires important investments in low-carbon electricity production, sustainable fuel production, and CDR. Concerning CDR, 22% of the available lignocellulosic biomass is used to sequester carbon definitely outside of the system. This deprives the system of a cheap and renewable resource. Such a method could be seen as the use of biomass as a construction material or as an increased natural carbon sequestration due to reduced pressure on forests by the reduction in the production of biomass energy. The system also uses all the geological sequestration potential available. The sequestration potential is then an important parameter of the model, and this emphasizes the need to take into account the technical characteristics of sequestration in models. It is primordial to enhance systemic research on the quantification of required quantities of CDR, and the optimal strategies to achieve this removal. The ReFuelEU scenario reaches climate neutrality, but this scenario relies on a profusion of non-fossil energy. The production of electricity to reach this neutrality (1,052 TWh) is significantly higher than expected by the reference documents from the French electricity transmission system operator Réseau de Transport d'Electricité (RTE) (2022) (645 TWh) and the French minister of sustainable development *Ministère de la transition écologique et solidaire* (2020) (580 TWh). This is partly due to the consideration of international transport and non-energy sector loss, which is not considered thoroughly in these documents. Another reason is the absence of modelization of energy efficiency in buildings. Finally, the hypothesis of no import of energy (other than “other refinery fuel” and jet fuel) is not probable, particularly for the electricity vector. However, this hypothesis is valid, especially considering that studies on the



feasibility and impacts of exporting massive quantities of green energy are scarce.

The important differences in energy production raise questions about the relevance of not taking into account the requirement for international transport and the non-energy demand of molecules in national strategies. Indeed, the differences due to the inclusion of these aspects are important. Then, the future energy mix will not be accurately forecasted without the consideration of international transport and non-energy demand. Hence, future national strategies should carefully consider the demand for these sectors.

Temporal electricity generation and consumption, within and among the TDs, is very high. The peak of electricity production reaches 219.6 GW on TD 4, which is more than double the all-time record for 102.1 GW in France on 8 February 2012. Such an increase in the mean and peak load will come at a high technical cost for the development of the grid and flexibility options. Indeed, the flexible operations of electrolyzers described in Section 3.1.2 would put the electrolyzers under important constraints and need to be demonstrated at the scale of the gigawatt. This flexible operation implies a maximum storage of 38 TWh of hydrogen. The use of car batteries as a way to store energy that can be re-injected on the grid called V2G is not yet considered at the scale of 10 GW. However, such an operation is important for the flexibility of the system and enables important economic optimization. Studies on the flexibility of the power system and its coupling with other vectors such as heat, hydrogen, and gas are necessary to understand the scale at which the hypotheses made in this study are valid.

4.2 Optimal use of resource in the system

The 70-OP scenario shows that it is not optimal to use biomass to produce decentralized heat. It also shows that to value biomass efficiently, it is important to understand the crucial role of the carbonaceous vector in the system. This explains that the most optimal pathway for the production of fuels is using the PBTl process. Indeed, this process has a better carbon and energy yield than the biomass-to-liquid (BtL) process and a better energy yield than PtL processes by avoiding carbon capture need and additional hydrogen production. As shown in the reviewed literature, taking into account the coupling of biomass and hydrogen in processes is not systematic. This work highlights that the consideration of the PBTl process is a crucial aspect of the energy transition.

The comparison between the different scenarios in Table 1 shows that important gains can be made from the consideration of every process for the production of jet fuel. That is, producing SAF from only the BtL process considerably increases the total cost of the system compared to the optimal case (+15.4 GEUR and +38 TWh of electricity production). The same goes for only considering PtL processes (+1.5 GEUR and +28 TWh of electricity production). Optimality relies only on e-bio-fuel in the French case, but e-fuel could play an important role in a country with less biomass available. Those two pathways come within the scope of the European law ReFuelEU. This law sets a minimum share of SAF coming from the PtL process without any justification of the figures used. Under the assumptions of the law, the system cost increases by 700 MEUR and power generation by 8.1 TWh from the optimal case. This highlights the need for further research on the optimal share of fuel from the three different processes to advise on the best

