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The bioenergies development: the role of biofuels and the CO_2 price[*]

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Abstract

Reduction in energy dependancy and emissions of CO_2 via renewables targeted in the European Union energy mix and taxation system, might trigger the production of bioenergy production and competition for biomass utilization. Torrefied biomass could be used to produce second generation biofuels to replace some of the fuels used in transportation and is also suitable as feedstock to produce electricity in large quantities. This paper examines how the CO_2 price affects demand of torrefied biomass in the power sector and its consequences on the profitability of second generation biofuel units (Biomass to Liquid units). Indeed, the profitability of the BtL units which are supplied only by torrefied biomass is related to the competitive demand of the power sector driven by the CO_2 price and feed-in tariffs. We propose a linear dynamic model of supply and demand. On the supply side, a profit-maximizing torrefied biomass sector is modelized. The model aims to represent the transformation of biomass into torrefied biomass which could be sold to the refinery sector and the power sector. A two-sided (demanders and supplier) bidding process led us to arrive at the equilibrium price for torrefied biomass. The French case is used as an example. Our results suggest that the higher the CO_2 price, the more stable and important the power sector demand. It also makes the torrefied biomass production less vulnerable to uncertainty on demand coming from the refining sector. The torrefied biomass co-firing with coal can offer a near-term market for the torrefied biomass for a CO_2 emission price lower than 20 euros/t_{CO_2}, which can stimulate development of biomass supply systems. Beyond 2020, the demand for torrefied biomass from the power sector could be substituted by the refining sector if the oil price goes up whatever the CO_2 price.

Keywords: Bioenergy, CO_2 price, Refinery market, Electricity market, Optimization.

JEL Classification: C61, Q16, Q41, Q42, Q58

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1 Introduction

Reduction in energy dependancy and emissions of CO_2 via renewables targeted in the European Union energy mix [1] (MEEDDM, 2010) and taxation system, might trigger the production of bioenergy and competition for biomass utilization. Biomass can be used in large quantities to produce second generation biofuels to replace some of the fuels used in transportation (diesel) and is also suitable as feedstock to produce renewable electricity (RES-E) by co-firing (De & Assadi, 2009).

Whereas use of pretreated biomass by torrefaction could significantly increase the RES-E production, it could also raise problems of competition in the use of biomass for second-generation biofuel units. Biomass to Liquid (BtL) technology needs a large quantity (more than 1Mt/y per unit) of torrefied biomass to produce distilates as diesel or jet fuel. From a technological point of view, torrefaction supply converted to BtL technology is the optimal synfuel production chain (Uslu et al., 2008).

Therefore an agent who produces torrefied biomass faces a large demand which will come from two mains sectors in potential competition for the resource: the BtL (Biomass to Liquid) units included in the refineries to produce second generation biofuels and power sector plants who use it to substitute coal. The competition for torrefied biomass will be driven by policies which incitate the power and refinery sectors to use biomass. On one hand, the EU has set a 10% minimum target for the market share of biofuels by 2020 in which the contribution of second generation biofuels from biomass will be considered twice that of first generation biofuels (European Parliament and Council of the European Union, 2009). On the other hand, to promote renewable energies and to reduce greenhouse gas emissions from energy consumption, several policy alternatives such as emissions taxes, tradable emission permits and feed-in tariff[2] for renewable energies have also been proposed in the power sector. Whereas feed-in tariffs are fixed by contract, carbon prices may vary over time and will have a particularly impact on this sector as electricity generation is an important source of total CO_2 emissions. Negotiating contracts with torrefied biomass producer may depend on the variability of the CO_2 market. The CO_2 price is therefore a critical source of uncertainty as it influences the competition among potential users of torrefied biomass. In this paper we focus on this important variable.

In light of the above, this paper shows how the CO_2 price affects demand of torrefied biomass in the power sector and their consequences on the supply of second generation biofuel units. The CO_2 emission price can be interpreted as an emission credit price or as a Pigouvian emission tax. We adress this by determining the CO_2 price threshold for which the investment in torrefaction units and bioenergies productions are profitable. The profitability

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[1] In 2007, the European Commission set the renewables target in the European Union energy mix to 20% of final energy consumption by 2020 compared to 1990. Member states have adopted the package of energy-climate and renewable energy (European Parliament and Council of the European Union, 2009) particularly regarding the operational measures to develop 20% of energy from renewables by 2020.

[2] Feed-in tariffs have been conceived as a measure to promote renewable energies in and of itself, with underlying driving forces including: diversification of energy supply, creation of new industries in the European Union, reducing energy dependance and pollution reduction including green house gases.

of the BtL units which are supplied only by torrefied biomass is related on the one hand to the demand for diesel sent to refineries and on the other hand, to the trade-offs of the power sector driven by the CO_2 price and feed-in tariffs. Through different policy scenarios, the optimal framework of bioenergy development is studied.

We consider a market driven producer of pretreated biomass who is a price-taker. We propose a linear dynamic model of supply and demand. The French case is used as an example. On the supply side, a profit-maximizing torrefied biomass sector is modelized. The model aims to represent the transformation of biomass into biocoal which could be sold to the French refinery sector and the French power sector. The refining sector has been modelized by Lantz et al. (2005), the electricity sector is represented by a dynamic linear investment model of the French power sector and has previously been modelized by Le Cadre et al. (2011). A two-sided (two demanders and one supplier) bidding process led us to arrive at the equilibrium price for torrefied biomass.

Our results suggest that the higher the CO_2 price, the more stable and important the power sector demand. It also makes the torrefied biomass production less vulnerable to uncertainty on demand coming from the refining sector. Indeed, the low oil price projections could prevent second generation biofuels production based on French torrefied biomass from being profitable for the refiner during 2020-2030. Imports of torrefied biomass could be necessary. However, the torrefied biomass co-firing with coal can offer a near-term market for biomass, which can stimulate the development of biomass supply systems. In fact, the torrefied biomass demand could be triggered by the power sector for a CO_2 emission price lower than 20 euros/t_CO_2 until no investment in gas power plants is necessary to replace the decommissioned nuclear power plants. Beyond 2020, the demand for torrefied biomass from the power sector could be substituted by the refining sector if the oil price goes up whatever the CO_2 price.

This paper is organized as follows. After a review of the literature in section two, section three presents models of the supply and demand of pretreated biomass. The linear programing models of the French power and refinery sectors are described for studying the equilibrium price for torrefied biomass and the related break-even CO_2 price. The data used in our model and the scenarios are presented respectively in the fourth and fifth sections. Results of the optimization models are in section six. We conclude our paper with some policy recommendations.

2 Literature

There is a clear market need for new forms of sustainable, clean solid fuels with high energy density. Biomass is key to the development of clean solid fuels. But this sustainable feedstock has to be densified prior to international or national long-distance transportation. Indeed, converting biomass into a densified intermediate can save on logistics and transport costs as Hamelinck & Faaij (2006) prove in their comparison and analyses of different bioenergy chains. In addition, it can improve the efficiency of the final conversion stage. In a sustainable development framework, the pre-treatment is a key step in the bioenergy production and has to be included in the design of sustainable production (O'Brien, 1999) and logistics networks (Neto et al., 2008). Broadly speaking, feedstock costs contribute around 20-65% of the total delivery cost whereas pre-treatment and transport contribute 20-25% and 25-40%, respectively, depending on the location of the biomass resources (Hamelinck et al., 2005). The pre-treatment technology called torrefaction in combination with pelletization is the optimum supply chain from an economic and energy efficiency perspective (Uslu et al., 2008). Torrefaction is a low-temperature treatment process that enables grinding solid lignocellulosic biomass, with limited energy consumption. Solid product has very different properties compared with the parent material. It has a higher energy density fuel than wood pellets (21 MJ/kg instead of 16 MJ/Kg) and lower moisture content (3% instead of 10% for wood pellets). Moreover wood torrefied pellets are competitive with heating oil at current oil prices (60$/barrel) (Mitchell et al., 2007; Uslu et al., 2008). The different sources of biomass studied in this paper are straw, forest residues, co-products from the sawmill industry, co-products for the wood processing industry, and short rotation coppice plantations.

