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Abstract

The main objective of this study is to develop a methodology adapted to the prospective environmental evaluation of actions in the energy sector. It describes how a bottom-up long-term energy model can be used in a life cycle assessment (LCA) framework. The proposed methodology is applied in a case study about the global warming impacts occurring as a consequence of the future production of synthetic diesel from biomass ("biomass to liquids" – BTL), a second-generation biofuel, in France.

The results show a high sensitivity of the system-wide GHG balance to (i) the policy context and to (ii) the economic environment. Both influence the substitutions occurring within the system due to the production of BTL. Under the specific conditions of this study, the consequences of introducing BTL are not clear-cut. Therefore, we focus on the lessons from the detailed analysis of the results more than in the precise-looking projections, illustrating how this type of models can be used for strategic planning (industry and policy makers). TIMES-type models allow a detailed description of the numerous technologies affected by BTL production and how these vary under different policy scenarios.

Moreover, some recommendations are presented, which should contribute for a proper systematization of consequential and prospective LCA methodologies. We provide argumentation on how to define a functional unit and system boundaries that are better linked with the goal of the study. Other crucial methodological issues are also discussed: how to treat temporal aspects in such environmental evaluation and how to increase the consistency of life cycle assessments.

Keywords: Consequential LCA; Energy prospective; Life Cycle Assessment; Second generation biofuel; TIMES model; System boundaries

1. Introduction

1.1. Context

The transport sector relies almost exclusively on oil and is responsible for about 22% of energy-related greenhouse gas (GHG) emissions in the world [1]. In a context of rising oil prices, concerns about global warming and energy security, alternative transportation fuels are being developed and biofuels are viewed as one of these alternatives. Biofuels produced from lignocellulosic materials should be introduced in a near future as a complement for conventional biofuels (first generation biofuels produced in commercial scale nowadays, usually from food crops). These second-generation biofuels are currently in research and development, pilot or demonstration phase and they *are expected* to be more efficient in terms of land use, GHG reductions and other environmental aspects [2].

The environmental evaluation of these products requires a life-cycle perspective in order to include all of the activities involved in producing, distributing, and using the biofuel [3]. Life cycle assessment (LCA) is seen today as the appropriate tool for this type of study and it has been largely applied on environmental impact studies about second-generation biofuels [4-9]. Most of the existing studies use the Attributional LCA (A-LCA) approach capturing environmental impacts associated to the steps physically linked in the products' life-cycle chain. However, there are raising concerns about the ability of this approach, also known as conventional LCA, to accurately represent impacts on complex systems[1] and to be used in decisions regarding the energy sector (public policies, industrial strategic planning, etc.).

An example of the use of LCA in energy policy is in the European Union's Renewable Energy Directive (RED) [11]. It defines a methodology to calculate life-cycle GHG emissions of biofuels based on the attributional approach, setting mandatory emission saving thresholds for a liquid fuel to qualify as biofuel. Delucchi [12] argues that A-LCA is not adapted for policy uses because it is "generally linear, static, highly simplified and tightly circumscribed, and the real world, which LCA attempts to represent, is none of these". In fact, the application of A-LCA for the comparison of life-cycle CO_2 equivalent emissions of different fuels assesses the following question: "What would happen to radiative forcing over the next 100 years if we simply replaced the set of activities that we have defined to be the gasoline / diesel life cycle with the set of activities that we defined to be the biofuel life cycle, with no other changes occurring in the world?" (adapted from [12]).

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[1] Complex systems are characterized by a large number of connected components that interact with each other and are able to adapt to changes in the environment. These interactions are often nonlinear and are at the core of the adaptability of the system – emergence of new states that are not a mere combination of the states of the individual components comprising the system [10].

Answering this question does not give us much information about the real effects on climate change associated to the introduction of biofuels in the liquid fuels market because the "no other changes occurring in the world" hypothesis is counterfactual. Therefore, using it for policy matters can be misleading. It has been recognized that often, well-intentioned policies are ineffective due to the narrow, event oriented, reductionist models that were used in their definition [13]. So the challenge is to develop tools (formal models and simulation methods) that help us understand complex systems (such as the energy, agricultural and transportation markets in the world's economy) and, consequently, be able to design better operating policies.

There is a large community of scientists working on the development of these tools to better assess the environmental impacts of biofuels. Recent examples are the works on *system-wide accounting* [14,15], on *consequential LCA* (C-LCA) [16,17] and on *Environmental Input Output LCA* (EIO LCA or hybrid LCA) [18]. What these works have in common, are assessment models with expanded boundaries in relation to A-LCA. They are mainly oriented for the incorporation of economic mechanisms into the models in order to observe underlying feedback. This present work can be seen as an effort to clearly integrate economic models with environmental evaluation principles.

1.2. Objectives

In this paper we describe the use of an economic model for environmental impact assessment in an LCA framework (i.e. following the ISO 14044 guidelines [19]: defining the system's boundaries, functional unit, etc.). We show that this integrated approach overcomes some limits of the methodologies applied nowadays: the model used is dynamic, captures nonlinear effects and is adapted for prospective studies taking into account policy actions – characteristics that are rarely found simultaneously in the approaches reviewed.

The model used in this study is called MIRET and it was developed with the economic model generator TIMES (The Integrated MARKAL EFOM System) [20] at IFP Energies nouvelles (IFPEN). It is a prospective optimization model representing the French energy production and transportation sectors (the agricultural sector is partially included due to the presence of biofuels, although in a simplistic way). This type of model is generally used for prospective studies [21-24] but it has already been used for environmental evaluations in the "New Energy Externalities Developments for Sustainability" European project [25].

The main objective of this study is developing methodology that is adapted for the environmental evaluation of actions in the energy sector. The use of a prospective optimization model for environmental evaluation can provide information for strategic planning (industry, policy makers, etc.). The mechanisms of our integrated assessment method are illustrated with a case study about environmental impacts occurring as a consequence of the production of synthetic diesel from biomass ("biomass to liquids" – BTL), a second-generation biofuel, in France.

The paper is structured as follows. In section 2, the methods are presented: we explain why a consequential and prospective approach is necessary for this case study; the choice for the case study is justified; the model used for the environmental evaluation is detailed in its structure / mechanisms and we explain how it was adapted to perform an environmental evaluation in an LCA framework. The main results for the case study are presented in section 3 together with the methodological discussion, followed by the sensitivity analysis. In the fourth section, the conclusions and methodological recommendations are presented.

2. Methods

2.1. A consequential and prospective approach

Our work builds mainly on recent developments of the C-LCA approach because it is recognized as an approach adapted for the analysis of changes (specific policy or action) within a life cycle [26]. C-LCA aims at identifying and quantifying the potential impacts that may occur as a consequence of a previous decision (e.g. investing in a new technology, implementing energy policy) [27]. It should better represent complex systems by accounting for indirect, economically induced impacts beyond direct physical relationships accounted for in A-LCA. For example, the introduction of a new technology for the production of biofuels could have consequences in the liquid fuels market, in the agricultural commodities market and any other market associated to the coproducts of this new technology. So the type of question C-LCA is designed to answer is: How will these markets cope with the rising (or declining) supply (or demand) of the products involved with this new technology and what will be the potential environmental impacts of the changes in these markets?

Furthermore, this work depends upon a prospective approach due to the specificities of our case study: a large commercial scale production of BTL is not expected before 2020. As a result, the evaluation of the consequences of its production has to go beyond 2020 (until 2030 in our case). This means that we need to understand the behavior of the affected markets in the long-term to effectively account for consequences. More details about the prospective character of the model are provided in the description of the model (section 2.3.).

The inclusion of market aspects in LCA models has been suggested by Weidema [28] to avoid allocating impacts among products and coproducts and therefore, better reflect the reality of the studied systems. This requires the expansion of system boundaries to include environmental data on the affected technologies. The burdens associated to them are subtracted from the final LCA result. This is known as the "substitution method" or "avoided burden approach" [27] and it is the recommended method by the LCA ISO standards [19].

Nonetheless, identifying the affected technologies when applying the substitution method was an issue. Weidema et al. [29] introduced a new method to systematically justify the choice of the affected system. This method can be referred to as a “step-wise approach” [30] and it was consolidated with the publication of the Calcas project report “Guidelines for application of deepened and broadened LCA” [31]. Authors applying the step-wise approach analyze a substantial quantity of data to determine:

- the scale and the time horizon of the potential change studied,
- the market delimitation,
- the changes in supply and in demand,
- the market constraints and
- the trends in the volume of the market.

Usually, this work is done upon examination of historical data [32-36]. In this paper, we show that a more systematic approach is better adapted for prospective studies than the step-wise approach. The employment of a long-term model allows for the observation of a larger number of effects happening simultaneously. Additionally, we can guarantee that these changes are all more consistent among each other since they are results of simulations done with one single model.

Another shortcoming from the step-wise approach is the difficulty to represent non-marginal (and non-linear) changes [37]. The literature shows that progressively C-LCA practice is moving from Weidema’s heuristic approach to the use of economic models, more adapted for the treatment of larger changes [30]. An example of early works associating LCA models with simple partial equilibrium models is from Ekvall and Andrae [38] about the shift to lead free solders. Instead of carrying out a “manual” analysis of the lead and scrap lead markets’ statistics, it was the partial equilibrium model that would allow the identification of the affected technologies. Eriksson et al. [39], investigating the environmental impacts of different fuels for district heating in Sweden, used a dynamic optimization model of the production of electricity and heat in the Nordic countries. They show that this more complex partial equilibrium model, based on bottom-up energy system models such as MARKAL [40], can be effectively used in C-LCA. They identify, with this model, a mix of technologies that should represent the marginal electricity in the Nordic countries rather than just one technology that would be identified with a step-wise approach. These findings are confirmed by the works of Pehnt et al. [41] and Mathiesen et al. [42] highlighting the difficulties of applying the step-wise approach in complex energy systems.

Recently, larger models representing several economy sectors and/or several world regions have been used in LCA studies [30]. These are specially applied in studies involving biofuels since the consequences of their production can have global effects not only in agricultural commodities (food markets) but also in energy markets (liquid fuels, electricity and heat) resulting in consequences such as indirect land use change (ILUC). For example:

- A partial equilibrium model on the whole world's agricultural sector, FAPRI-CARD[2], was used in Searchinger et al. [44] to estimate the effects of the growing production of ethanol in the United States.
- A general equilibrium model, GTAP[3], was used in Kloverpris et al. [46] to estimate the effects of the growing demand for wheat in Brazil, China, Denmark and the United States.

In all of these C-LCA studies we have made reference to, the market mechanisms are not endogenized to the environmental evaluation model. They are derived from the outlook in specific sectors (step-wise approach) or from economic models, and later included as input into the LCA model [47]. In this work, the environmental information is directly integrated to the economic model for more consistent results (see section 2.4).

2.2. Case study definition

The goal of this case study is to identify and quantify the environmental impacts in consequence of the following decision: To produce BTL in France. Currently, in Europe, projects concerning second-generation biofuels are receiving R&D investments from public and private sectors and informing these stakeholders about the environmental impacts of their investments is important. These projects are usually supported by classical ecodesign initiatives (in order to reduce materials and energy consumption in the supply chain of the product). By using an economic model for environmental evaluation, we propose a complementary approach in this case study, offering a broader view of the consequences of the BTL production.

Also known as the thermochemical conversion of lignocellulosic biomass[4] into synthetic diesel, this pathway for the production of second-generation biofuels consists of the following five main steps:

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[2] Farm and Agricultural Policy Research Institute: Developed by Iowa State University and University of Missouri-Columbia, FAPRI is a system of econometric models covering many agricultural commodities (grains, oilseeds, biofuels, sugar, cotton, dairy and livestock) [43].

[3] Global Trade Analysis Project: Developed at Purdue University, GTAP is a general equilibrium model that simulates the world economy through 57 sectors and 113 regions [45]

[4] Forest residues, agricultural residues (e.g. wheat straw), herbaceous energy crops (e.g. switchgrass) and woody biomass (e.g. poplar)

- Pretreatment: Necessary so that the biomass can be loaded into the gasifier. Mainly size reduction (chopping, grounding, pelletization) and thermal treatments such as torrefaction and pyrolysis.
- Gasification: In the gasifier, the biomass suffers a partial oxydation and is converted into what is known as syngas, composed mainly of hydrogen (H_2) and carbon monoxide (CO).
- Gas conditioning: Impurities are removed from the syngas during gas cleaning steps, due to the high sensibility of the catalyst used in the following conversion steps. The ratio between H_2 and CO is increased to suit the Fischer-Tropsch reaction optimal conditions [48,49]. It can be done by a reaction called Water Gas Shift or external H_2 may be fed into the system.
- Fischer-Tropsch (FT) synthesis: In the FT reactor, in the presence of a catalyst, the conditioned syngas is converted into a liquid mix of hydrocarbons.
- Upgrading: The main products obtained from this mix of hydrocarbons, after the upgrading (hydrotreatment / hydrocracking) steps, are synthetic diesel fuel, naphtha and kerosene. In this paper, we refer to BTL as the mix of these products.