policy strategy. It is also important to value the carbon resources, which are centralized CO₂ emissions because the model shows that 51% of centralized emissions are captured in the ReFuelEU case. Among these 51% emissions, probably less will be commercially available because of technical characteristics (distance and output concentration in CO₂). In addition, 58% of captured emissions of CO₂ are sequestered, but this share is limited by the physical availability of the sequestration sites, which include abroad sites. So, in other countries with a higher availability of sequestration sites, sequestration might be limited by centralized CO₂ availability and not by geological sequestration potential.

Furthermore, the law set that after 2041, the CO₂ contained in e-fuel must originate from biogenic sources or should be directly captured in the atmosphere. However, centralized sources of biogenic CO₂ emissions are limited in a climate-neutral system, and direct air capture is more expensive than point-source carbon capture. In the RF-EU case, 57.3 Mt of CO₂ is from biogenic sources among the centralized emissions, which is far from the quantity of carbon used in e-fuel production of 11.7 Mt. However, this could be a problem if there is no shift from the use of biomass for decentralized heating to using for industrial heating. Then, if there is an additional requirement on the biogenic origin of the carbon sequestered, there could be a conflict between these different uses of carbon in the system, leading to sub-optimality. All these findings reinforce the idea that it is primordial to take into account the systemic aspect of the problem when considering such complex issues. More specifically concerning carbon flows, this underlies that the required biogenic origin of carbon is not a guarantee of a positive impact on the system.

4.3 Inclusion of aviation

The total impact on the climate of fossil aviation is 41 MtCO_{2,eq}, with emissions of CO₂ reaching 24 Mt and a non-CO₂ effect of 17 MtCO_{2,eq}. Section 3.2 shows that the integration of SAF production will lead to an important increase in energy production needs for the energy system. The import of fossil jet fuel (for 100 EUR/MWh) is always optimal for the system, and it is possible to reach climate neutrality even with 100% import of fossil jet fuel. This import of fossil fuel is optimal only because there is an option to sequester carbon at a relatively low cost using biomass. This option may not be available in reality due to the complexity of natural carbon cycles, and coupling biomass as a source of energy and a way to sequester carbon should be studied under biomass availability consideration.

Replacing fossil jet fuel with SAF at 70% induces a decrease of 15.9 MtCO_{2,eq} in CDR need, which is approximately 70% of the 24 MtCO₂ of emissions due to the combustion of jet fuel. SAF production comes at a high energy cost; indeed, producing SAF at 70% of the demand (70-OP) requires 110.7 TWh of hydrogen, 64.8 TWh of biomass, and 11.7 Mt of captured CO₂. This falls within the order of magnitude given by Académie des Technologies (2023) for France's SAF production (140 TWh of hydrogen and 36 TWh of biomass for 70% of France's demand but with 60% of jet fuel at the output of the FT process). The defossilization of aviation can be achieved only with significant investments in clean energy production, electrolyzer, and FT production plants. This

requires money, and the total cost increase due to the inclusion of aviation is 23.3 GEUR in the 70-OP scenario and 26.1 GEUR in the 100-OP scenario. Such a cost raises the question of whether and how aviation should be defossilized, as opposed to controlling its consumption.