The torrefied biomass can be used in large quantities to produce second generation biofuels to replace diesel used in transportation and is also suitable as feedstock to produce renewable electricity by co-firing torrefied biomass with coal (De & Assadi, 2009). However, the conversion technologies for second generation biofuels are not commercially available so far (IEA, 2008). Although gasification-based routes and the Fischer-Tropsch processes[3] involve mature technologies already used at commercial scale, there is very limited experience in integrating biomass gasification with downstream processes for the production of liquid or gaseous transport fuels (Bioenergy, 2008). The technology and the complete chain are currently in the pilot/demo stage in Europe. First commercial units are expected to go on-line in the next few years (CHOREN, 2007; Berndes et al., 2009). Whereas cellulosic ethanol infrastructure investments have been largely studied by North American studies (Dwivedi et al., 2009; Miao et al., 2010; Kocoloski et al., 2011), no refinery model includes lignocellulosic diesel processes. The need to determine the marginal cost related to the utilization of the biomass requires the use of appropriate models where the complete design of biofuel supply chain is included in the economic analysis. To this aim we adopt the Linear programming (LP) approach which is frequently used to represent the complex scenario of production in the refinery (Alireza & M., 2007).

On the other hand, the co-firing of biomass with fossil fuel is an attractive and cost-efficient near-term option to increase the use of biomass in the electricity production (Baxter, 2005). Whereas the biomass rate of incorporation in power units is technically limited to 10% if biomass is used as a raw material, thermal pre-treatment as torrefaction could significantly increase this rate by more than 50%. This is due to its interesting properties. In fact torrefied biomass is a dry feedstock, with low content of sulfur and ash, and with energy content closed to the coal energy content (between 20.4-22.7 Mj/kg (Uslu et al., 2008) against 15-27 Mj/kg for coal). As a consequence, torrefied biomass can either be used as a substitute to the coal

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[3] The design of second generation biofuel production process includes three steps: the first one is the pre-treatment of biomass by torrefaction, the second is the gasification of the torrefied biomass and the last is the synthesis of diesel with the Fischer-Tropsch process.

in existing coal-fired power plants (co-firing) or can be sold to energy companies that have invested in units of co-generation and collective boilers.

While the torrefied biomass could play a significant role in the bioenergy production, it has never been studied as a source of renewable fuel with a low CO_2 prices in the power sector and an input in a refinery. On the power generation side, Fuss & Szolgayova (2009) have already considered the CO_2 price as an additional trigger to make the switch from an established fossil fuel plant (coal) to a renewable technology profitable, even if the rate of technical change would have been higher. Rentizelas et al. (2010); Fan et al. (2010) also take into account CO_2 uncertainty in the planning of the electricity production. However, existing studies that evaluate the effect of various scenarios for emission allowance price evolution on the future electricity generation mix (Cowie & Gardner, 2007), have not taken into account competition for biomass. On the biofuel side, Babcock et al. (2011) examine the market conditions for the emergence of a competitive cellulosic biofuel sector, and showed that the competitiveness of the sector depends both on the institutional context (subsidies) and on the competition with the traditional ethanol chain, but not on the competition with the other coal consumers. Methods and applications are thus missing to assess the fuel choice flexibility of energy sectors in a competitive context. To our knowledge this is the first attempt to study the competition between the refinery and the power sector for biomass in an uncertain context of CO_2 prices and for different scenarios of fossil fuel prices. In this paper, the economic analysis is focused on a part of the bioenergy production chain defined by Yazan et al. (2011): the pre-treatment (storage, dying and torrefaction) of biomass and the thermo-mechanical conversion to an energy carrier (electricity and biofuels).

3 The models of supply and demand of torrefied biomass

Renewable energy technologies from the power sector and the BtL process need some pre-treated biomass. In this section we develop in this section the modeling approach for electricity generation, oil refining industry, the torrefied biomass supply, and the equilibrum between these three sectors for the torrefied biomass market. Thus, we propose a linear dynamic model of a cost-minimizing sector for electricity generation and the refining industry. They provide us dual values related with torrefied biomass. A model of a profit-maximizing torrefied biomass sector uses these values as a selling price. A two-sided bidding process led us to arrive at the equilibrium price for torrefied biomass.

3.1 Electricity generation

The electricity model developed by Le Cadre et al. (2011) includes all the different power plant types: nuclear power plants, thermal power plants, wind turbines, photovoltaics power and hydraulic power plants (hydraulic water-flow, lake station, and pumping stations). Biomass is used to be burned in small dedicated power plants or in large thermal power plants by co-firing with coal. The aggregated supply faces the demand for electricity on the grid. The load curve is based on a screening curve of the needed capacity with a seasonal and time categorization. In our aggregated approach, we consider four seasons s and three hours τ. We do not modelize the load grid so the demand addressed to the electricity producer represents the final consumption plus the lost load (in the transmission). For the future periods, due to notable climate uncertainty, we consider several levels of demand for each sub-period (time and season). A probability of occurence is associated with each demand.

The supply of electricity is the combined supply from hydro and nuclear power plants as well as the supply of co-firing (coal and torrefied biomass), single fuel and renewable power plants (for a description of the units see (4) in appendix). The power plants are assumed to be cost minimizing[4]. Investments are allowed to cope with increasing generation needs as well as imports and exports.

The objective function The model stimulates the power production problem in face of a power demand uncertainty. The objective function, z_E, is also the minimization of the expected total cost of production. Our expected total cost formulation, TC, over each 5-year step t is:

$$\begin{aligned} z_E = E[TC] = & \sum_a pr_a * (\sum_{u,\tau,s} (l_{\tau,s} * vc_u * P_{u,\tau,s,a} + \sum_f (p_f + p_{CO_2} * e_f) * X^E_{f,u,\tau,s,a} \\ & + (p^{imp}_{\tau,s,a} + p_{CO_2}) * Mp_{\tau,s,a} - p^{exp}_{\tau,s,a} * Xp_{u,\tau,s,a})) \\ & + \sum_u (fc_u + ic_u) * Cap^E_u \end{aligned}$$

with pr_a, the probability associated to the random event a[5]. The cost is divided in different parts: the first one is the sum of operational and maintenance variable costs of each unit, vc_u (proportional to the energy generated, in euros/MWh). $P_{u,\tau,s,a}$ (in MW) is the power loaded on the grid for unit u at sub-period τ, the season s and the demand related to the random event a. $l_{\tau,s}$ (in hours) is the length of the sub-period τ at the season s. To the latter is added fuel and climate policy costs where $X^E_{f,u,\tau,s,a}$ (in MWh) is the need of fuel f, for the unit u at the sub-period τ, season s and the demand related to the random event a. p_f is the price of the fuel f (in euros/MWh), p_{CO_2} (in euros/t$_{CO_2}$), the emission price of CO$_2$ and e_f is the emission factor of CO$_2$ per fuel f. $Mp_{\tau,s,a}$ and $Xp_{u,\tau,s,a}$ are respectively imports and exports of electricity (in MWh), $p^{imp}_{\tau,s,a}$ and $p^{exp}_{\tau,s,a}$ the selling prices (in euros/MWh). The fourth part of the objective function is the total fixed cost where fc_u and ic_u are respectively the operational and maintenance fixed cost and the investment annuities (in euro/MW).

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[4] For a literature review on the modelization of the optimum electricity generating portfolio, see Rentizelas et al. (2010).

[5] For the need of modelization, we propose three different demands representing years with different climate conditions as observed in France during the last five years. So we have a climate uncertainty which impacts the power demand under three ways. A probability is associated to each random event a of the demand. For more details, see Le Cadre et al. (2011).

Cap_u^E is the nominal capacity of production (in MW). The investment cost is calculated as a series of equal annuities, spread over the entire lifetime of the specific technology.