There are many possible technological options for the configuration of this process chain. One critical point is the means of production of the utilities (electricity and heat) used in the process. We focus, in this study, in the autothermic pathway where biomass provides all process energy needs and electricity may be coproduced (schematic process in Figure 1) rather than in the allothermic pathways fed with electricity or natural gas.

Figure 1 – BTL simplified autothermic production steps (source: IFPEN)

The C-LCA approach seems particularly interesting for the evaluation of biofuels since their impacts on other sectors (agriculture, forestry, heat/electricity production) may be important. The production of BTL is a good example of a multi-input multi-output system and for this reason it was chosen for the case study. The expected primary consequences (directly affected technologies) of the introduction of this product in the market are:

- A higher demand for lignocellulosic biomass (and utilities if the allothermic cases were considered). In other words, the introduction of BTL will generate a competition with other technologies that use these constrained resources in France.
- A higher supply of diesel in the road transportation liquid fuels market, kerosene in the jet fuel market and naphtha in the petrochemical market. In our case study, we can also expect a higher supply of electricity that is coproduced in the autothermic process.

MIRET shows itself to be an appropriate tool for the quantification of the environmental impacts associated to these consequences. MIRET is a model that attempts to represent the whole French energy and transportation sectors (more detail on section 2.3.). The process data is sourced from internal (IFPEN) techno-economic studies on autothermic BTL using torrefaction as a pretreatment for the biomass. The main information introduced in the model is presented in

Table 1. The base year of the model is set at 2007 and the time horizon of the study was fixed at 2030 because, as already mentioned, we estimate that industrial scale BTL production in France starts in 2020 and the analysis of the consequences in the long-term is required. The geographic scope of this type of study is typically hard to determine in advance because of imports and exports that occur across the markets in question [27]. As we will see in the results section, the impacts occurring in France are more precisely determined than the ones occurring outside the French borders.

Table 1 – Process information for the production of 1kg of BTL with an autothermic pathway (source: IFPEN)

2.3. The model

The models generated with TIMES have a common mathematical structure. A model, in this case, is a set of data files which fully describe the energy system for a region in a format compatible with the model generator TIMES. A TIMES-type model can be classified as a bottom-up model meaning it has a rich representation of technologies available to meet energy needs exogenously defined.

A simplified structure of the model is represented on Figure 2. It shows the four main sets of information that are the model's inputs:

A) **Demands for energy and energy services**

Household and industries are not modeled but they are represented by electricity and heat demands. The transport sector energy services are represented by long distance and short distance mobility and freight demands.

B) **Availability and price of primary energy resources**

In the model, the natural resources (crude oil, natural gas, coal and uranium) are all imported to France at prices from the World Energy Outlook Scenarios (Current Policies Scenario – CPS, New Policies Scenario – NPS, 450 Scenario – 450S)[5] [1]. Biomass resource production in France is described by limited amounts of each crop that can be used in the energy sector (starch crops – wheat, corn; sugar crops – sugar beet; oil crops – rapeseed,

[5] In the prospective studies conducted by the International Energy Agency, three scenarios are considered. The NPS is the central scenario where all the energy and environmental policies announced by the different countries are implemented. In the CPS, only the existing policies are taken into account. In the 450S, policies are designed so that the atmospheric CO_2 concentration is limited to 450 ppm (in order to limit global warming to 2°C by 2100).

sunflower; lignocellulosic biomass – forest wood, crop residues, dedicated energy crops). There is also the possibility to import lignocellulosic biomass in the form of wood chips. So, not just the price but the availability constraint of biomass resources is important in their description.

C) Technologies

Technologies convert primary energy resources on energy carriers (heat, electricity and fuels) or processes that convert energy carriers on energy services in the case of the transport sector. All technologies are characterized with conversion yields, emissions, investment costs, operation and maintenance costs, availability year, etc. The model includes a simplified oil refining unit, biofuel conversion units (first generation: ethanol, FAME[6] and HVO[7]; second generation: cellulosic ethanol and BTL), electricity generation (power plants – all technologies; combined heat and power), heat generation, preparation of fuels for transport at blending (diesel, biodiesel B30, gasoline grades E5 and E10 and E85, jet fuel – including fossil and bio bases), and end-use technologies for road mobility (personal vehicles and light utility vehicles – thermal, hybrid, plug-in hybrid / gasoline, diesel, natural gas, flexfuel, electric cars ; buses and trucks – thermal, hybrid / gasoline, diesel, biodiesel)

D) Constraints

The model takes into account technical constraints (technology capacities, resource availability, etc.) and political constraints (mandatory consumptions of renewable energies, GHG emissions cap, etc.).

The main sources of information for these inputs are shown in Table 2.

Figure 2 – Simplified structure of the MIRET model

Table 2 – Main sources of information for the models' inputs (Source: Lorne & Tchung-Ming [24])

Using these inputs, the model simultaneously makes decisions to find the optimal solution (optimal technology mix) in order to satisfy the energy demand at a minimum total cost. The decisions are mainly on technologies investment and operation, primary energy supply and energy commodities trade. The model, based on linear programming optimization, computes the flows of energy and materials as well as their shadow prices[8] in such a way that, at these prices, the suppliers

[6] FAME: Fatty Acid Methyl Ester produced from the transesterification of vegetable oils (from rapeseed, soybean, palm, etc.) or animal fat with methanol.

[7] HVO: Hydrotreated Vegetable Oils are a mix of hydrocarbons having properties very close to those from BTL products. They are produced from the hydrogenation of vegetable oils or animal fat.

[8] The term "shadow price" denotes a price derived from the marginal value of a commodity. It is used to distinguish the competitive market prices from the prices observed in the real world [20].

of energy produce exactly the amount the consumers are willing to buy [20]. The objective function minimized in the model is represented in Equation 1:

$$OBJ = \sum_{t \in periods} DISCOUNT(t) \begin{bmatrix} INVCOST(t) + INVTAXSUB(t) + INVDECOM(t) \\ +FIXCOST(t) + FIXTAXSUB(t) + VARCOST(t) \end{bmatrix} - SALVAGE \quad (1)$$

where: *OBJ* is the net present value of the total cost (discounted to the selected base year); *t* is the set of years/periods for which there are costs; *DISCOUNT(t)* is the discount function; *INVCOST(t)* and *INVTAXSUB(t)* are linked to investment costs (e.g. construction of facilities); *INVDECOM(t)* represents decommissioning (dismantling) capital costs; *FIXCOST(t)* and *FIXTAXSUB(t)* are linked to fixed annual costs (e.g. operation of facilities); *VARCOST(t)* represents variable costs (proportional to some activity); SALVAGE represents the unused portion of the technical lives of investments (facilities) whose technical lives exceed the model's horizon[9].

In the course of minimizing costs with demand constraints, the optimal solution returns step-wise increasing supply curves – this is the so-called duality theory [20]. These fundamental results of linear programming are explained here in order to clarify how TIMES-type models can be used in the identification of affected technologies.

The supply curves are built for both intermediate products, and final energy/energy services demands (Figure 3). It is often said that supply curves rank technology by economic merit order. Figure 3a represents one such stylized curve, with exogenous demand *d* (blue line) to be satisfied. It can be interpreted as follows: the less expensive technology (T1) is used first until its capacity is exhausted or no more feedstock is available; then the next technology (T2) is used and so on, until the demand is satisfied. Technologies T1 to T5 represent the technology mix used to produce the good in quantity *d*. In the Figure 3a, technology T5 (in red) is said to be marginal[10]. On the other hand, T6 is not competitive (not used).

The optimal technology mix to supply the good in *d* can change for either of the two reasons: (i) a competitive technology T4b becomes available (e.g. because the feedstock availability is increased – represented in the Figure 3b, or (ii) technology 6 is forced to be part of the mix (e.g. because of a policy requiring the use of this technology – represented in the Figure 3c. In both cases presented in the Figures 3b and 3c, T5 remains the marginal technology.

In this study, the level of penetration of BTL technologies will be controlled. Therefore, what happens is:

[9] For more detail on the model's formalism (linear programs, constraints, etc.) refer to Lorne and Tchung-Ming [24]

[10] Marginal technologies are produced or replaced due to additional demand or supply respectively.

- on the offer side, the supply curves for diesel fuel, kerosene and naphta (and electricity coproduced with autothermic technology) are affected in either way presented in Figure 3b or 3c. These modifications may spread along the pathways, due to resource constraints, for example. While technologies are used differently in the new equilibrium, the associated upstream emissions will themselves change (see the next section, 2.4., for information on how upstream emissions are associated to technologies and commodities);
- the introduction of a new pathway modifies the total supply cost of the given energy carriers. Because those are intermediate products, demand-side adaptations are likely to occur, notably through changes in the car fleet. In that case, the demand for the good (represented as *d* in the above figures) may switch.

Figure 3 – a) Example of supply curve implicitly constructed within TIMES; b) Effect of the introduction of a competitive technology (T4b); c) Effect of forcing a technology (T6) to be part of the mix.

Some other properties of the model are worth mentioning for a better understanding of the case study results:

- Linearity: Outputs of a technology are linear functions of its inputs. This allows the equilibrium to be computed using linear programming. This also means that a technology capacity is available at any fraction of a given unit size rather than discrete values that would better reflect reality (economies of scale are ignored).
- Atomic economic agents: This property guarantees that the markets are competitive and no supplier or consumer can affect the equilibrium price. This assumption is strong because it neglects all sorts of market imperfections that are part of today's and future energy markets. However, it remains of important interest in terms of normative understanding.
- Economic agents have perfect foresight: Agents are assumed to have perfect information about present and future market’s parameters. This allows the minimum total cost to be computed in one step.

One last important feature of this model is its prospective nature. Some studies have highlighted the need to take into account technological innovations on LCA [50-52]. This is especially relevant for the evaluation of a new technology in a large time-horizon, 2007 – 2030. In MIRET, technological innovation can be introduced by informing the year from which a certain technology will be available and by the evolution of technological data (yield, costs, etc.) in the time period considered. For example, in the car fleet, electric vehicles are available from 2020 and the internal combustion engines constantly improve their yields of fuel consumption between 2007 and 2030.

2.4. Adapting the model for C-LCA

The prospective optimization model had to be adapted to perform C-LCA. This section describes the integration process of the life cycle information into the optimization model. This adaptation work basically consists in integrating life-cycle energy consumptions and emissions factors to all the technologies and commodities described in the model (this version of the model contains 192 technologies). Since the main objective of this study is methodological, one single impact indicator was chosen for this first development stage[11], Global Warming Potential (GWP). In order to do that, the three main GHG were tracked throughout the system: carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Two different kinds of commodities were distinguished and treated differently:

- Commodities produced in France: mainly agricultural products (rapeseed, sunflower, sugar beets, etc.), but also some intermediary products such as oxygen and hydrogen. Life-cycle heat, electricity and diesel consumptions were associated to the production of these commodities. These correspond not only to process energy consumptions but also to the production of process inputs. In agriculture, for example, were included aggregated energy consumptions related to machinery operation (tractors, irrigation, etc.) and to the production of fertilizers, pesticides, etc. In the case of crops, it is essential also to incorporate the field N_2O emissions to the model.
- Imported commodities: mainly primary energy resources (coal, uranium, crude oil, natural gas, etc.), but also some manufactured products such as vegetable oils are possibly imported to France in the model. Life-cycle emission factors for CO_2, CH_4 and N_2O were associated to these commodities. In the case of natural gas, for example, these emission factors correspond to its extraction from nature, treatment and transportation to the French borders.

There are also some "exported" commodities that receive a similar treatment as the imported commodities. These are the products that are not consumed in the system described in MIRET but are not necessarily exported from France. A good example is the rapeseed meal coproduced with vegetable oil (used for the production of biofuels: FAME and HVO). Rapeseed meal is usually used in France as animal fodder and our model does not have a full description of the agricultural and livestock sectors. Therefore, the commodities such as rapeseed meal, which are not consumed

[11] Impact categories other than GWP are expected to be integrated into MIRET in a near future. For GWP, we have taken into account the temporal profile of the emissions (section 2.5.) but for other potential impacts such as eutrophication, the spatial profile is also important. TIMES-type models can be regionalized and, therefore, the locations where the emissions occur and their associated impacts can be assessed.

within the boundaries of the model, are "exported" together with negative life cycle emission factors. It is a treatment analogous to the application of the substitution method.

Emissions and energy consumption data are mainly from Ecoinvent [53], the most complete LCA database available at the European level today. This allows keeping a certain homogeneity of data sources.

Distinguishing and treating differently the commodities that are produced in France from the imported commodities is important to maintain consistency within the calculations. For example, the electricity consumed in the production of French products is provided by the mix of technologies resulting from the model's simulation and we do not need to use an electricity mix from an LCA database. The relevant aggregate emission factors, such as the ones associated to electricity production, are built endogenously within the model.

However, a problem that may appear from this integration process is double counting [25]. The electricity, heat and diesel consumptions associated to French products are already accounted for in the energy demands of the industrial sector. In our case, the changes in demands are very small (less than 0.3 %) but we can only assume that double counting does not affect our evaluation because the environmental impact results presented in this paper are *relative* results – they are calculated from the difference between scenarios (see section 2.5.) and, therefore, the over estimated demands are cancelled out.