4.4 Production cost and import

The results given in Section 3.3 show that the production cost of SAF varies with the emission reduction associated with this production. These results highlight that it is possible to reach climate neutrality even with the remaining fossil fuel in the system. However, this requires the use of an important part of available biomass to sequester carbon. The import of fossil fuel reduces the need for electricity production and carbon capture because there is less need for hydrogen production and the combination with captured CO₂ for e-fuel production. Comparing the cost of the system in the 0-AV scenario and the 100-OP provides an estimate of the total impact of the production of climate-neutral SAF on the cost of the system. When normalized with the quantity of energy required to match the aviation demand, this yields a cost of 234 EUR/MWh of climate-neutral SAF. Hence, there is an agreement with the way to compute the cost of jet fuel described in Section 3.3, which yields 237 EUR/MWh. Then, a consolidated order of magnitude for the cost of producing jet fuel for the system is 235 EUR/MWh or 2.22 EUR/L or else 0.111 EUR/(pax.km). The production cost of SAF is high when compared with the current cost of fossil fuel (mean price of 66 EUR/MWh over 2023). This difference allows for a calculation of the mitigation cost associated with the production of SAF. Total GHG emissions on combustion of 1 MWh of jet fuel are equivalent to 0.469 tCO_{2,eq}. Then, the mitigation cost associated with the production of climate-neutral jet fuel is 360 EUR/tCO_{2,eq}; this value can be compared with the US Environmental Protection Agency (2023) social cost of GHGs (280 EUR/tCO_{2,eq} in 2050). Such results underline that mitigation cannot always rely on purely economic incentives.

The increase in jet fuel cost will lead to an increase in the future cost of flying. Based on the share of jet fuel in the cost of flying an airplane (18.7% in the United States) from Argus Media, it is possible to compute the increase in the cost of a plane ticket due to the replacement of fossil fuel by SAF. This is based on the historical prices of fossil jet fuel from Argus Media and the calculated price of SAF. Then, for 100-OP, the increase in the total price of a plane ticket would be 60% with current technology. However, the future share of jet fuel in the cost of flying an airplane should decrease in the future with the improvement of airplane motor technology. So, with a 1% improvement in motor yield per year, the total cost increase in a plane ticket would only reach 48%. This increase would only reach 33% in the scenario RF-EU due to the inclusion of 30% of cheap fossil fuel in the supply. An increase in this magnitude could lead to a change in demand, but such effects are not assessed in this work. It should also be noted that this calculation is based on the market price of airline tickets for the United States, which includes factors other than airline costs (reduction or absence of taxes, tax exemptions, etc.). The results are therefore indicative and may change if the air transport market changes.

4.5 Integration of the Fischer–Tropsch process in the system

Section 3.4 highlights that the quantity of jet fuel at the output of the FT process is a key parameter of the system. The price of SAFs increases with the low conversion of FT to jet fuel. When the share of jet fuel at the output increases from 40% to 100%, the quantity of electricity required decreases by 30 TWh. Consequently, SAF production cost decreases by 33%, reaching a cost of 179 MEUR/MWh for GWP₁₀₀.

This is due to the inefficiency of the co-products of jet fuel in the FT process. Indeed, even though there is always the same quantity of energy in the output, the sole determinant of the quantity of fuel produced is the aviation sector. Hence, the quantity of gasoline and diesel produced depends on the selectivity of the FT process. The results highlight that the value of gasoline and diesel by the system is only due to the “necessary” production of jet fuel. The sub-optimality of co-products impacts jet fuel production cost. That is, the use of diesel is less efficient than hydrogen for trucks, and the production of HVCs from gasoline is less efficient than the production from methanol. Hence, this additional charge due to the sub-optimality is transferred to the cost of jet fuel, increasing jet fuel cost with decreasing jet fuel share in the output.

Then, it should be advised to seek the maximum conversion of FT into jet fuel. This can be done by favoring process configurations that maximize the output of jet fuel by using good catalysts and recycling longer carbon chains in the process. Clarification on the maximal conversion of FT to jet fuel that can be attained physically could be beneficial. This conversion depends on the physical requirement behind the blend of molecules identified as jet fuel. Indeed, there is no consensus in the literature on the maximal conversion rate that can be achieved, and Lin et al. (2022) gave 42% with basic theory and 72% with the right catalyst. An internal source gave 50%, Eilers et al. (1990) gave 60%, and Klerk (2011) gave 63%. So, the value taken in this study (50%) falls in the lower range of the values given by the literature.