We minimize the expected cost under the following constraints.

The power supply As mentioned before, we assume exogenous demand of electricity. For each random event, the demand has to be satisfied at each sub-period by the aggregated power loaded on the grid such as:

$$\sum_u P_{u,\tau,s,a} + Mp_{\tau,s,a} \geq dem_{\tau,s,a} - AP + \sum_u Xp_{u,\tau,s,a} \ \forall \{\tau, s, a\}$$

where the demand depends on the sub-period, the season and the alea. $AP = \sum_{u1} P_{u1,\tau,s,a}$ is the sum of must-run supply from the units[6], u_1, with $u_1 \in u$.

Capacities contraints The production level is limited by installed capacities for all the units expected for the hydraulic power plants. For these units, we have to take into account the cumulated energy in the reservoirs (Le Cadre et al., 2011). We get for the units u:

$$capi_u^E + Inv_u^E = Cap_u^E$$
$$P_{u,\tau,s,a} \leq Cap_u^E * disp_{u,s} \ \forall \{u, \tau, s, a\}$$

where $capi_u^E$ is the initial capacity, Inv_u^E, the capacity investment for unit u over a one-year horizon (8760h) and $disp_{u,s}$, the availability rate of the unit u at season s. We take into account the decommissioning of the different power plants over the time.

The need of different fuels For each unit, we allow one or several fuels to be used. Thus, the thermal power plant could substitute coal by torrefied biomass or raw biomass. We employ a linear energy efficiency conversion process, i.e., the power plant has a constant output efficiency $\eta_{f,u}$ given any fuel distribution. $\eta_{f,u}$ is the yield matrix per fuel associated with all units. The co-firing power plants can use fossil and biomass. The demand function of fuel f can be written as follows:

$$\sum_f \eta_{f,u} * X_{f,u,\tau,s,a}^E = P_{u,\tau,s,a} * l_{\tau,s} \ \forall \{u, \tau, s, a\}$$

with a constraint on fuel availability such as $\sum_{u,\tau} X_{f,u,\tau,s,a}^E \leq fuelav_{f,s}$ where $fuelav_{f,s}$ is the availability of fuel f at season s.

At the equilibrium between the demand and the supply of electricity, we get the price for which the power sector is ready to buy torrefied biomass at each step t and the demands for torrefied and raw biomass.

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[6] The power production of combined heat and power plants is included in the must-run supply (as the hydraulic water-flow station). Indeed, the combined heat and power production is generally dictated by heat heat demand, not electricity demand so the fuel use is contingent on the heat demand. In France, different call for tenders define the settlement of these power plants. Thus, we consider, from a technical point of view that the heat and also power productions provided by these units are constant. We have summed up the shares of fuel quantities used for power production per combined heat and power plants in France. For more details, please contact the authors.

3.2 Refining industry

The model of the refining industry is based on the OURSE (Oil is Used in Refineries to Supply Energy) model (Lantz et al., 2005). The refining model is able to simulate the impact on the refining industry of changes in the crude oil supply (in costs and qualities) as in the oil product demand (in terms of level, structure and specifications). It also enables an assessment of the consequences of a carbon emission regulation (bounds and taxes) as well as the adoption of various kinds of alternative fuel policies. The OURSE model based on a linear programing model, is frequently used in the refining industry, both for refinery management and investment analysis, since a marginal cost pricing is relevant for the oil products. The model includes the following equations: (i) balances of intermediate and final products, (ii) demand equations, (iii) product quality control, (iv) capacity constraints, (v) crude oil supply and (vi) pollutant emission (Babusiaux, 2003). The objective function is to minimize a global cost function.

In our simulation, the OURSE model[7] is adapted to represent a typical upgraded refinery. It includes diesel production with the Fischer-Tropsch process. The model has been calibrated to modelize a 10 Mt per year refinery with a typical French demand (**?**). In our modelization, we have taken into account the compulsory share of biofuel incorporation in the pool of final products (diesel, gasoline...). As a consequence, the biodiesel can be produced by first generation biofuel units (mostly refinery of rapeseed grains in Europe), second generation biofuel units (BtL units in Europe) or the biodiesel could be produced from imported palm oil. According to the current legislation (we will focus on this topic in part (4.2)), the refiner can free itself from the incorporation constraint by paying a tax which is proportional to the non-produced quantities of biofuels. This tax system has been introduced in the objective function, noted z_R. This function is the sum of the supply cost (CIF price of crude oil), the processing and the investment cost and (eventually) pollution permits or taxes. For all saturated equations, the model provides a dual value different from zero at the optimum. This is particularly true for the equation of torrefied biomass availability. We note λ_{TOP}, the shadow value related with this equation. This variable measure the marginal cost related with the utilization of the torrefied biomass, TOP, such as: $\lambda_{TOP} = \partial z_R / \partial X^R_{TOP}$

3.3 Torrefied biomass supply chain

We consider a linear dynamic optimization model with an agent who decides to invest in the pre-treatment process by torrefaction to densify the biomass and reduce logistic costs. We consider he is price-taker. The agent will invest in torrefaction units and will produce if and only if his payoff is positive and greater than the alternative which is to sell no pre-treated biomass to the power sector[8]. The model aims to represent the transformation of biomass into biocoal which could be sold to refineries to supply the BtL units and power plants of the power sector. We model units that are able to use different types of biomass (wood, straw, short rotation crops). The final product is the remaining solid, which is often referred to as

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[7] For a comprehensive description of the model see Tehrani & Saint-Antonin (2008)

[8] The refining industry can buy only torrefied biomass to supply its BtL units.

torrefied biomass or biochar. This product can be finely ground to a lower energy cost and be injected under pressure in the gasifier.

The objective function The optimal investment decision is to determine the profit function for a risk neutral agent. The expected payoff over a period is defined such as:

$$\begin{aligned} z_T = E[\pi] &= \sum_a pr_a * (\sum_b pf_E * Q^{T,E}_{b,a}) + \sum_b pf_R * Q^{T,R}_b \\ &- \sum_a pr_a * (Mp^T_a * p_M + \sum_b p_b * Q_{b,a} + \sum_j pd_j * Qd_{j,a}) \\ &- \sum_m (op_m + ic_m) * (capi^T_m + Inv^T_m) \end{aligned}$$

In our modeling approach, we have two consuming sectors for TOP: Electricity (E) and Refinery (R). Both sectors have different quality constraints, so the quantities of each torrefied biomass will differ in function of the raw biomass composition and cost. pf_E and pf_R (in euros/t) are the selling price for the Electricity generation sector and the Refinery sector. p_M is the imported market price (in euros/t). p_b et pd_j are respectively the buying prices of biomass and fuel (gas, electricity) (in euros/t). $Q^{T,E}_{b,a}$ (in tons) is the quantity of mixed different torrefied biomass b to supply the power sector demand related to the random event a. Mp^T_a is the imported quantity of torrefied biomass (in tons). $Q_{b,a}$ and $Qd_{j,a}$ are two variables determining the need for raw biomass and fuel at period t. op_m and ic_m are respectively, operating and investment costs of each productive unit m with $m \in \{Dryer, Torrefaction, Combustion, Pelletization\}$. $capi^T_m$ (in t/y) is the capacity of the productive unit m and Inv^T_m, the level of investment.

The irreversibility of the investment is introduced through the capital cost, which depends not only on the ongoing investment at period t but also on the capital already invested during previous periods.

The equations for the intermediate and final products balance the input quantities with the output quantities for each product. The material balance for the intermediate product expresses that the production is equal to the internal use.

Product quality constraints The final products must meet a number of legal and technical quality specifications such as the ash content (for torrefied biomass for cogeneration), sulfur (for co-firing) and calorific value. Linear constraints are obtained by multiplying the intermediate product quantities (in weight term) by their qualities and by setting a minimum or a maximum specification to the final product. When there is no linear relationship, this characteristic is replaced by an index which can be use in a linear constraint.