2.5. Functional unit and system boundaries

Zamagni et al. [47], in a recent C-LCA literature review, highlight the fact that the definition of a functional unit for a system with expanded boundaries (to include affected processes) requires more understanding and research. In fact, we observe that in some C-LCA studies the functional unit is defined just as it would be defined in an A-LCA study. This is probably done with the intent to present results that are comparable with the results of classic A-LCA studies. For example:

- Reinhard & Zah [36] assess the effects of the substitution of 1% of the annual diesel consumption in Switzerland by the domestic production of rapeseed biodiesel (FAME). They present their results per MJ of biofuel produced.
- Searchinger et al. [44] assess the effects of the production of 56 billion liters of corn ethanol in the US above projected levels for 2016. They also present their results per MJ of biofuel produced even if they show that the GHG emissions due to land-use change would be 10 % lower for a smaller increase of ethanol production (30.6 billion liters instead of 56 billion liters).

This functional unit (MJ or a unit of biofuel produced) is suitable for A-LCA studies, where the potential impacts values are modeled as being linear to the quantity of the analyzed product. However, in C-LCA, this linearity does not apply [37,54] and presenting the results per unit of the assessed product could be misleading. Therefore, we suggest that the functional unit should be more connected to questions asked in the beginning of the study. Indeed, Rebitzer et al. [54] affirm that "large consequences do not scale linearly with the magnitude of the change, the results of a consequential LCI are easier to interpret if the functional unit reflects the magnitude of the change investigated."

In our case study, the goal is to observe the consequences of the introduction of the BTL technology in the French energy and transportation sectors with a time horizon set at 2030. Thus, we define a functional unit that involves the whole assessed system. The function of this system is *to satisfy the energy and energy services demand (heat / electricity household and industry demands, population mobility demand) in France from 2007 to 2030*[12]. The associated functional units (FU in the graphics presented in this paper) are the quantities of energy and mobility demanded in France for the time-period considered which are provided exogenously to the model.

The C-LCA model developed for this study generates GWP results, associated to life-cycle GHG emissions, for all processes described in the model in the time-period considered. By comparing a scenario where the decision in question was taken with a "no action" scenario the consequence of the decision "to produce BTL in France" is assessed (as in [14,43]). In other words, subtracting the GWP result for a scenario in which BTL is produced from the GWP result of a scenario where no BTL is produced, we obtain a value that represents the consequences of the decision taken in potential environmental impacts terms.

In order to be coherent with the choice of the functional unit, our system boundaries coincide with the limits of the model used for the environmental assessment: the whole set of technologies described in our model, all of them containing life-cycle information, are included. This approach differs from most C-LCA studies where the definition of the system's boundaries corresponds to the identification of the affected technologies. All the information that can be gathered by following the step-wise approach is implicit in the structure of the model. This means that building the model and adapting it for C-LCA demands considerable work but once it is done,

[12] Note that this definition follows the ILCD provisions for functional units [27]: it includes the function (what: to satisfy energy and energy services demands) provided by the studied system (French energy and transportation sectors), the quantities involved (how much: energy and energy services demands in France) and the duration (for how long: from 2007 to 2030). However, it does not include qualitative information about the functional unit (in what way or how well the function is provided). The goal of the study is to compare different ways (technology mix) of providing the function of the system.

the identification of affected technologies is more straightforward. Hence, the ideal model would include all the technologies that could possibly be affected by the decision in question. The affected technologies would be identified by making simulations with the model and the comparison between "action" and "no action" scenarios.

By choosing to include the whole set of technologies within the system's boundaries, we avoid eventual problems that may arise from multi-functionality – difficulty to compare two systems serving different functions [47]. Our systems always deliver the same function, whether they produce BTL or not, whether they are under REFERENCE or POLICY (see section 2.7. for a description of the different scenarios considered), etc.

2.6. Integration of dynamic aspects in the results evaluation

The C-LCA model developed computes emissions between 2007 and 2030. In other words, the life cycle inventory (LCI) of GHG is built for this period. Traditionally, in life cycle impact assessment (LCIA) the mass values for each pollutant accounted for in the LCI are associated to the potential impacts they may cause through linear characterization factors [19]. However, questions have been raised about the accuracy of these linear characterization factors when emissions occur over a long period of time [55]. An instantaneous release of a pollutant does not have the same impact as releasing the same amount of this pollutant at a small rate over several years [56].

In order to treat this matter (to sum the impacts of emissions happening over a long period of time) more rigorously, we used time-dependent characterization factors from IPCC [57] for each GHG to calculate the GWP. Hence, the temporal profile of the emissions is considered consistently as in the work from Levasseur et al. [56]. This means that for each scenario, we would obtain as a result, a curve representing the cumulative radiative forcing associated to the emissions of the LCI. However, to simplify the results analysis, the time horizon for the evaluation was set in 100 years (2107) and the result is read as one single number in W/m2 converted into kt of CO2 equivalent.

The following Figure 4 illustrates the effect of accounting for the dynamic effects of GHG emissions in one of our scenarios. We can observe that the impacts of emissions happening closer to the end of the time horizon considered are lower than the impacts calculated traditionally. From this point of view, we can conclude that early action has a greater effect against global warming. We consider that it is scientifically more sound to treat the LCI dynamically when possible.

Figure 4 – Effect of the introduction of time-dependent characterization factors for GHG on the GWP

2.7. Scenario construction

It is well known that long-term prospective models have large uncertainty. Most of the epistemological uncertainties (as defined in [58]) of the study come from not knowing what are the market constraints in the future. In C-LCA, it is important to have information on market constraints in order to accurately quantify changes in supply and demand of affected technologies [31]. Constraints of different nature can be included in MIRET: physical constraints (biomass availability, production capacities, etc.) and political constraints (minimum or maximum activity for a given technology, emission quotas, etc.). Uncertainties about political constraints in the long-term are very high so the results of our case study were analyzed under different political environments. The use of scenarios to cope with the uncertainty problem of prospective studies has been suggested as an interesting mechanism that should contribute for more consistent and robust C-LCA [31,42,47].

Two contrasting scenarios were built. A REFERENCE scenario where the model is run under no political constraints and a POLICY scenario including the European Union's RED [11] with the National Renewable Energy Action Plans (NREAP) [11], and the Fuel Quality Directive (FQD) [59]. These are the political constraints that have an important interference in the energy sector. In practice, the points of these regulatory texts that were converted into equations in the optimization model were:

- The RED mandates a 10 % incorporation of energy from renewable sources in transport by 2020. And it states that the contribution made by biofuels produced from wastes, residues, non-food cellulosic material, and ligno-cellulosic material (2nd generation biofuels) to achieve this 10 % incorporation, shall be considered to be twice that made by conventional biofuels [11].
- Each Member State of the EU has a NREAP describing how they will achieve the mandatory share of energy from renewable sources in gross final consumption by 2020. In France, the target is 23 % for the overall renewable energy incorporation. The expected technology mix in each year of the time-period considered (roadmap) was also included.
- The FQD states that fuel suppliers should gradually reduce life cycle GHG emissions of their products by 2020. It mandates this reduction to be at least 6 % by 2020, compared to the European Union's average level of life cycle GHG emissions in 2010.

All of these targets are set in 2020 so we are obliged to make assumptions about their evolution until 2030, the end of our model's time horizon. We adopt the hypothesis that the targets are maintained constant after 2020 with the exception of the double counting for the contribution made by 2nd generation biofuels in achieving the 10 % incorporation of renewable fuels in transports. We consider that this is an incitation for investment on new biofuel technologies and that once the technologies achieve maturity the measure should be gradually relaxed. So the contribution of 2nd generation biofuels was 1.5 times that made by conventional biofuels in 2025 and 1 in 2030.

3. Results and discussion

All the results presented in this section are for BTL produced with an autothermic process, as described in section 2.2. (Figure 1 and
Table 1), with data provided by IFPEN. In the section 3.1., we show how the political environment can influence the overall results in this case study. In 3.2., we explain how the model enables the identification of the affected technologies and how we can fully explain our numerical results by carefully analyzing simulation data on affected processes. Section 3.3. is consecrated to the presentation of the sensitivity analysis of the results to different price scenarios and BTL conversion yields. In the following sections, the model's limits (section 3.4.) and the choice for the functional unit (section 3.5.) are discussed.

3.1. GWP results for autothermic BTL

One of the goals of this exercise is to observe how the political environment can affect the model's results. For this, we analyze the consequences of introducing one BTL commercial scale autothermic production unit in France in 2020. We consider that the production capacity of this unit is 100 kt of BTL / year (which represents around 0.2% of all liquid fuels consumed annually) and that it works at full capacity until the end of the time period analyzed.

This decision does not trigger any large-scale consequences[13] in the background system – i.e. changes in installed capacity. The ILCD Handbook [27] recommends the application of A-LCA (Situation A: micro-level decision support) for these cases. Nevertheless, we consider that this approach is not adapted for decisions in the energy sector because of its specific nature. For example, in electricity generation, fuel turbine power plants may be used only when the electricity demand achieves a peak during the day – installed capacity does not change due to daily changes in demand. This means that when a relatively small-scale decision is taken (production of 100 kt of BTL / year), even if it causes no changes in installed capacity of energy generation, the environmental impacts associated to the decision may vary[14]. A consequential approach (Situation

[13] "Large-scale ("big") consequences shall generally be assumed if the annual additional demand or supply that is triggered by the analyzed decision exceeds the capacity of the annually replaced installed capacity that provides the additionally demanded process" [27].
[14] This is also due to the linear character of the model: investments in technologies are described with continuous values allowing the observation of "small" changes (more detail on section 3.2.).

B: meso/macro-level decision support) is necessary for this type of evaluation – market mechanisms need to be integrated in the evaluation model in order to assess environmental impact variations.

Figure 5 represents the yearly GHG emissions for the whole system represented by MIRET (functional unit: *energy and energy services demands in France from 2007 to 2030*) for the REFERENCE and POLICY scenarios with and without the BTL production unit installed in 2020. Note that the significant decrease over time of GHG emissions observed in these curves is due to the integration of dynamic aspects in the results evaluation (section 2.6). Because of the scale of the Figure 5a, we cannot notice a difference in GWP caused by BTL production. We present the Figure 5b, representing only in a small area of the graphic in Fig. 5a, to show that the GHG emissions are the same for the cases with and without BTL until 2020, diverging a little after that. The difference between the curves in the REFERENCE scenario is of -5853 kt of CO_2 eq. and for the POLICY scenario, the value is of and -2115 kt of CO_2 eq.[15] (see Figure 6). This is exclusively due to the introduction of BTL in the system.

Figure 5 – Yearly GWP for REFERENCE and POLICY scenarios with and without one BTL production unit (100 kt / year) installed in 2020

Figure 6 – GWP affected to the decision to produce autothermic BTL for the REFERENCE and POLICY scenarios

These quantitative values are to be interpreted with precaution. More important than this case study's overall results, is to understand how they were obtained. The strength of this methodology is the possibility to explain these results by the detailed observation of the affected processes (section 3.2). An important conclusion from Figure 6 is that, effectively, the political environment strongly affects the environmental evaluation since the technologies impacted by the decision to produce BTL are not the same under REFERENCE and POLICY. Without a systemic prospective approach (as provided by the model MIRET), it becomes very difficult to describe these political environments and their effects on technological and resource choices. Hence, the corresponding environmental consequences cannot be detected effectively.

3.2. Identification of affected technologies for autothermic BTL

As mentioned before, bottom-up models have a rich representation of technologies and are based on economic mechanisms that favor the observation of affected technologies after a perturbation in the system (section 2.3.). The impact of each affected technology on the final GWP results can be examined with great detail as shown in Figure 7 and Figure 8 for the REFERENCE

[15] Values calculated for the whole time-period considered. The overall effect is very small. For means of comparison, the GWP calculated for the whole system in 2007 was 375075 kt of CO_2 eq.

and POLICY scenarios respectively. These figures represent the difference between "action" and "no action" cases for the contribution to the GWP of each affected technology in the system.

These figures illustrate a large difference between step-wise and modeled approaches of C-LCA. One small change in the system may affect not only a single process in the affected markets, but a set of processes (some of the affected technologies are not represented in these figures because their impact is very small). Moreover, changes would likely affect several markets; constraints, such as security of supply or resource constraints, and public policies, may imply additional processes to be affected. In a sense, small changes can propagate across a system and a systemic analysis can provide more consistent results, compared to a step-wise approach.

Figure 7 – Contribution to the GWP of the affected technologies in the REFERENCE scenario

Figure 8 – Contribution to the GWP of the affected technologies in the POLICY scenario

A first analysis of Figures 7 and 8 gives an overview of the consequences of the BTL production in France. Nonetheless, it is easier to explain the results when these contributions to the GWP are grouped per sector and each sector is analyzed separately: agriculture, electricity production, heat production, conversion processes (refineries, biofuels units, etc.), transports, imports and exports.