Future energy system studies should take into account this aspect of the FT process, especially when focusing on aviation. As highlighted, the literature review studies found in the literature (Dray et al., 2022; Bergero et al., 2023; Sacchi et al., 2023) use 100%, 100%, and 18%, respectively, as the efficiency conversion of FT fuel into jet fuel. These values are not within the range found in the process literature; hence, the implications of such hypotheses should be discussed.

4.6 Limitations

There are several limitations to this study.

- The numbers used in the model are subject to uncertainty; as a consequence, the numbers produced are also subject to uncertainty. The propagation of uncertainty has not been studied here but will be part of future work.
- Other environmental impacts such as biodiversity, land allocations, water use, and dependency of biomass on the quantity of resources are not considered (Daiglou et al., 2017).

- The cost impact and sensitivity of transporting resources such as biomass, hydrogen, or CO₂ to the final location of use are not included in the analysis.
- The technology called biomass sequestration does not reflect the issues behind definitely sequestering CO₂ using biomass.

These limitations are perspectives for the improvement of the model used in this study.

5 Conclusion

This paper describes the integration of carbon flow quantification into the EnergyScope TD energy system model. A quantification of the energy required to achieve climate neutrality in France is given. It shows that a significant amount of electricity (1,081 TWh/year) is required to achieve climate neutrality. The quantity of primary energy needed is higher than that in the reference documents on France’s energy transition. This is because the present study takes into account the bunkers of international sea and air transport and the demand for non-energetically used molecules. The results show that neutrality can be achieved, without assessing the feasibility of the evolution of the production system and infrastructure.

The optimal use of carbon resources should be a greater concern in the energy systems community than it currently is because of the massive changes that will result from the absence of fossil fuels. The combination of biomass and hydrogen is rarely considered in other studies, although the findings of this study show that this is a fundamental pillar of the energy transition and particularly one the most optimal processes for jet fuel and methanol production.

The impact of aviation on this carbon-neutral energy system is then analyzed in more detail. In particular, the different resources required in different policy scenarios are quantified. The cost of producing SAF in the system is calculated, as well as the impact on the system of the proportion of jet fuel as a product of the FT process. Eliminating all fossil fuels from aviation increases the cost of the system by 6,800 MEUR per year and electricity production by 57 TWh, compared to a fossil case. This shows that the defossilization of aviation will have a high technological and financial cost impact on society due to the need for sustainable carbon-based energy carriers. This work highlights that the proportion of SAF produced by the FT process is a key parameter in the system, even if it is not often considered in studies. Total neutrality of the aviation sector can be achieved through technological change at the expense of a major transformation of the infrastructure, but other options such as reducing the demand for aviation should also be considered.

Building on the work carried out and especially on the carbon flow quantification, it would be interesting to improve the modelization of biomass resources; such an improvement could lead to a study on the optimal use of biomass in the system. Indeed, as already shown in several studies, there is a relationship between the optimal pathway for the production of fuel and parameters, such as biomass potential, biomass use, and carbon sequestration availability. Similarly, the results could be improved by including a study of the impact of land-use changes on the CO₂ balance in relationship with the quantity of biomass used in the system.

Moreover, future work will focus on the European energy system as a whole, taking into account the differences in resources, demand, and geography between European countries. It will be particularly interesting to see how these differences affect the best strategy for fuel production and whether fuel trade between countries will be favored over local production.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation. Part of the data used is available on <https://energyscope.readthedocs.io/en/master/> the model used is available on <https://github.com/energyscope/EnergyScope/tree/EnergyScopeFR>.

Author contributions

LM: conceptualization, data curation, formal analysis, investigation, methodology, validation, visualization, writing—original draft, and writing—review and editing. GB: conceptualization, funding acquisition, investigation, methodology, supervision, and writing—review and editing. FM: conceptualization, funding acquisition, investigation, methodology, writing—review and editing, and supervision.

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Conflict of interest

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fenrg.2024.1359641/full#supplementary-material>

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