The following equation stands for a maximum specification of quality whose pooling rule is linear in weight terms such as the ash content of torrefied biomass for the co-firing sector:

Ash content

$$\sum_{b} as_b * Q_b^{T,i} - qs_i * X_{TOP}^i \leq 0 \qquad (1)$$

where $Q_b^{T,i}$ is the b-th component quantity, torrefied for sector i. as_b is the ash content of the biomass, b; qs_i, the ash specification for sector i and X_{TOP}^i, the demand in torrefied biomass from sector i.

We assume that the ash component and composition of the pool of torrefied biomass for the production of second generation biofuels is greater than or equal to 6%. For other sectors, the ash end composition must be constant, the lowest possible and lower than coal.

Sulfur content Sulfur vapor rises into the boiler then condenses and solidifies. In the combustion of biomass, part of the sulfur contained in the material is converted into sulfur oxides, pollutants that energy companies seek to reduce emissions. A maximum amount of sulfur is required for this sector as well as for heating homes. The constraint equation is of the form (1).

The energy content of the blending The energy content of the blend should be between 20 and 22 MJ/kg and should be constant for co-firing with coal in order not to decrease the boiler efficiency.

Capacity constraints The flow of biomass entering the unit is limited by its production capacity. Thus, the production capacity is expressed as follows:

$$\max\{Q_b^m\} \leq capi_m^T + Inv_m^T$$

We assume that capacity expansions are the result of the addition of processing units with given technical and economic size. Thus, costs are proportional to capacity increases.

Raw biomass availability constraint The raw biomass is first processed in the dryer unit. This unit supplied by natural gas[9] and torrefaction gas, splits biomass into dried biomass and flue-gas. The total quantity of each raw biomass to be processed must be equal to the sum of the different quantities processed through different sets of uses. The availability of each raw biomass is limited (we will focus on this topic in part (4.1)).

3.4 The equilibrium

The equilibrium price between the supply and demand of torrefied biomass is obtained by a two-sided bidding process within Walrasian price adjustment. First, we adress an initial price pf_E and $pf_R = \lambda_{TOP}$ to the both sectors: generating electricity, E and refining, R. After

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[9] The natural gas consumption is low as we consider here, in this paper, an autothermic process. The feedstock is used as utility fuel and the natural gas is used to start the process of torrefaction. As a consequence, the owner of the torrefaction unit should not have to pay for CO_2 emissions of the process.

optimization, these sectors address to the supply side a demand of torrefied biomass and a dual value associated with the constraint of torrefied biomass availability. They represent the new values of buying price. If the torrefaction sector profit is negative, we add at the initial price pf_i the shadow value associated to the demand constraints. We repeat these steps until reaching the equilibrium price of the torrefied biomass, pf_i^* for both sectors.

At the equilibrium, we have, for all a:

$$Q_{b,a}^{T,E*} + Q_b^{T,R*} + Mp_a^{T*} = X_{TOP,u,\tau,s,a}^{E*} + X_{TOP}^{R*}$$

All the optimization models for biomass torrefaction, electricity generation, and the refining industry have been written in the GAMS language associated with the Cplex optimization code (1,800 equations, 7,500 variables for the refining model; 10,080 variables for the electricity generation model; 370 equations and 310 variables for the torrefaction model).

4 Economic analysis and data

Nowadays, biomass accounts for around 10%[10] of energy needs in France and it is mainly used for household heating (European Commission, 2010). Because of the resource availability, there is a potential development of bio-energy. The competition has raise several problems about land use between agricultural production and crop dedicated production for the first generation of biofuel. For the second generation of biofuel, we do not have a competition for land use but the bio-energy users (refining industry, electricity producers, iron and steel industry, etc.) should compete for biomass supply. Furthermore, different incentive schemes characterize the development of renewable energy (production or use) in each sector. In this context, the objective of our empirical application is to study the use of torrefied biomass in France through the modeling framework that we have presented above. We consider here only two demands coming from the refining and the power sectors as they are the most promising demanders in the short term. The data employed in this study consists of biomass potential, policies and technico-economic data on the technologies. The latter are used to calibrate our model.

4.1 Biomass potential

The resource data on volumes are from the French project REGIX (Unified references, methods and experiences to enable a better assessment of potential agricultural and forestry lignocellulosic resources for bioenergy in France), MEEDDM (2010) and RENEW (2008, 2004). We present the potential available for energy utilization in table (1). We have five types of biomass: wood industry co-products (OTH1), forest residues and coppice under timber forest (WOOD), straw (STRA), Short Rotation Crop from Agriculture (SRCA), Short Rotation Crop from Forest (SRCF). They have different physicochemical properties that we take into account in our model (cf. table 5 in appendix). Thus, the torrefaction model could operate a trade-off between composition and costs.

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[10] 13.95 Mtoe of the energy production come from biomass and waste in 2010 in France.

4.2 Environmental policies

French policies for electricity production from renewable resources We do our analysis based on French RES-E promoting policy instrument, namely feed-in tariffs (FIT). The hydro power production is computed as RES-E production, but it is not subsidized. Both policies include CO_2 emissions price as climate policy. According to MEEDDM (2010), the FIT levels fixed over the next 20 years are summed up in table (6) in the appendix.

A compulsory production of BtL The Directive (2009/28/EC) (MEEDDM, 2010) requires that the target of 10% of biofuels is achieved in 2020. The production of first generation biofuels production account for around 7% of automotive fuels in 2010 (see table (7) in appendix) and this share could not easily increase because of the conflict over land use. So the target could be reached with second generation biofuels production. Moreover, article 21 of the Directive (2009/28/EC) states that 'the contribution made by biofuels produced from wastes, residues, cellulosic materials and non-food lignocellulosic materials (second generation biofuels) is treated as two times the other biofuels'. To achieve these objectives of incorporation, we assume the French government will continue to use two economic tools. The first one is the tax exemption for partial exemption from the domestic consumption tax (ICT) that applies to petroleum products in quantities set by the State and is allocated for agreement as to certain industries, for bidding. The second tool is the General Tax on Polluting Activities (TGAP) which was created by the Finance Act 2005 to encourage the incorporation of biofuel. An incorporation rate is set each year and the distributors who make the fossil fuels on the market must be at or above the threshold for inclusion. These two tools act in a complementary way. As the refining model is able to simulate the consequences of adoption of alternative type of policies, we take into account the French taxation regarding biofuels.

Table 1: French biomass potential forcasts

Type of biomass	Humidity	Calorific power	Quantity of biomass available for energy purpose		
	%	MJ/kg	Mt/year		
			2006 (1)	2015	2020-2030
WOOD	40	19.75	23.76	28.91-31.66	31.36 - 37.5
OTH1	0	19	0.3	1.5	2.7
STRA	15	16.5	1.23	1.25	2.5
SRCA	25	18.12	-	-	2
SRCF	50	19.75	-	-	3.5

(1) Observed
Source: MEEDDM (2010); RENEW (2008, 2004).

4.3 Main input of the models

The French power sector The main inputs of the French power model are the available capacity, the costs of the power plants, and the availability rates. We have taken into account the different types of power plants and the future technologies which should be settled. All these units and available capacities are summarized in table (4).

The availability rate as a function of our seasonal decomposition, operational life-time of units and the yields come from RTE[11](Réseau de transport d'électricité, 2009). The data of capital and operation and maintenance costs come from (MEEDDAT, 2008; DGEC, 2011; EDF, 2011). Costs for hydroelectric and renewable generations were obtained respectively from RTE and EDF (2011).

Regarding the present capacity of each generation technology, RTE has published public data on all generating facilities for 2008. Concerning potential capacities, certain generation technologies such as cogeneration, wind, solar, and hydroelectric (MINEFI, 2006) have maximum potential generation capacities, which are constrained by resources. Data on maximum wind generation capacity and hydroelectric potential were obtained from (DGEMP-OE, 2008). For the planning of power plant phase-out, see DGEMP-OE (2008).