In Figure 9, we observe that there are no changes occurring in the agriculture sector due to the introduction of one BTL production plant in France – the GHG emissions of this sector are exactly the same whether BTL is produced or not. Relatively small changes are observed in the process and heat sectors. A reduction of emissions in the power sector was expected considering that electricity is coproduced in the autothermic process but the reductions are not the same for REFERENCE and POLICY. In the remaining sectors (transports, imports and exports) we observe different behaviors between the REFERENCE and POLICY scenarios.

Figure 9 – Contribution to the GWP of each sector of the modeled system

In the next sub-sections (3.2.1. - 3.2.4.) the level of activity of each technology in the most affected sectors will be compared to fully explain these differences. The graphics presented are obtained by the subtraction of the activity of each technology in the sector concerned for the cases with and without BTL. The positive values represent technologies that appeared or that had higher activity levels as a consequence of the production of BTL, and negative values represent the technologies that were replaced or had their activities reduced.

3.2.1. Electricity production – substitution effects for autothermic BTL

During the whole time-period considered, almost 13 PJ of electricity are coproduced at the BTL autothermic plant. In Figure 10 and Figure 11, we observe that this electricity was introduced in the grid substituting electricity produced from fossil fuels – coal and natural gas. The CO_2 released from the combustion of biomass (biogenic CO_2) is not accounted for considering that it was previously captured from the atmosphere by the plants. This explains why the GWP decreases in the power sector in both scenarios.

A greater reduction of GHG emissions is observed in the REFERENCE scenario in comparison to the POLICY scenario (see Figure 9). The reason is that the marginal technologies in POLICY have better yields and emit less GHG than in REFERENCE. In REFERENCE, substituted electricity is produced mainly from coal while, in POLICY, most of the technologies replaced consume natural gas (~2.83 and ~2.54 kg of CO_2 are released with the combustion of 1 kg of coal and natural gas respectively). As in previous works from Eriksson et al. [39], Pehnt et al. [41] and Mathiesen et al. [42], these results rely on the identification of a mix of technologies to represent the marginal electricity. This is permitted by the use of a model capable of determining this mix over time and under different political environments for C-LCA.

Note that the reduction in demand for coal and natural gas in electricity production is reflected also in the imports sector (see section 3.2.4.). These "secondary" consequences are not accounted for in the previous works just mentioned.

Figure 10 – Electricity production technologies substitution effects in the REFERENCE scenario

Figure 11 – Electricity production technologies substitution effects in the POLICY scenario

3.2.2. Heat production – substitution effects for autothermic BTL

Even though the emissions in the heat sector remain the same with the introduction of BTL in the REFERENCE scenario (see Figure 9), an important technological change is noticed. In Figure 12, representing the affected technologies on the heat sector, we observe that biomass based heat is replaced by heat produced from biogas. We consider that the CO_2 emissions from the combustion of biomass and biogas have a neutral effect on climate change, and that is why the heat sector was apparently not affected.

This can be interpreted as follows. Lignocellulosic biomass is consumed for heat production in the case without BTL production. In the REFERENCE scenario, there are no constraints favoring the use of biomass in this sector. When the BTL production facility is introduced in the system, it starts consuming the biomass that was once used for heating. Hence, the heat sector "chooses" to produce heat with biogas, the next available technology in MIRET's built-in supply curve (see section 2.3.)

Even though our model has a poor representation of heat production technologies (problem treated in section 3.4.), this result highlights a possible competition for resources in the heat sector.

Figure 12 – Heat production technologies substitution effects in the REFERENCE scenario

In the Figure 11, we have observed that some cogeneration (of heat and electricity) technologies fed with natural gas were substituted in the POLICY scenario. These are simply replaced by newer heat production technologies, also fed with natural gas and, therefore, a small reduction of emissions in the heat sector is observed (see Figure 9).

3.2.3. Transport sector – substitution effects for autothermic BTL

Most of the impacts in the transports sector can be explained by a close look at the liquid fuels consumption. Based on intuition, one would expect a decrease in the transportation GHG emissions due to the production of BTL. However, this is only observed in the REFERENCE scenario (Figure 13): synthetic diesel and synthetic kerosene, coproduced in the BTL plant, replace conventional (fossil) diesel and kerosene (used as jet fuel for aviation).

Counter-intuitively, in the POLICY scenario, a mix of synthetic diesel (from the BTL plant), FAME and conventional diesel replace HVO (Figure 14). This occurs because of the RED constraints (see section 2.7.). The consequence of the mandate for the incorporation of 10 % of renewable energies in transports by 2020 is that the marginal liquid fuels are biofuels – HVO is the fuel replaced. But what “allows” a higher consumption of fossil diesel when BTL is introduced in the system, is that the contribution of second-generation biofuels to achieve this renewables incorporation target is considered to be twice that made by conventional biofuels.

This is another example of important information that can be provided to policy makers from the use of a model such as ours for environmental evaluation. This particular point from the RED (second generation biofuels count double) was introduced with the intention to stimulate investments for the production of less impacting biofuels. However, an adverse consequence is observed: the increase in fossil fuels consumption.

Figure 13 – Liquid fuels substitution effects in the REFERENCE scenario

Figure 14 – Liquid fuels substitution effects in the POLICY scenario

The biomass transportation also impacts emissions in the transports sector. In the REFERENCE scenario, the lignocellulosic material that was transported for heat and electricity production is transported for BTL production with the introduction of this technology in the mix. This means that the quantity of biomass transported is the same whether BTL is produced or not, only small differences in travelled distances are observed and this does not impact significantly the results. In the POLICY scenario, however, there is a supplementary quantity of biomass imported to France for BTL production. These wood chips are transported in trucks to the conversion plant and this has an important impact of 570 kt CO_2 eq. in the final result.

3.2.4. Imports and exports – substitution effects for autothermic BTL

The impacts in the import and export sectors are a consequence of the substitution effects presented in the previous sections. For example, in the REFERENCE scenario (Figure 15), less coal and natural gas are imported due to a smaller consumption of these resources for electricity generation (section 3.2.1.), less diesel is imported due to a reduction in the consumption of this fuel substituted by synthetic diesel from biomass (section 3.2.3.). Also, there is a reduction in naphtha imports because of synthetic naphtha production in the BTL plant although this substitution effect is not presented earlier because the use and end-of-life phases of naphtha's life cycle are not included in MIRET. All these factors explain the lower GWP in the imports sector when BTL is produced (see Figure 9).

The same is observed in the POLICY scenario, the GWP is lower in the imports sector with the introduction of BTL in the system (see Figure 9). The affected process that most contributes for this decrease is the palm oil importation – since there is less HVO produced (section 3.2.3.) with the introduction of BTL, less palm oil needs to be imported to France. We recall here, that Ecoinvent emission factors were directly associated to imported products and the GHG emissions from palm oil's life cycle are particularly high notably due to direct land use change (deforestation), N_2O emissions from the field and also methane emissions from the decomposition of empty fruit bunches used for landfilling [60].

As explained in section 3.2.2., in the REFERENCE scenario, biomass that was used in heat production is deviated for the production of BTL. In POLICY, the national lignocellulosic resources are still used in the heat sector due to the French NREAP. Therefore, it becomes necessary to import wood chips for the production of BTL. In Figure 16, we observe that a relatively large quantity of wood chips is imported, however the life cycle GHG emission factors from Ecoinvent associated to this biomass feedstock are much lower compared to palm oil. Note that the land use change impacts from the increase in the demand of wood chips are not assessed in this study, which can be seen as a limit of MIRET.

Figure 15 – Imports in the REFERENCE scenario

Figure 16 – Imports in the POLICY scenario

In Figure 9, we can also observe a small reduction of emissions in the export sector under the POLICY scenario due to the introduction of BTL. This is a consequence of a growth in the exports of glycerine (an increase of 8.6 kt over the whole time period considered). Glycerine is a coproduct of FAME production and this biofuel has an increased consumption (74.7 kt) when BTL is introduced in the POLICY scenario (section 3.2.3.). As explained in 2.4., commodities that are not consumed within the boundaries of the model, are "exported" together with negative life cycle emission factors from Ecoinvent.

3.3. Sensitivity analysis

In LCA, sensitivity checks are conducted to assess the reliability of the final results [27]. In biofuel A-LCA studies, uncertainties are related to data quality in the LCI (regarding the technological, geographical and time-related representativeness of processes in the system) and also methodological choices such as the allocation procedure. In C-LCA there are important uncertainties related to the market mechanisms – in terms of substitutions occurring in competitive markets – driven by prices, costs and public policies. The estimation of overall uncertainty is essentially achieved by scenario analysis [61-63] and by Monte-Carlo Simulation [8,64,65].

As a first approach, we present here some classical sensitivity analyses conducted over some of the model's parameters: price scenarios and BTL conversion yields. We choose not to present sensibility analysis results over individual emission factors because their influence in the results is linear and therefore predictable. For instance, in the POLICY scenario, palm oil imports have a strong negative influence in the final results of our assessment (-1337 kt CO_2 eq. directly proportional to the quantity of imported palm oil – Figure 8). There is a relatively high uncertainty on Malaysian palm oil life-cycle emissions in Ecoinvent (e.g. around ±30% for CO_2 from land transformation) but no significant conclusions can be drawn from the variation of these emission factors within their confidence interval. Only linear impacts in the results would be observed.

All the results presented in section 3, until this point, were obtained from simulations under prices from the NPS [1] (section 2.3) – this is our BASE case. Figure 17 represents the variation of the results for other price scenarios from IEA's World Energy Outlook: CPS and 450S. For each of these scenarios, the natural resource (coal, crude oil, natural gas, etc.) prices and the CO_2 price (in the form of an emission tax) have different evolutions between 2007 and 2030. The analysis of our results show that most of the influence in the results comes from the CO_2 price. Relatively small changes occur in REFERENCE, mostly due to small changes in substitutions occurring in the electricity sector. In POLICY, however, the gain in GHG emissions from the introduction of the BTL plant is reduced to -573 kt CO2 eq. with the 450S prices. This is mainly because the marginal electricity technologies (that are replaced by the electricity coproduced in the BTL plant) are "low emitting" technologies in a scenario where CO_2 prices are high (such as the 450S where the 450 ppm of CO_2 in the atmosphere limit is respected).

Figure 17 – Price scenario sensitivity analysis

It has been shown that yields can vary within a 10% range depending on the Lower Heating Value (LHV) from the biomass entering the process [48]. Therefore, we present results for the sensitivity analysis on the BTL conversion yields (+10% for the high mass yield case and -10% for the low case) in Figure 18. There are no significant changes occurring in REFERENCE. The emission gains decrease with the yield in the POLICY scenario. This happens because less biomass needs to be imported and transported for higher yielding BTL plants. As explained in the section 3.2.3., the same quantity of biomass is transported in the REFERENCE scenario whether BTL is produced or not.

Figure 18 – Autothermic BTL conversion yield sensitivity analysis

3.4. Exploring the model's limits

In this section we adopt a rather different approach of sensitivity analysis. Model results are usually far more sensitive to the model's boundaries than to variations in parameters [13], such as presented in the previous section (3.3). Therefore, we investigate how the boundaries of the model affect the environmental evaluation results.

The first issue treated here is the fact that MIRET does not have a description of the industrial sector, notably of the petrochemical and chemical industries. Consequently, the model does not provide information on naphtha's valorization and end of life. Synthetic naphtha (bio-naphtha) is one of the products from the BTL plant and it replaces naphtha produced in the French refineries or imported to France. The variation in the GWP associated to the reduction of fossil naphtha production / imports due to the BTL introduction is accounted for in the model. However, the use of naphtha and end-of-life steps of products made from naphtha are not included within the model's boundaries. Since bio-naphtha's carbon is biogenic and not accounted for in the GWP calculation, it is important to know if the naphtha's carbon content is released or not to the atmosphere.

In France, most of the available naphtha is used in the production of olefins that are feedstock for the fabrication of plastics. In these polymers, the carbon content of naphtha is "stored" and may not be released as CO_2 in the time horizon of this study. The results presented in section 3.1. would remain unchanged if this hypothesis is true. However, plastics can be disposed as municipal solid waste and be incinerated for energy recovery generating CO_2 emissions. In France, incineration corresponds to about 40% of plastics' end-of-life [66]. In Figure 19, we observe what the results would be for the REFERENCE and POLICY scenarios for autothermic BTL depending on the quantity of plastics originated from naphtha burned for energy recovery within the time horizon of this study. Our original results, presented in the beginning of section 3, correspond to the points where 0% of naphtha based plastics are incinerated. We considered for these calculations that the emissions related to naphtha's use phase (processing steps into the final products) are negligible compared to the emissions from end-of-life (incineration).

Figure 19 – GWP affected to the decision to produce autothermic BTL as a function of the quantity of naphtha based plastics incinerated for energy recovery

Indeed, naphtha's end-of-life has a great impact in the final results. GHG emissions could have a supplementary decrease of up to 1248 kt CO_2 eq. depending on the chosen hypothesis for carbon release to the atmosphere due to plastics energy recovery within the time horizon of this study. This demonstrates the importance of "challenging" the system's boundaries as a sensitivity analysis.