The assumption of the *Annual Energy Outlook* (EIA, 2009) also provides an estimate of the costs of modifying a coal-fired generation unit to allow biomass co-firing. Like Levin et al. (2011), we assume a conversion cost in the middle of the range and following Hansson et al. (2009), we allow up to 10% of current coal generation capacity to be converted to biomass co-firing. Moreover, torrefied biomass is considered a perfect substitute of coal.

The French refinery sector The model is designed to operate over the period 1997-2030, the BtL process is integrated in one representative refinery of the multi-refineries composing the French sector. This process is designed as follows: synthesis gas is first produced via the gasification of torrefied biomass. After purification, syn-gas can be converted to synthetic diesel or jet fuel using *Fischer-Tropsch* synthesis of hydrocarbons. The final stage is the hydro-treatment. The products of this chain are mostly middle distillates like diesel and naphtha and possible co-products such as steam and/or electricity (Lantz et al., 2005). The representative unit has a capacity of treatment of 10 Mt/y. Moreover, the model allows the blending of biomass-based derivatives (alcohol and ester) products. The minimum request of biofuels stands for gasoline and diesel oil. It is defined in energy term. As mentioned before, the second generation product accounts for two times their energy value in this constraint.

The torrefaction sector The choice of torrefaction technology was done from descriptions of technologies proposed by Uslu et al. (2008); Bridgeman et al. (2007); Bergman (2005); Bergman et al. (2005a,b). We focus on the ECN torrefaction process which is the more detailed technology available in the literature. The mass yield of this step is estimated to be between 80 and 90% (anhydric weight loss)(Bergman et al., 2005a). The torrefied biomass has physical properties very similar to those of coal. We modelize net mass flows (in tons)

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[11] RTE is a French company with public capital and has been a subsidiary of EDF since 2005.

corresponding with torrefaction of biomass.

The discount rate is a parameter of the model and has been assumed to be equal to 8% for the three models.

5 Scenarios for 2030

We investigate three scenarios which are partly derived from the IEA World Energy Outlook (International Energy Agency, IEA, 2010) scenarii which are differentiated by the assumptions about government policies. Fuel prices are directly based on IEA World Energy Outlook. French electricity and fuel demands have been built by using IEA initial data.

- The first scenario refers to 'The New Policies Scenario'. It takes into account the broad policy commitments that have already been announced and assumes implementation of national pledges to reduce greenhouse-gas emissions by 2020 and to reform fossil-fuel subsidies.
- The second scenario refers to 'The Current Policies Scenario' (equivalent to the Reference scenario of past outlooks). It takes into consideration only those policies that had been formally adopted by mid-2010.
- The third scenario is the 'The 450 Scenario'. It assumes implementation of the high-end of national pledges and stronger policies after 2020, including the removal of fossil-fuel consumption subsidies, to achieve the objective of limiting the concentration of greenhouse gases in the atmosphere to 450 parts per million of CO_2-equivalent and global increase to 2°Celsius.

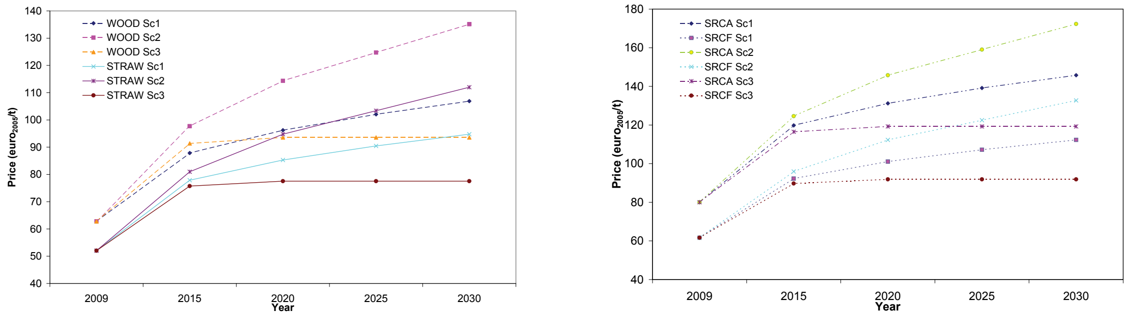
Assumptions about population and economic growth are the same in each scenario (see appendix for more details).

5.1 Fuel prices

The projections of prices over the period 2015-2030 are presented in table (8) in the appendix. We convert the fuel prices presented in dollars_{2009} by the International Energy Agency, IEA (2010) to euros_{2005} which is the year of our model's calibration. We use an exchange rate of euros/dollars and both French and American Consumer Price Indexes (CPI). They are determined by the Federal Reserve Economic Data (FRED) for USA and Institut National de la Statistique et des Etudes Economiques (INSEE) for France.

Scenario 1 is characterized by a constant growth of 2.8% for oil prices on the entire period to reach 67.0 euros/baril in 2030. In the scenario 2, we have a constant growth of 3.7% for oil prices on the whole period to reach 79.3 euros/baril. Finally, scenario 3 is characterized by a constant growth of 3.7% until 2020 then the oil price stagnates to 54.8 euros/baril.

Regarding the set of biomass prices, Babcock et al. (2011) emphasize that the feedstock price is a key driver of the production cost of second generation biofuels, this price being determined locally due to the fact that biomass transportation costs are high with respect to the biomass value and that there is no existing market for cellulosic biofuel feedstock. So we use the selling prices determined by the French project REGIX which corresponds to full costs including the material, the harvest and packaging costs, storage and transport. We assume, for the projections, that biomass prices follow the mean annual growth rate of crude oil as oil is the main variable cost of production. Our projections of biomass prices are presented in figures (1a,1b).



(a) Wood and Straw prices

(b) Dedicated energy crops prices

Figure 1: Biomass price assumptions by scenario

We note that the boilers of thermal power plants can only be provided with dry biomass. However, the torrefaction units will buy biomass with the level of humidity indicated in table (1). Indeed, the first step of the torrefaction process is the drying of biomass. So the WOOD, STRAW, SRCA, SRCF prices presented in figures (1a,1b) are respectively around 30, 15, 20 and 35% lower than dry biomass price paid by the power sector.

5.2 Demand growth scenarios for the power sector by 2015-2030

The demand per period was determined from historical data for the French sector, from 2005 to 2009 furnished by the French electric network of transport, RTE [12]. The variation of the demand during the different sub-periods τ and season s in the past five years reflects the temperature variation. So we estimate three different levels of demand, $dem_{\tau,s,a}$, per period related to three different probabilities of occurrence a (*c.f.* table 9 in appendix). For the projections, we propose three scenarios of demand over the period 2010-2030: low, medium

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[12] http://www.rte-france.com/fr/nous-connaitre/qui-sommes-nous/information-in-english

and high levels of electricity consumption from the economic sectors. We have an average annual growth rate per scenario over each five year step t[13].

5.3 Policy instruments

We examine two different policy instruments: emission price and feed-in tariffs (FIT). Emission price is a climate policy instrument, and FIT is RES-E policy instrument. The FIT is a price that is paid for RES-E production instead of the electricity price. If the power production of unit u is subject to FIT, we consider that it will be deduced from the variable cost, $vcost_u$. The variable cost for plants in the case of FIT, $p_{fit,u}$, is also:

$$vc_u = vcost_u - \max\{0, p_{fit,u}\}$$

We assume that FIT is not given for power generated from biomass in co-firing. Indeed, it is currently the case in France.

The climate policy, i.e., emission price is targeted at the fossil fuel used in co-firing and at the fossil-fueled single power plants. We measure the CO_2 emitted by different units of the power sector using the emission factors summarized in table (10) in the appendix. The emission price is paid for every unit of CO_2 emissions originated from energy production. The renewable fuel is accounted for as carbon neutral in the climate policy considerations.

6 Results

6.1 The purchase price of torrefied biomass by the refining sector

We first consider the price for which the refinery would be willing to buy torrefied biomass. As the first commercial process of BtL is expected to go on-line around 2020 (Berndes et al., 2009), we study the BtL supply in a refinery scheme from 2020 to 2030. For this purpose, we use a typical upgraded refinery (with a fluid catalytic cracking unit) which processes 10 Mt of oil per year and for which the production is oriented on middle distillate (jet fuel, heating oil, and diesel oil). Following the current and future incentive for biomass use, the incorporation of BtL in the diesel oil pool is compulsory, as previously mentioned. After optimization, the refining model gives the refinery throughput and the shadow values associated to the saturated constraints. Thus, from the diesel oil pool equations, we get the shadow value associated to the torrefied biomass demand constraint (*cf.* table(2)). Because we use a linear programing approach, this value is the price for which the refiner is ready to pay for getting the torrefied biomass.

The shadow price of torrefied biomass is positively impacted by the Brent price increase (*cf.* table (2)). The diesel oil shadow price increases when the crude oil price increases. Indeed, the oil price increase pushes up the value of the diesel pool components and in the same way, the shadow value associated with torrefied biomass whom the incorporation is

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[13] For more details, see (Le Cadre et al., 2011).

compulsory. Nevertheless, the shadow value increases less faster than the oil price because the torrefied biomass is just one component of the diesel pool. In our case, the shadow value increases to around 1.4% between 2020 and 2025 and of around 1.9% between 2025 and 2030 for scenario 1. In scenario 2, the increase is around 2% and in scenario 3, the shadow value is constant.

Then, we study the impact of CO_2 tax on the shadow value related to torrefied biomass in the refinery sector. In our model, we have a representative refinery unit of 10 Mt/y emits 1.8 Mt/y of CO_2. We study the sensitivity of the torrefied biomass shadow value to a CO_2 tax in a BtL unit and we do the analysis for the year 2030. The variation range of the shadow price is from 195.2 euros$_{2005}/tto197.4euros_{2005}/tforaCO_2$ price which varies from 25 to 166.6 euro$_{2005}$/t$_{CO2}$. On the same way, the introduction of CO_2 tax pushes up the cost of diesel production and increases the shadow value of the torrefied biomass. In our modelization (cost minimization under demand constraint), we have a low impact of the tax on the shadow value of diesel and therefore we observe low impact on the shadow value associated to torrefied biomass. A CO_2 tax seems to be less restrictive than a compulsory biofuels production. However, a profit-maximization model allowing imports of intermediate products could lead to different results[14].

6.2 Breakeven CO_2 prices and equilibrium selling prices of torrefied biomass.

Our approach can be decomposed into two successive steps. First, we determine the market price, pf_R^* for which the torrefaction sector could produce and sell the quantity, X_{TOP}^R, addressed by the refinery sector over the period 2020-2030. Above this price, the BtL units could be supplied with torrefied biomass at a price pf_R^* for which the expected payoff of the torrefaction sector is positive. Then, we compare pf_R^* with the shadow price of the torrefied biomass (table (2)) in order to know if the BtL units will buy the resource at this price or not. Secondly, we find the trigger price, $p_{CO_2}^E$ for the power sector. That is, the price in which the co-firing of torrefied biomass with coal starts so the demand, $X_{TOP,\tau,s,a}^E$ from the sector $i = E$ is positive. We get the equilibrium selling price, pf_E^* at this point. The market prices to both sectors and the break-even CO_2 price are summarized in table (3).

For a CO_2 price inferior to $p_{CO_2}^E$ price, there is only one demand addressed by the refiner to the supplier of torrefied biomass (we remember only two demands coming from the power

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[14] For example, the refiner could decide to import components for blending instead of paying the CO_2 tax.

Table 2: Shadow price of torrefied biomass from the refining model, λ_{TOP} (in $euro_{2005}/t$)

Scenario	2020	2025	2030
Scenario 1	171.8	184.2	202.5
Scenario 2	194.6	215.7	239.8
Scenario 3	153.4	153.4	153.5

and the refining sector are studied in our paper). However, the supplier cannot always supply the refiner with torrefied biomass for the selling price that it proposes over the period. In fact, λ_{TOP} is inferior to the market price, pf_R^*, until 2025 in scenario 1. The refiner gives a lower value to the torrefied biomass than the market price. Without any additional subsidies, the supplier would not sell biomass to the refiner who should import TOP (if it is cheaper) to reach the target of biofuel production. In period $t = 2030$, $pf_R^* = \lambda_{TOP}$ so the expected payoff of the torrefaction sector is positive and it is finally profitable for the refiner to buy TOP. Under scenario 2 which corresponds to the reference scenario, pf_R^* fits with the shadow price of torrefied biomass for the refinery sector all along the period ($pf_R^* = \lambda_{TOP} \forall t$). In this case, the BtL units could be provided with TOP as the payoff of the torrefaction sector is positive for these selling prices. Finally, when the oil Brent price is too low over the period, pf_R^* is higher than the shadow price for torrefied biomass. BtL units could not be supplied with TOP produced by French torrefaction sector for the marginal cost proposed by the refinery sector. This analysis raises the issue of the French torrefaction sector profitability over the period 2015-2030 if the oil Brent price goes down (scenario 3) or follows the trend of scenario 1.

Regarding the power sector, different sources of energy can supply the demand of electricity in function the CO_2 price. We use our model to look for the break-even CO_2 price to determine the torrefied biomass demand addressed by the power sector to the torrefaction units. Our model gives an equilibrium price pf_E^* related to this threshold. For the three scenarios of oil Brent price, the power sector addresses a demand as soon as 2015, from a break-even CO_2 price, $p_{CO_2}^E$ around 20 euro/t$_{CO_2}$. Until 2020, the market price remains relatively stable between 210 and 220 euro/t. Over 2025-2030, regarding our assumptions on French nuclear plants decommissioning[15], the optimization of the power production leads

Table 3: Equilibrium prices for torrefied biomass and break-even CO_2 price (in euro$_{2005}$/t)

Scenario	Price	2015	2020	2025	2030
Scenario 1	Refinery: pf_R^*	-(1)	186	188.4	202.53
	Demand Electricity: $p_{CO_2}^E$	18	18	61	61
	Electricity: pf_E^*	213.3	215	217.7	219.0
Scenario 2	Refinery: pf_R^*	-	194.6	215.8	239.9
	Demand Electricity: $p_{CO_2}^E$	18	17	78	59
	Electricity: pf_E^*	213.2	218.9	221.4	223.9
Scenario 3	Refinery: pf_R^*	-	184.9	184.9	184.9
	Demand Electricity: $p_{CO_2}^E$	19	21	23	25
	Electricity: pf_E^*	212.6	213.3	213.3	213.3

(1) The first commercial process of BtL is expected to go on-line around 2020.

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[15] We consider here the retirement of nuclear plants at end-of-life. It is one case study. Another case study has been modelized with the renewal of the nuclear fleet. The results are not presented in this paper as they are less sensitive to the CO_2 price variation. To measure the impact of CO_2 tax, we focus on the more

to the investment in gas units and windmills (with FIT for electricity production). Figure (2) shows the electricity production by power plants over 2030 for the three scenarios and illustrates the consequences of the nuclear phase-out on the French power production. These investments impact the break-even CO$_2$ price level. $p^{E}_{CO_2}$ jumps to more than 60 euro/t$_{CO_2}$. Thus, the demand of torrefied biomass is triggered only by a higher carbon price in scenario 1 and 2. However, for a low oil price, the trigger price $p^{E}_{CO_2}$ stays low all through the periods t so torrefied biomass could be delivered to the power sector offering to pay pf^{*}_{E}. Coal-burning plants use torrefied biomass which reduce investment and production from gas units (see scenario 2 on figure 2).