Another model limit treated in this section is the fact that the heat sector is not completely described in MIRET. By the detailed observation of the affected technologies we observed that the heat production could significantly influence the REFERENCE scenario result (section 3.2.2.). Since this sector is roughly modeled, we cannot rely on the marginal heat production technology as being biogas. In Figure 20, we can observe what the result for autothermic BTL produced under the REFERENCE scenario would be for a different marginal heat technology. An extreme case was chosen to illustrate the whole range of variation this sector can have on the results: heat produced from the combustion of lignite.

Figure 20 – GWP affected to the decision to produce autothermic BTL in the REFERENCE scenario depending on the source of marginal heat production.

Once again, this exposes how the model's boundaries have a great influence in the overall results. If the heat that was once produced by the combustion of lignocellulosic biomass is replaced by heat produced from the combustion of lignite, the system's GWP is increased of 25665 kt of CO_2 eq., when satisfying the French energy and energy services demand between 2007 and 2030.

Prior conclusions from the case presented originally (Figure 6) where biogas is the marginal heat production technology are reversed.

These huge uncertainties about the result do not jeopardize the use of this methodology for the environmental evaluation of future technologies. They reinforce the fact that we should focus on the lessons this economic prospective model can provide rather than in the numerical results.

An important conclusion about these results is that the production of BTL can affect the energetic sector in such a way that the GHG benefits of this technology may be at stake. C-LCA biofuel studies usually focus on land use change and the impacts in the energy system are overlooked. For example, EPA's "Renewable Fuel Standard Program Regulatory Impact Analysis" [43] is a very complete and comprehensive study that estimates the global warming and other air pollutants impacts associated to biofuel production mandates in the US by 2022 (more than 36 billion gallons of biofuels are required). It uses numerous models[16] for the assessment of biofuel production impacts including land use change but the consequences on the energy sector are not considered. These are potentially important taking into account the extent of the mandate and that other energy resources are consumed for the production of these biofuels: e.g. new corn ethanol production facilities consume ~0.5 MJ of natural gas to produce 1 MJ of fuel [67]. Considering that corn ethanol is the most representative biofuel in the US, the consequences of increasing the demand for natural gas should be assessed as we do in this work.

There are still other limits of our model that should be treated in order to produce more reliable results. C-LCA methodology is clear in stating that all relevant affected technologies need to be included in the system's boundaries [47]. The tool used in our case study does not completely include all affected technologies within its boundaries – MIRET is a partial equilibrium model that includes a full description of the transports sector and the energy sector (the heat and the agriculture sectors are only partially described) for only one region, France. It is obvious that our vision of the affected processes outside these boundaries is limited (there are imports of petroleum, coal, natural gas, uranium, wood chips, palm oil, soybean oil, etc.).

We observed, for example, that in some cases the importation of wood chips is necessary for the production of BTL in France. It is not possible to accuratly determine the impacts associated to these importations with MIRET. It does not provide information about the regions in which the

[16] Forestry and Agriculture Sector Optimization Model (FASOM) for changes in domestic agriculture and fertilizer use; Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET) for GHG emission factors for fuel and fertilizer production; CENTURY and DAYCENT for estimation of N_2O emissions from fertilizer use; FAPRI-CARD for impacts on international agricultural and livestock production; Winrock International data for the estimation of what land types are converted into cropland and what are the associated GHG emissions; GTAP to test the robustness of FASOM, FAPRI-CARD and Winrock results.

wood is produced, and neither about the land use changes occuring as a consequence of the increase in demand for the lignocellulosic resources in these particular regions. Land use change and indirect land use change would be better assessed with the use of partial equilibrium models on the world's agriculture, livestock and forestry sectors or with general equilibrium models [68-70].

Moreover, the list of unit processes impacted by a decision such as the one considered in this case study could be even more extensive if we consider also rebound effects. Rebound effects can only be captured if all the demands are endogenized to the model (integration of price elasticity to the demand of energy and energy services).

3.5. Functional unit discussion

Another point that should enter the discussion concerning the case study results is the functional unit's choice. As highlighted in section 2.5., we consider that presenting the results per MJ of BTL produced is not adapted for the presentation of environmental impacts that are not linear to the quantity of the product analyzed. Moreover, we observed in our case study that the GWP depends also on *when* the BTL is produced. Solely for matters of illustration of this issue, Figure 21 is presented with results in g CO_2 eq. / MJ for different quantities of BTL produced (0, 0.66E+11, 1.98E+11, 3.30E+11 and 4.62E+11 MJ) in the whole time-period considered and for different yearly distributions of BTL production units installed: curve A represents an even production of BTL during the whole time-period, curve B represents a growing production of BTL between 2020 and 2030, curve C represents the production of BTL starting only in 2025. The nonlinear effects become evident from the observation of this graphic. And this is not just due to the use of dynamic characterization factors for the evaluation of the GHG impacts, the affected processes are not the same depending on the year the BTL plants are installed.

Figure 21 – GWP per MJ of BTL produced for different yearly distributions of BTL production units. A – represents an even production of BTL between 2020-2030. B – represents a growing production of BTL between 2020-2030. C – represents the production of BTL between 2025-2030.

Additionally, these results are not at all comparable to those of a classic A-LCA even if the magnitude of the values may lead us to think differently. In A-LCA, *absolute* values for the environmental evaluation are presented for a given product. For autothermic BTL, these values typically run low compared to the fossil fuel reference: 4 – 6 g CO_2 eq. / MJ against 83.8 g CO_2 eq. / MJ for diesel oil [11]. The C-LCA results in Figure 21 are not *absolute* values. They represent the difference between impacts in a situation where the studied decision was taken and a situation where the decision was not taken (*relative* values). They should be interpreted differently: for each MJ of BTL produced, the GWP of the whole system decreases of 28.5 – 43.1 g CO_2 eq.

4. Concluding remarks and methodological recommendations

In this work we contribute to the development of methodologies for the environmental evaluation of future technologies especially in the energy sector. The nature of the initial question asked in our case study ("What are the environmental impacts associated with the decision to produce BTL in France?") leads us to apply a consequential and prospective approach. A consequential approach is adapted for the identification of changes occurring as a consequence of a previous decision ("to invest in the production of BTL"). A prospective approach is necessary for the treatment of technologies that are still not produced commercially nowadays (second generation biofuels). It is essential to choose an assessment tool that is well adapted to answer the proposed question. We show, in this paper, that bottom-up energy models are suitable for this type of task although we cannot precisely answer this very broad initial question due to some limitations of MIRET.

Being able to model complex systems (such as the energy and transports markets) is important for a better estimation of the environmental impacts associated to changes in these systems. These changes, which may be non-marginal, are characterized by nonlinearities that can be observed with the use models. We provide, with this study, argumentation exposing why and how market mechanisms should be integrated in an LCA framework.

Previous consequential studies lack in systematization [47] and in this paper we suggest some recommendations concerning the definition of functional units and system boundaries. When assessing the consequences of a decision in a system, the functional unit should concern the totality of the system. In our case study, it was appropriate to define the functional unit (accordingly to ILCD provisions [27]) as: *the energy and energy services demand in France from 2007 to 2030.*

The system's boundaries should be in line with the functional unit and hence linked with the investigated question. We recommend that the environmental impacts should be assessed for the whole system in scenarios with and without the assessed decision. The differences between these scenarios (obtained by the subtraction of impact results from both of them) correspond to the environmental impacts that may be attributed to the decision. It is more coherent to associate these results with a decision than with one unit of product (1 kg, 1 MJ, etc.) due to the nonlinear relations in the system. Note that the subtraction of the impacts calculated for a system with and without the assessed decision can only be done because the systems provide exactly the same functions.

One of the main characteristics of a C-LCA is the identification of affected technologies. In the proposed methodology, the processes that were influenced by the decision are identified during the analysis of the results – they are not determined beforehand. We highlight the possibility to explain with great detail the substitution effects occurring in the system. Since the number of affected technologies can be elevated, a systematic approach (such as the use of a bottom-up model) is required to guarantee that different consequences are *coherent* among each other.

When studying future technologies such as second-generation biofuels, a prospective approach is necessary. Technological innovations and possible political environments should, therefore, be included in the evaluation. The use of a bottom-up model is highly recommendable in order to keep *consistency* within all different possible futures assessed.

Time is a very important parameter in consequential studies and it is rarely treated consistently. We recommend practitioners to clearly define the time horizon in which the consequences of the studied decision will be accounted for. The time horizon for the impacts associated to the identified consequences may be different and should also be clearly defined (in our case study, consequences were analyzed until 2030 and global warming impacts, until 2107). We also recommend the inclusion of dynamic impact characterization factors when possible.

Also, we emphasize the relevance of adapting the optimization model for environmental evaluation by integrating (hardlinking) life-cycle information into the described commodities and technologies. By following the methodology described in the section 2.4., emission factors are endogenized to the model. In fact, Ekvall [71] has argued that hardlinking economic and LCA models produces faster results and a unique, completely *consistent* solution whereas the iterations of softlinking depend on subjective choices and may result in solutions that are not fully consistent. Additionally, with the emission factors endogenized, there is the possibility to change the model's objective function for an environmental optimization instead of an economic optimization.

Finally, we highlight the fact that LCA is an iterative approach and depending on the information gathered during the different LCA steps (inventory construction, impact assessment, interpretation), the initial question might need to be refined [27]. In our case study, for example, it is not possible to guarantee that the broad question "what are the environmental impacts associated with the decision to produce BTL in France?" is precisely answered with the model MIRET. In fact, we assess the global warming impacts by 2107 occurring as a consequence of the production of BTL in France until 2030 – we answer a much more narrow question. Moreover, the consequences observed are mainly on the French energy and transports sectors and the effects in other regions of the world can only partially be included in the evaluation. That is why practitioners should always precisely list the limitations of the model used (section 4.3.).

This work can be considered as a step for the consolidation of consequential and prospective LCA methodologies. Further work should concentrate in the application of the above recommendations in other case studies contributing for a proper systematization of these approaches. The use of other types of economic models should be tested as well.

Research on the estimation of uncertainties of prospective models could also provide an important contribution in better structuring these environmental evaluation methodologies. The application of Monte-Carlo simulation could be interesting but extremely large computational resources would be required due to the large number of parameters in these models and the time required for each simulation. Other procedures should be investigated in order to determine the impacts of prices, emission factors, technology yields, etc. on the model's uncertainty.

Moreover, this work contributes to a debate started by Zamagni et al. [47] on how to better link questions and models. Clearly, a special attention should be devoted to the correct formulation of research questions and to the choice of models used to answer these questions in future consequential and prospective LCA studies.

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Figures, tables and equations

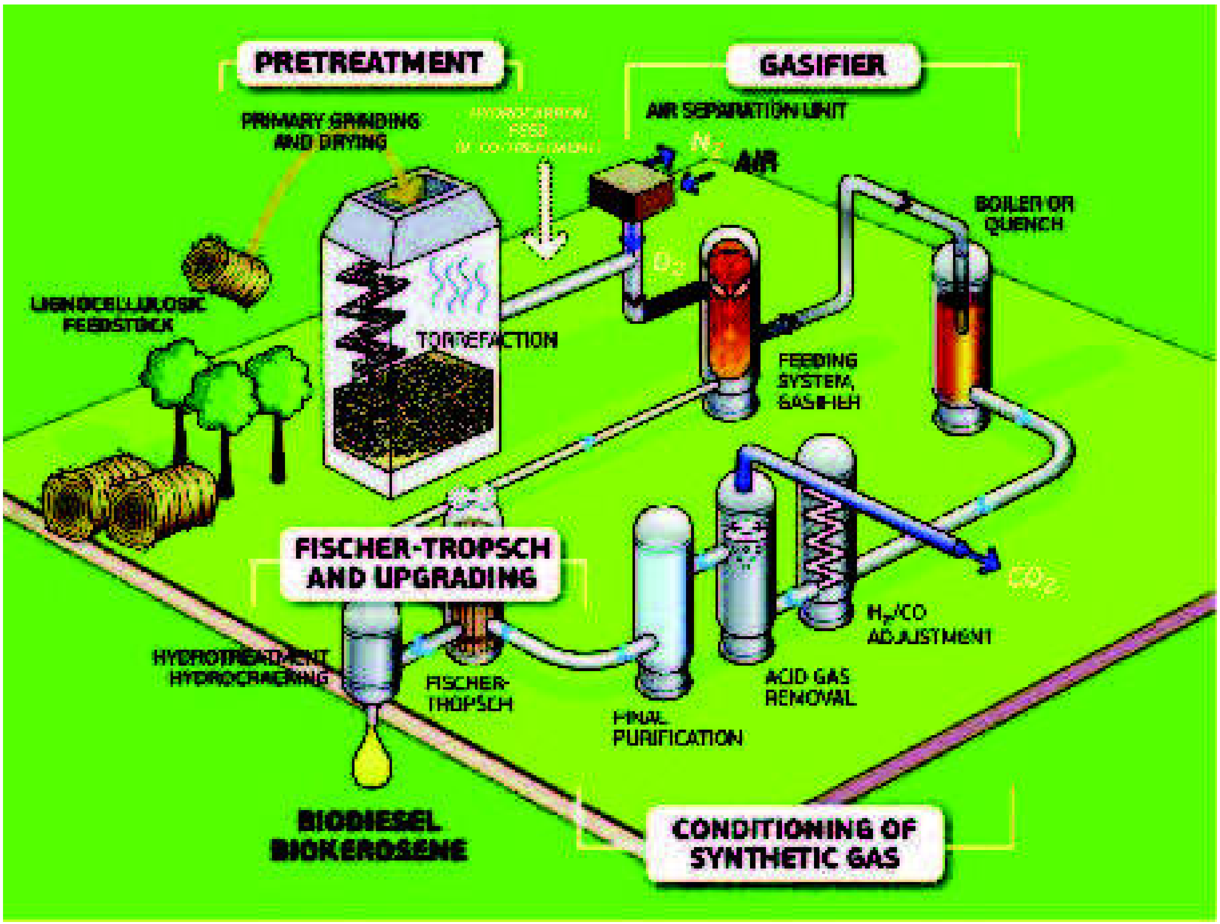


Figure 1

Inputs	Biomass (26% humidity) (kg)	10.23
Outputs	Electricity (MJ)	8.65
	Diesel (kg)	0.50
	Naphtha (kg)	0.30
	Kerosene (kg)	0.20