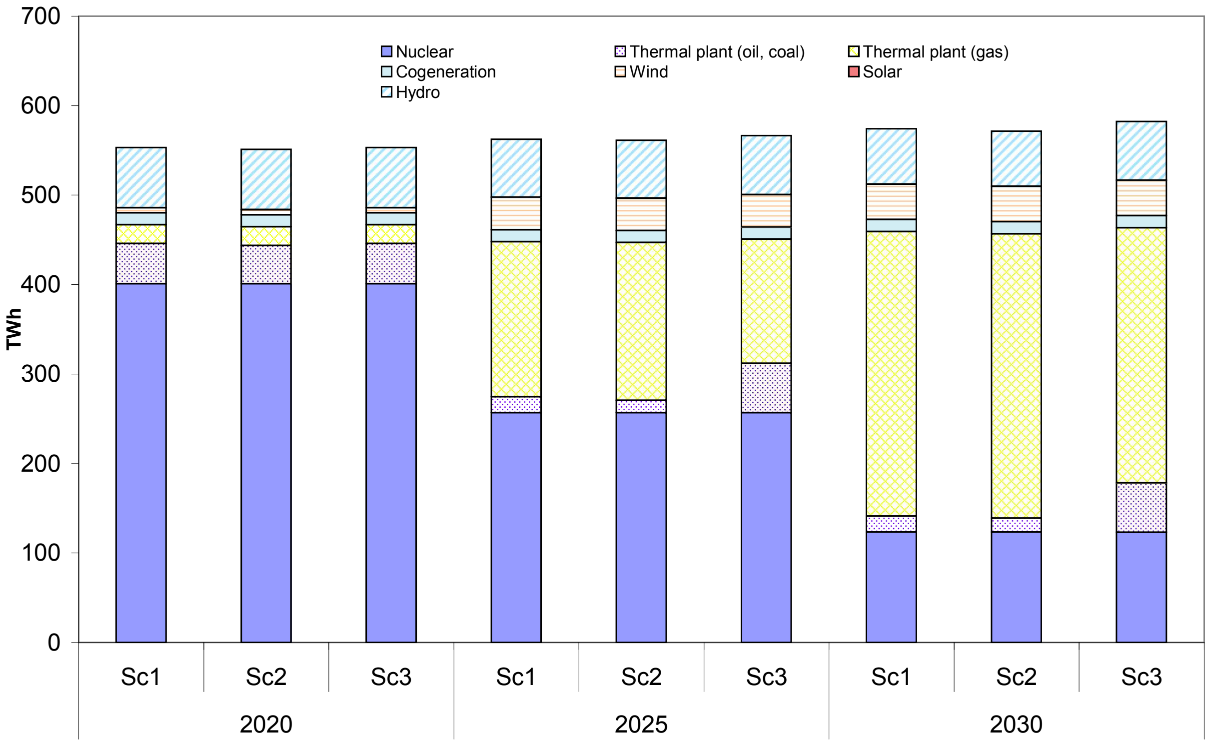

Figure 2: Expected electricity output by generation technology in the three scenarios with break-even CO$_2$ price, $p^{D,E}_{CO_2}$.

In conclusion, we have defined the market prices to both sectors and the break-even CO$_2$ price for which the demand of torrefied biomass from the power sector is triggered. We need now to compare this price with the CO$_2$ price projections related to the IEA scenarios in order to define if so or not, the power sector demand could pave the way to second generation biofuel production.

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sensitive scenario which is the renewal of the nuclear fleet with the more profitable units for the power sector: thermal power plants (with gas) and renewable energies.

6.3 Paving the way to second generation biofuel production with the co-firing

In this part, we compare the CO$_2$ price $p^E_{CO_2}$ at a given future time period t with the expected CO$_2$ price for the three scenarios. As a reference, we will use the CO$_2$ price projections (table (8) in appendix) for the three scenarios of fuel prices detailed in the above section. Further details of carbon pricing and how it is modeled can be found in International Energy Agency, IEA (2010).

In scenario 1, the cap-and-trade systems covering the power and industry sectors are assumed to be established in Australia, Japan, and Korea as of 2013 and in OECD countries after 2020. The carbon pricing indicates that $p^E_{CO_2}$ is a lower price than expected. As a consequence, a torrefied biomass demand could be addressed by the power sector as soon as 2015 but the coal substitution by torrefied biomass (TOP) could stop over 2025 regarding our assumption on the nuclear phase-out (retirement of nuclear plants at end-of-life). Until 2020, this demand in torrefied biomass provides an avenue for the early contruction of torrefaction plants and could stimulate the development of biomass supply systems. Once the BtL units come on board, the refining sector could benefit from the use of these early torrefaction plants built thanks to the CO$_2$ price. In fact, to supply the power sector demand, the torrefaction units should produce around 400 000 t for 2015 and 800 000 t over 2020. The torrefied biomass co-firing with coal offers also a near-term market for lignocellulosic biomass, which could be available for the refining sector. Indeed, it provides a more favorable market compared to the power industry. This argument has been also proposed by Berndes et al. (2009). Thus, in this case, carbon price could pave the way to second generation biofuel production.

In scenario 2, carbon pricing is assumed to be limited to EU countries and to New Zealand. The price of CO$_2$ under the EU emission Trading System is projected to reach 15.8 euro$_{2005}$/t in 2015, 18.3 euro$_{2005}$/t in 2020, 20.4 euro$_{2005}$/t in 2025 and 22.5 euro$_{2005}$/t in 2030. Regarding these projections, the power sector could adress a torrefied biomass demand in period $t = 2020$ but the trigger price $p^E_{CO_2}$ is too high over the next periods to replace coal by torrefied biomass. We could reach the same conclusion as above regarding the torrefied biomass market development. An oil price growth could pave the way to the biomass supply chain in order to produce second generation biofuel.

Finally, in the third scenario, cap-and-trade systems covering the power and industry sectors are assumed to start in 2013 in OECD countries plus non-OECD EU countries and after 2020 in Brazil, China, the Middle East, Russia, and South Africa. In this context, torrefied biomass could play a major rule in the power sector where $p^E_{CO_2}$ is lower than the carbon price expected by International Energy Agency, IEA (2010). The coal price tends to decrease over the period, so the thermal power coal plants remain profitable during peak hours .

To conclude, for the CO$_2$ prices expected by the International Energy Agency, IEA (2010), the scenario 2 of fuel and carbon prices could make profitable the second generation biofuels over 2020-2030. The torrefaction production should start at period $t = 2020$ because no demand will be addressed before this date. Scenario 1 and 3 could trigger investment in torrefied biomass units before 2020 with a demand coming from the power sector and thus pave the way to BtL production. Finally, fuel prices projected in scenario 3 would not be able to make BtL production profitable. However, the power sector could be provided with biomass during the period analyzed to produce renewable electricity.

7 Conclusion

Torrefaction is considered to be a pre-treatment technology that makes biomass more suitable for co-firing and biofuel applications. By improving grindability of biomass, torrefaction may enable higher co-firing rates in the near future. However, the demand addressed to the torrefaction units will depend on the profitability of BtL units which is itself related to the demand for diesel addressed to refineries. At the same time, the power sector will do its trade-off based on subsidies, price of ton of CO_2 and coal price as torrefied biomass is a substitute of coal. Negotiating contracts with torrefied biomass producers may depend on the variability of the CO_2 market. The price of CO_2 is therefore an important source of uncertainty that can influence the competition among potential users of torrefied biomass. We consider the production of BtL as compulsory from 2020 to 2030. In this policy context, we evaluate three different scenarios and we look for the impact of the CO_2 price on the production strategy of the power sector. We have built a torrefied biomass market model that allows endogeneous fuel choice for power plants and refineries. The models are used in a numerical application, where fuel consumptions are analyzed. A French case is used as an example.

Our results indicate that the higher the CO_2 price, the more stable and important the power sector demand. It also plays a major role in the biomass supply chain, which will be less vulnerable to uncertainty on demand coming from the refining sector. Indeed, the second generation biofuels production based on French torrefied biomass is sensitive to the oil price. A low oil price over 2020-2030 could prevent a biofuels production based on French torrefied biomass from being profitable for the refiner. Thus, imports of biomass could be necessary and French biomass can be used by the power sector. Moreover, the torrefied biomass demand can be triggered by the power sector for a low cost of CO_2 before 2020. Beyond 2020, the demand coming from the power sector could be substituted by the refining sector if the oil price goes up whatever the CO_2 price. Finally, the CO_2 price drives the torrefied biomass co-firing with coal. It can offer a near-term market for biomass, which can stimulate the development of biomass supply systems. Thus the green power production due to a low CO_2 price could pave the way to BtL production.

This paper provides insights how climate and energy policies can promote the bioenergies development. If policymakers focus on biomass as a resource for renewable energy production, the CO_2 price could drive the bioenergy market. Torrefied biomass could be used by the power sector without any obligation to produce renewable energy. It is interesting in case the feed-in tariffs are to be reduced over the next 20 years. It renders guidance for policy makers for renewable energy commitment for 2020-2030. As torrefied biomass is a homogeneous feedstock with high energy potential and storable all the year, it represents an interesting substitute to coal and a low-risk investment for power sector regarding the other alternative renewable systems. Regardless of the long-term priorities of biomass use for energy, the stimulation of biomass pre-treatment by development of near term and cost-effective markets could be a strategy for France. For the short term, pretreated biomass could be first used by the power sector in order to reach the 20% of renewable energies and 20% emission reduction targets for 2020. Thus, it could help to put in place a profitable biomass supply chain and trigger investment in biomass diesel infrastructures.

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Tables

Table 4: Technologies and fuels

Technology	Notation	Fuel used	Notation	Capacity (GW)
Nuclear	NPP	Uranium	OU	63.26
Coal Thermal	THC	Biomass, coal	TOP,COAL,RAW	7.07
Fuel Oil	THF	Heavy Oil	HFO	5.7
Combustion Turbine	CTP	Domestic oil, Gas	HTO	1.63
Combined Cycle Gas Turbine	CCG	Gas	GAS	6.74
CHP (1) with gas	COG	Gas, Biogas	GAS and BIG	4.661
CHP with coal	COC	Coal, Biomass	COAL, TOP, RAW	0.443
CHP with fuel	COF	Heavy oil, Domestic oil	HFO and HTO	0.186
CHP with waste	COO1	Wood industrial coproducts	OTH1	0.455
CHP with waste	COO2	Others (waste)	OTH2	0.924
CHP with biomass with torrefied biomass	COT	Torrefied biomass	TOP	0
Wind Power	WPO	Wind	WIN	3.4
Photovoltaics	PVP	Sun	SUN	0.048
Hydraulic water-flow station	HYW	Water	WAT	7.6
Hydraulic lake station	HLA	Water		13.6
Hydraulic pumping station	HWP	Water		4.2

(1) Combined Heat and Power (CHP).

Table 5: Properties of biomass types used in torrefaction (elemental composition in wt.%)(Bergman et al., 2005a; Vassilev et al., 2010)

Biomass	C	H	N	O	S	Ash	LHV
	(% wt.)						(MJ/kg)
Straw	44.3	5.8	0.4	42.4	0.16	7.1	16.1
Wood	47.2	6.0	0.4	45.2	0.08	2.5	17.0
Srca (1)	48.4	5.9	0.32	42.1	0.15	3	18.09
Srcf (2)	47.2	6.1	0.34	44.8	0.075	1.6	17.7

(1) Short Rotation Crops from agricultaral sector (miscanthus here).

(2) Short Rotation Crops from forest sector (willow here).

(3) With $C = Carbon$, $H = Hydrogen$, $N = Nitrogen$, $O = Oxygen$, $S = Sulfur$.

Table 6: Feed-in-tariffs per technology used in the model

Technology	Date of the law	Length of the contract	Tariffs
		years	cents of euro per kWh
Wind power	November 2008		8.2 over 10 years then between 2.8 and 8.2 over 5 years depending on the site
Photovoltaics power	January 2010	20	between 42 and 58 depending on the integration in the building of the cells
	March 2002	22	15.25 in metropolitan France
Hydro power	March 2007	20	6.07 on land
Cogeneration	July 2001	12	6.1 to 9.15 depending on the gas price, the power, and the operating time
Burning biomass	December 2009	20	4.5 (1)
Biogaz	July 2006	15	between 7.5 et 9 depending on the power

(1) plus bonus based on capacity, efficiency and the resource used.
(2) plus bonus based on energy efficiency.

Table 7: A high percentage of biofuel incorporation in diesel and gasoline pools

	2005	2006	2007	2008	2010	2020
Directive on biofuels objectives (2003/30/EC) (1)						
EU(27)	2				5.75	10
France	1.20	1.75	3.50	5.75	7	10
Current trade (1)						
EU(27)	1	1.9	2.6	3.3	5.3	-
France(TOTAL)	1.00	1.76	3.57	5.71	> 6.04	-
France(Diesel)	1.04	1.74	3.63	5.75	> 6.27	-

Source: CPDP 2008, EuroStat 2009, IEA 2008, EurObserv'ER 2009.
(1) Expressed in energy content.

Fuel prices

The *World Energy Outlook* of the IEA assumes a GDP growth of an average of 1.6% per year over the period 2008-2035 (2.1% over 2010-2015 and 1.6% over 2020-2035). The rates of population growth assumed in the Outlook for European Union are based on the recent projections by the United Nations, 2009. Europe's population is increasing slightly by 0.2% per year on average over 2008-2035 (0.4% over 2010-2015 and 0.1% over 2020-2035).

Table 8: Fossil-fuel import and CO_2 prices by scenario (Real term, 2005 prices)

Commodities	Unit	2009	2015	2020	2025	2030
Scenario 1						
BRENT CIF	dollars/b	54.87	82.13	89.94	95.39	99.93
COAL CIF	dollars/t	94.48	94.84	98.47	100.65	102.02
GAS CIF	dollars/Mbtu	6.85	9.76	10.66	11.30	11.84
CO_2	euro/t_{CO_2}	13.41	18.29	23.17	25.60	28.04
Scenario 2						
BRENT CIF	dollars/b	54.87	85.39	99.93	109.02	118.11
COAL CIF	dollars/t	94.48	94.93	102.20	105.56	108.29
GAS CIF	dollars/Mbtu	6.85	9.85	11.12	11.85	12.75
CO_2	euro/t_{CO_2}	13.41	15.85	18.29	20.42	22.56
Scenario 3						
BRENT CIF	dollars/b	57.87	79.86	81.76	81.76	81.76
COAL CIF	dollars/t	94.48	90.12	84.03	74.94	66.31
GAS CIF	dollars/Mbtu	6.85	9.57	9.76	9.85	10.03
CO_2	euro/t_{CO_2}	13.41	20.42	27.44	45.72	64.02

Source: (International Energy Agency, IEA, 2010).

Table 9: Demand of electricity per season, sub-period and alea

Season	Sub-period	Length of $\tau^{(1)}$	Demand in function of the alea$^{(2)}$		
s	τ	$l_{\tau,s}$	$dem_{\tau,s,a}$		
			a1	a2	a3
S1	τ_1	249	79.20	79.41	83.88
	τ_2	872	73.07	71.38	74.43
	τ_3	1039	66.39	65.40	66.32
S2	τ_2	745	61.58	60.39	61.03
	τ_3	719	57.90	57.08	57.41
S3	τ_2	1870	53.61	53.36	53.30
	τ_3	1778	46.83	46.89	46.89
S4	τ_3	1488	39.71	39.71	39.57

(1)in hour per year.
(2)in GW per year.

Table 10: Emissions factor of CO_2 per fuel

Fuel	Notation	PCI	Emission factor	
		(GJ/t)	(t CO_2/GJ)	(t CO_2/MWh)
Coal	COAL	32.5	0.10	0.361
Heavy oil	HFO	40	0.078	0.281
Domestic oil	HTO	42	0.075	0.270
Natural gas	GAS	49.6	0.057	0.206
Biogaz	BIG	14	0.075	0.270

Source: Chêne-Pezot (2005)

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