Table 1

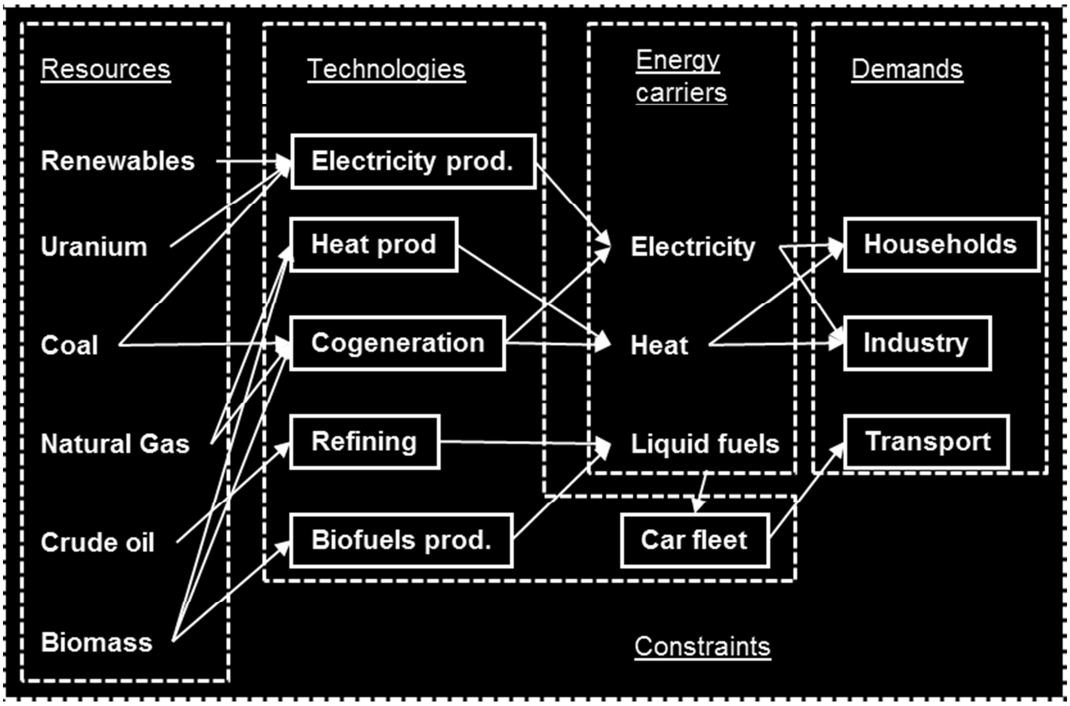
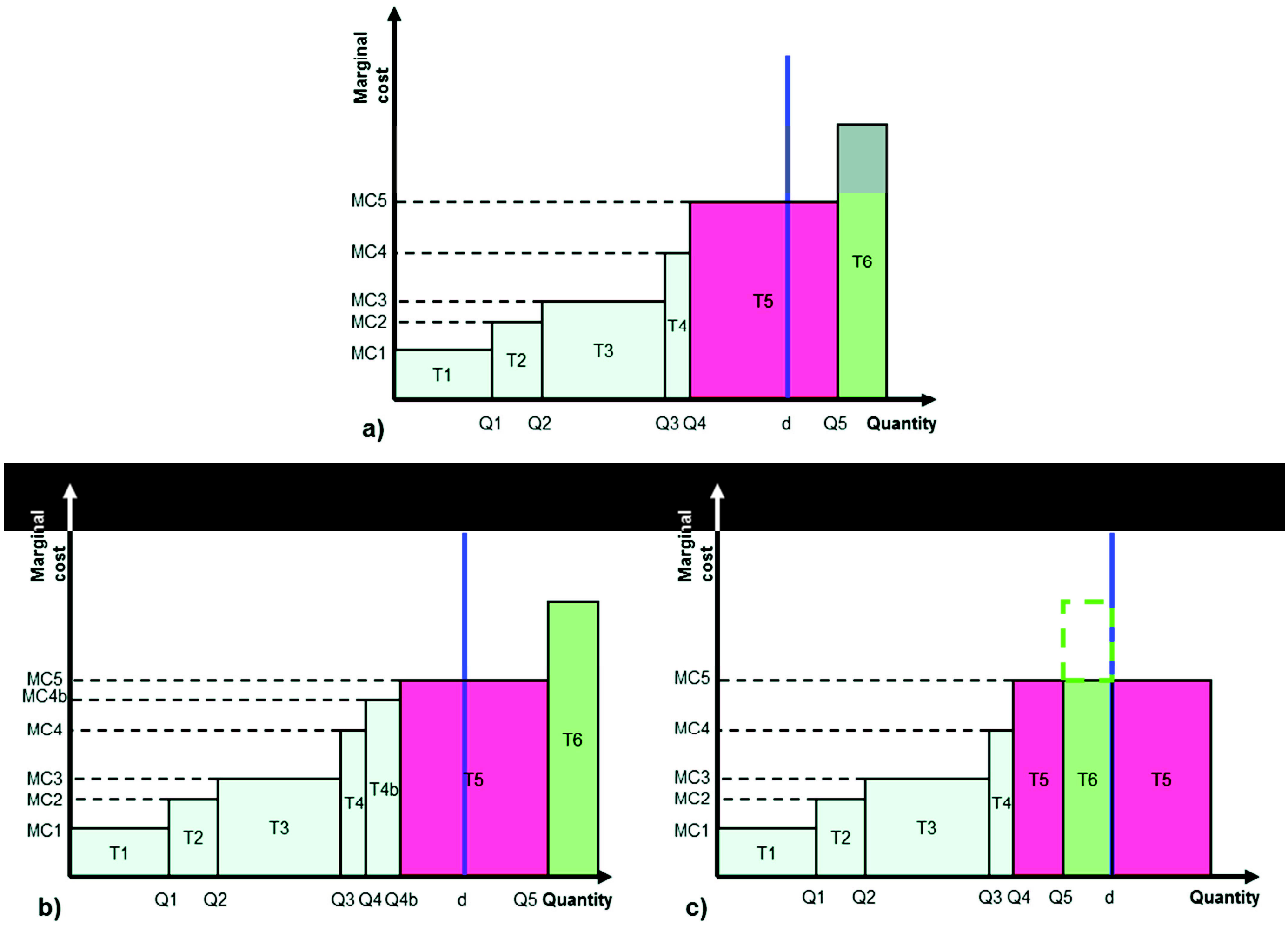


Figure 2

Scenario components	Sector	Data sources
Primary energy	Fossil energy	International Energy Agency (IEA)
	Agricultural biomass	French National Institut for Agricultural Research (INRA)
	Woody biomass	French Institut of Technology for Forest Based and Furniture Sectors (FCBA)
Energy technologies	Refining	IFPEN (Internal)
	Biofuels production	IFPEN (Internal)
	Road mobility (passengers and freight)	IFPEN (Internal)
	Power plants	Électricité de France (EDF), IEA, Ministère de l'Économie et des Finances (MINEFI)
Demand scenarios	Other oil products	IFPEN / Économie du Développement Durable et de l'Énergie (EDDEN, ex-LEPII)
	Passenger and freight mobility	Centre d'Analyse Stratégique (CAS)
	Electricity	Réseau de Transport d'Électricité (RTE)
Policies	Carbon price	European Comission (EC)
	Biofuels	EC

Table 2



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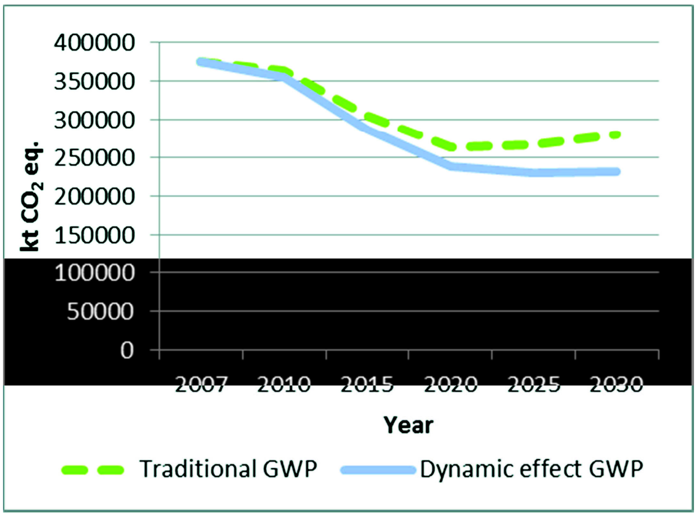

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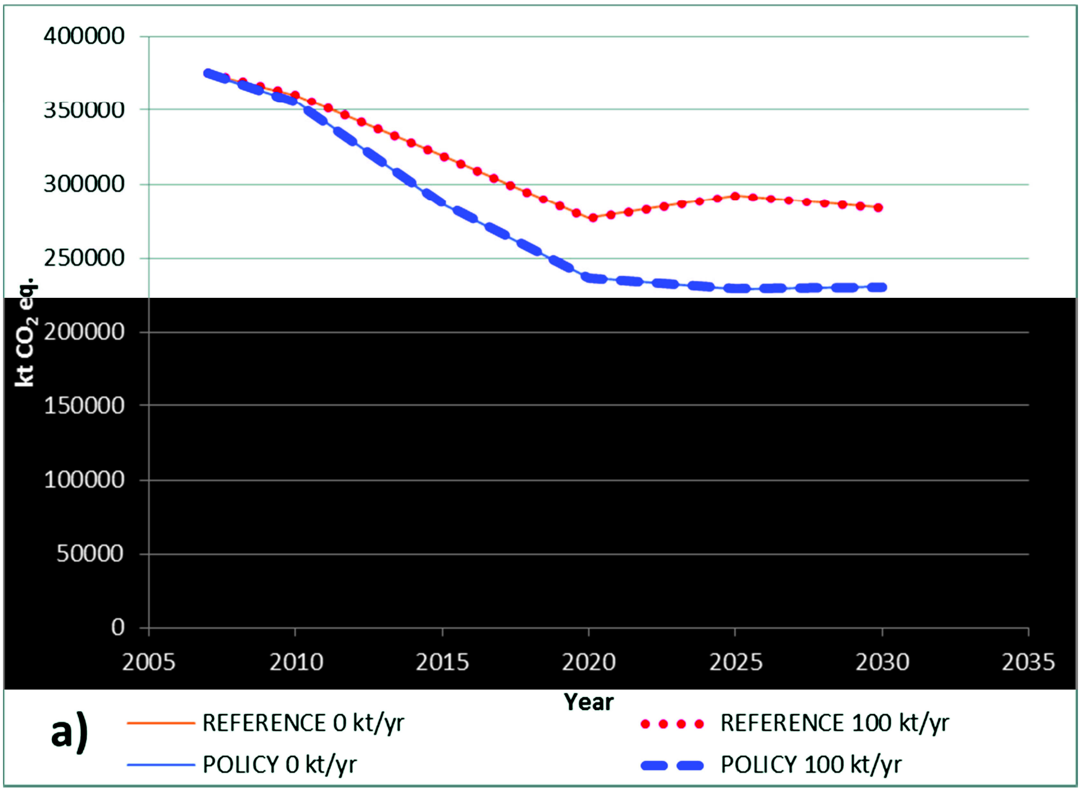

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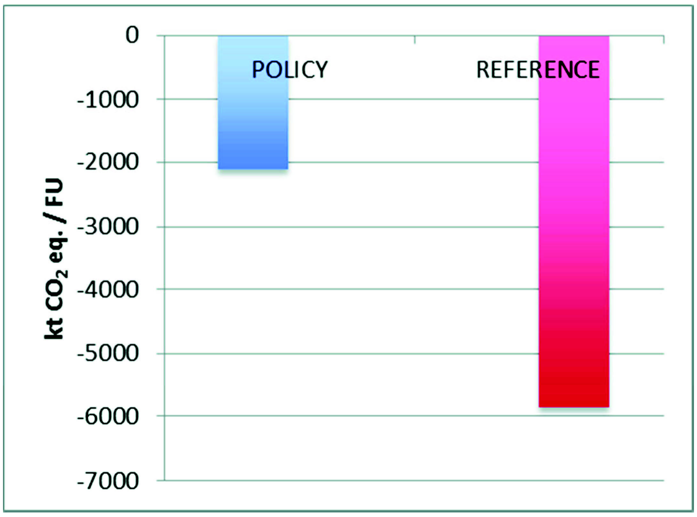

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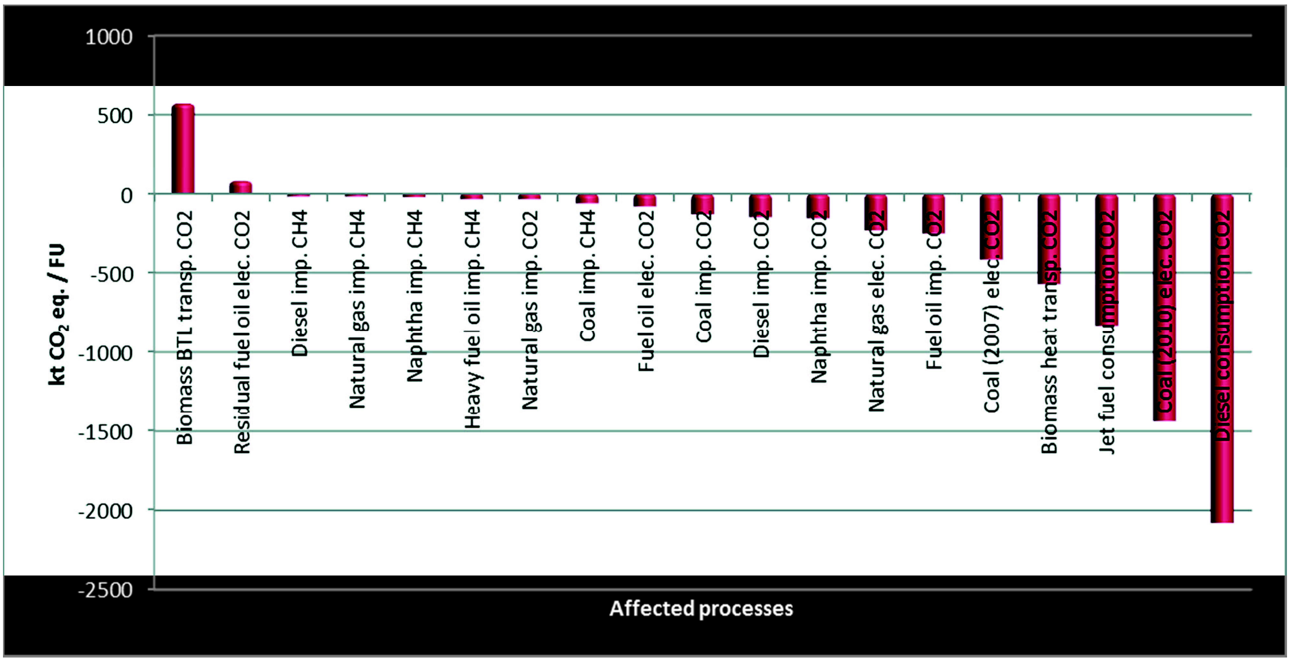

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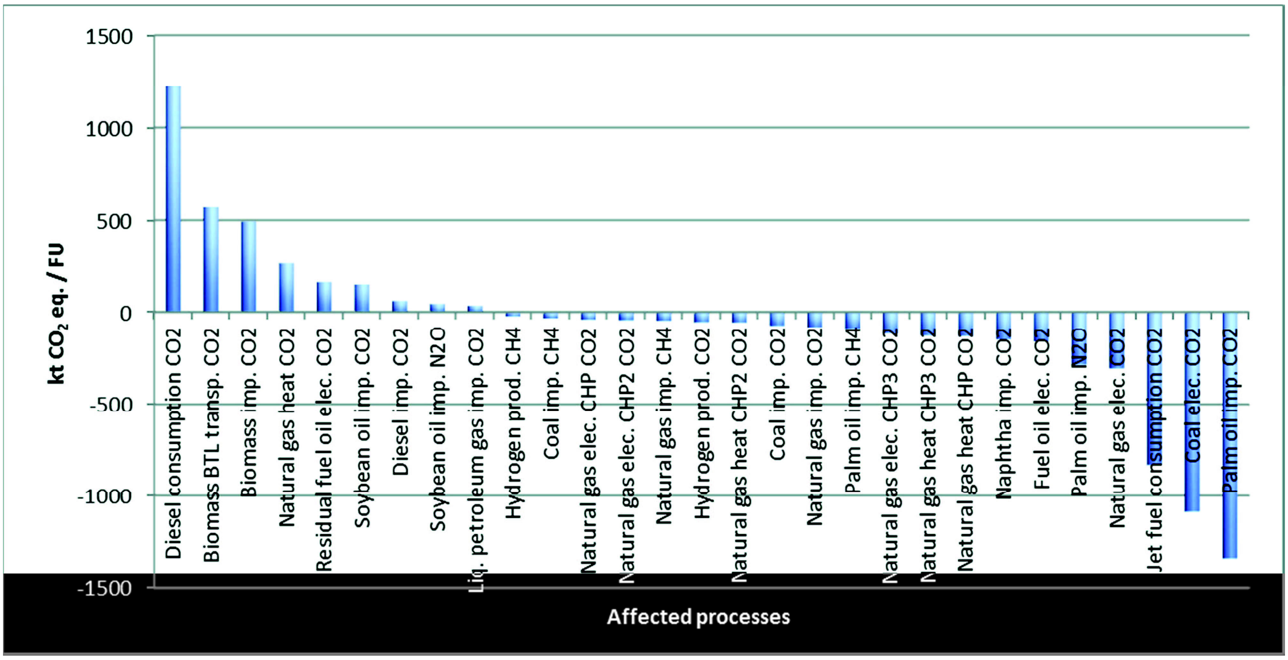

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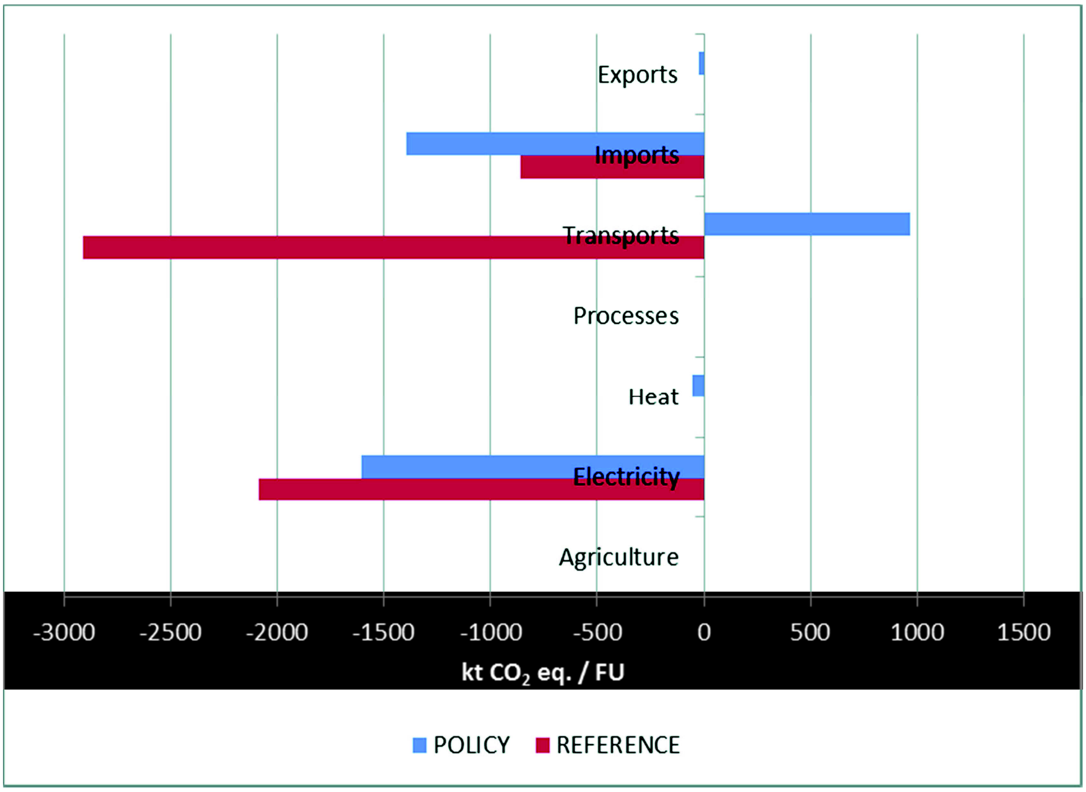

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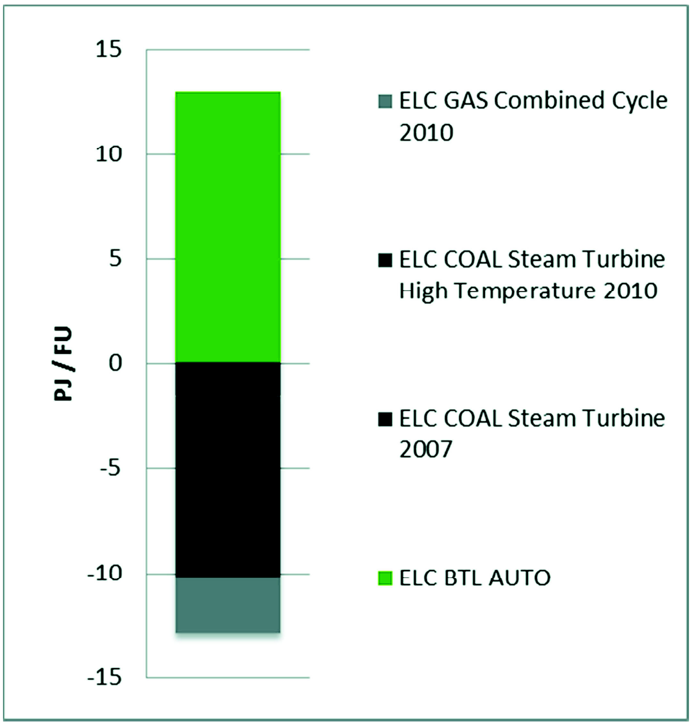

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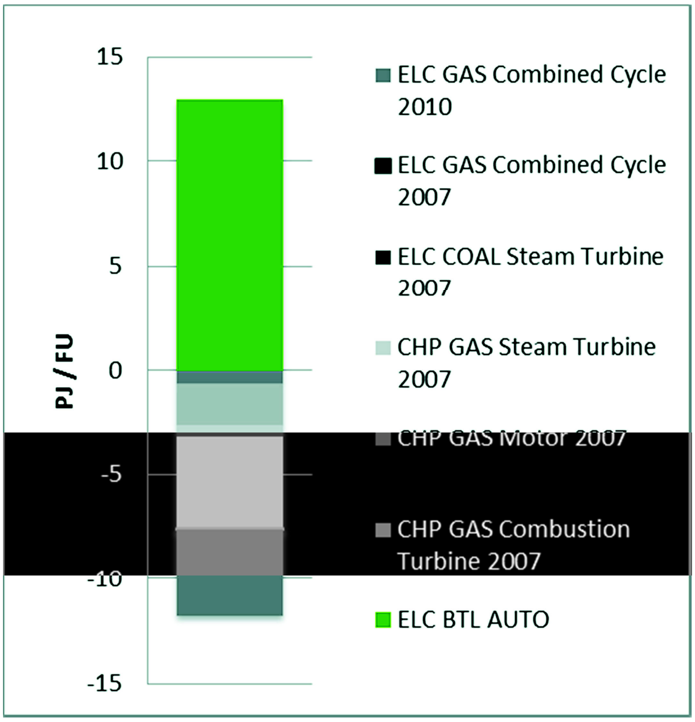

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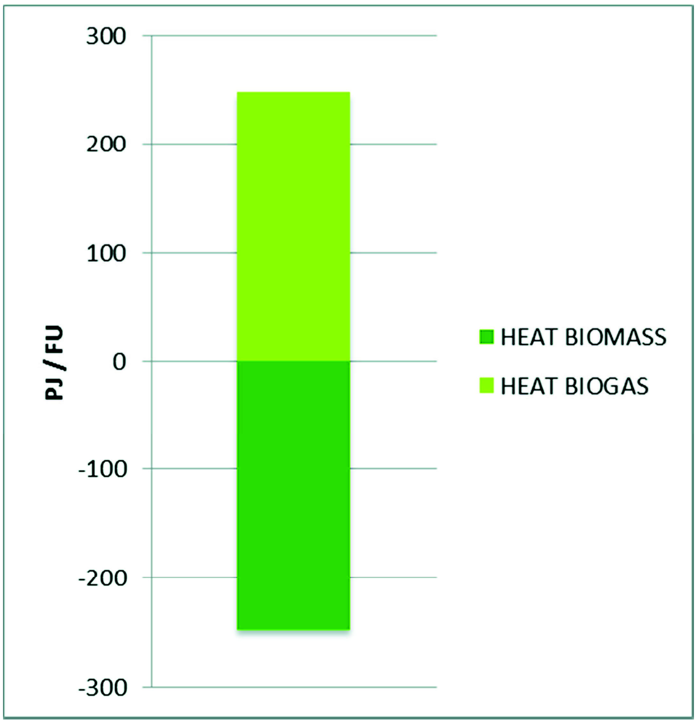

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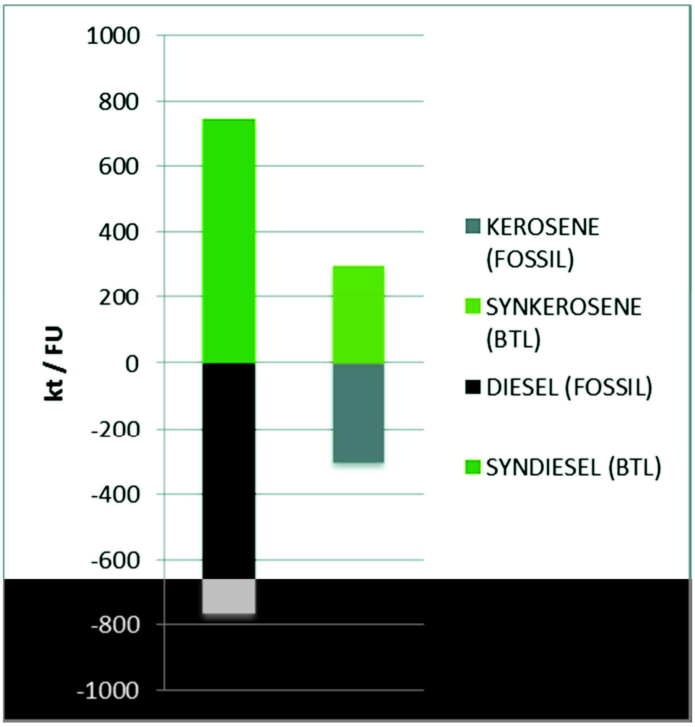

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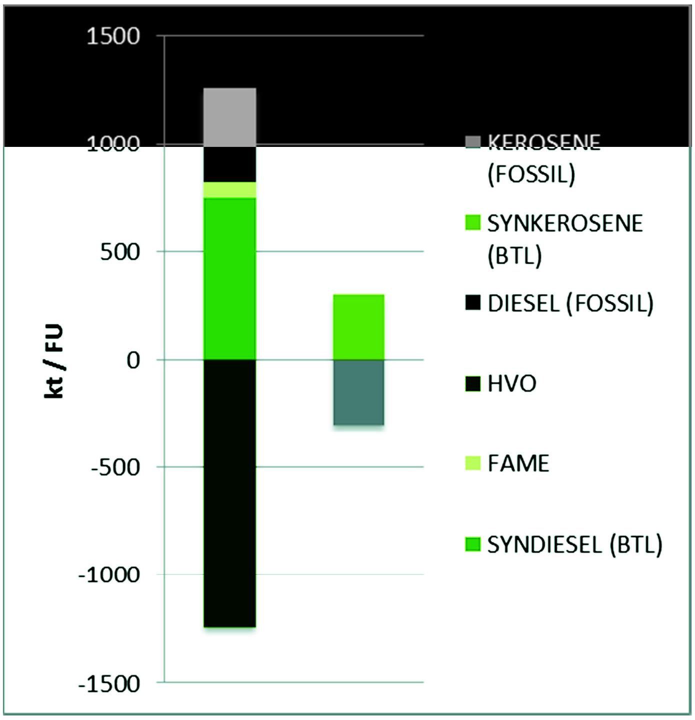

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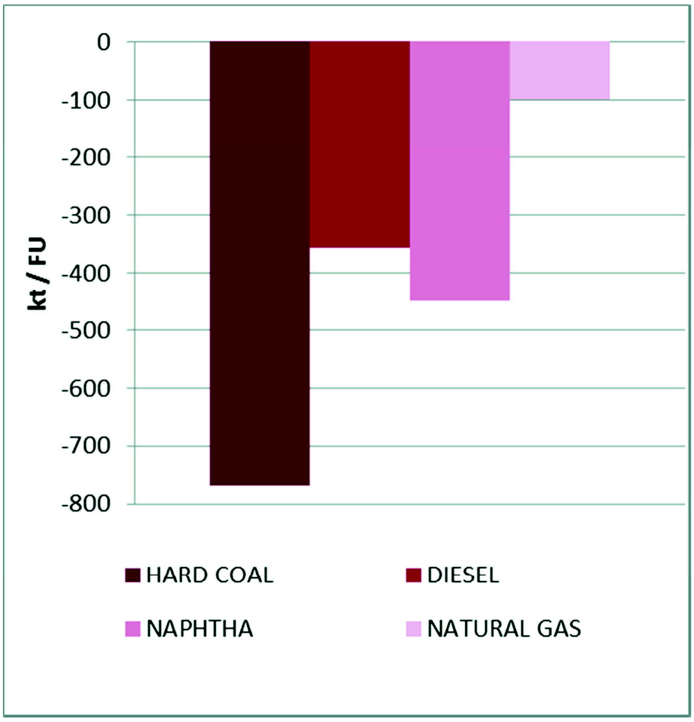

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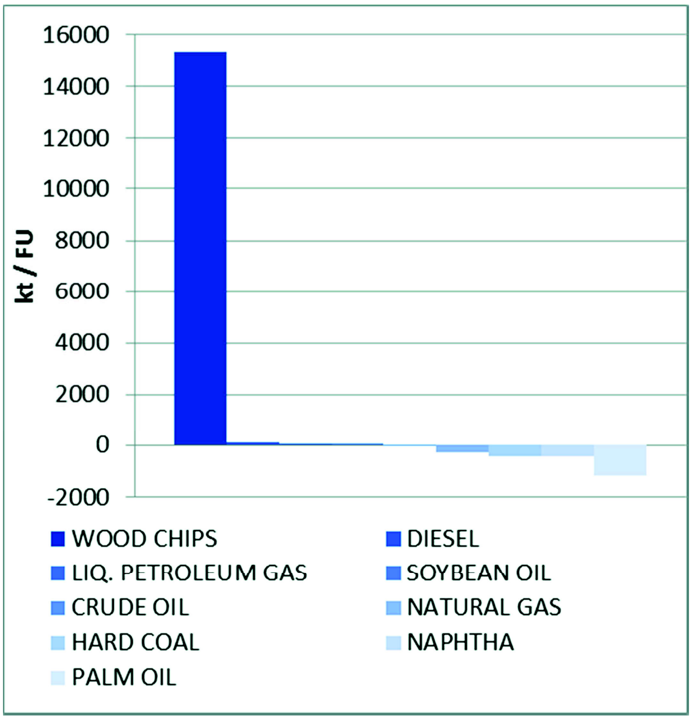

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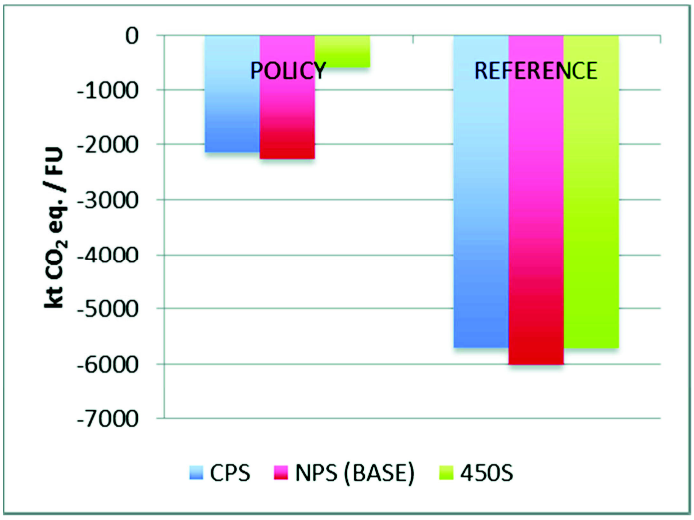

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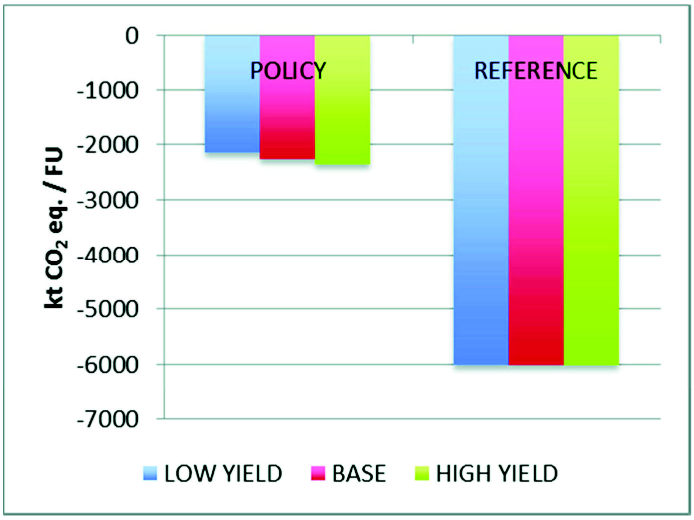

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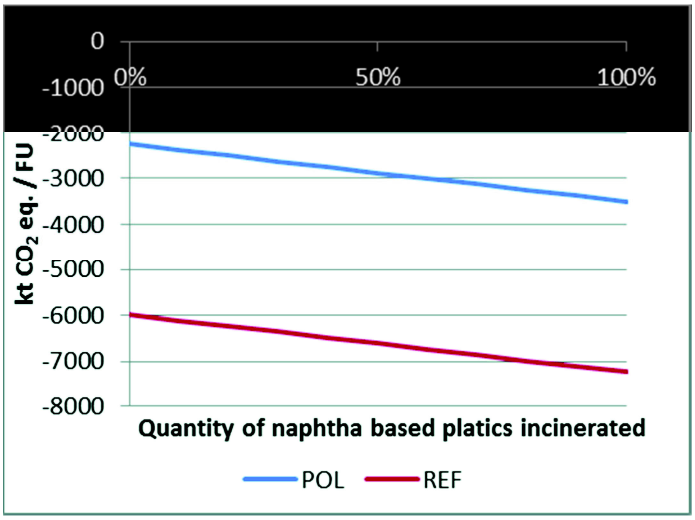
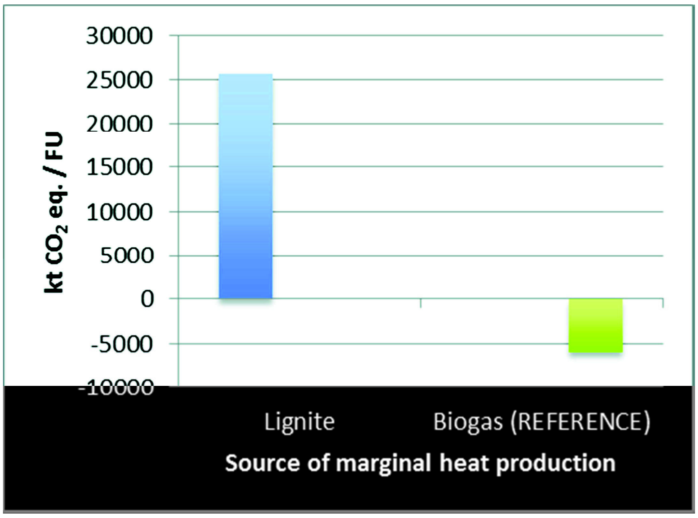


Figure 19



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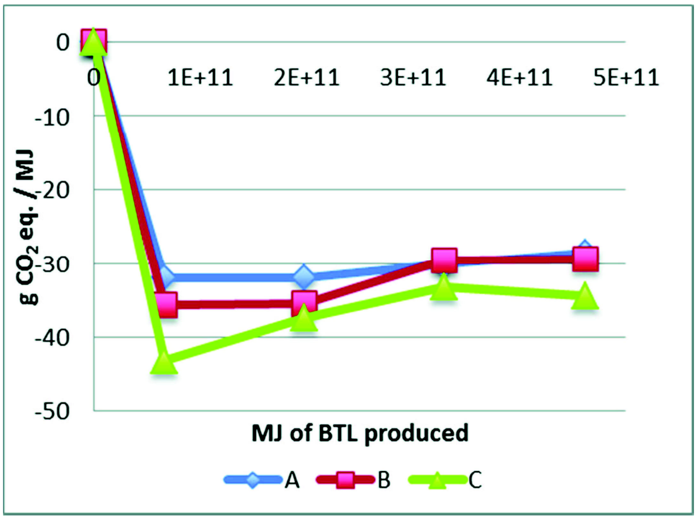

Figure 21

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