DAUPHINE UNIVERSITÉ PARIS
CLIMATE ECONOMICS CHAIR

WORKING PAPER
n° 2017-07• August 2017

KEYWORDS
.
Forestry sector
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Bioenergy
.
Biomass-based electricity
.
Carbon pricing
.
Nuclear power
.

Heat or power: how to increase the use of energy wood at the lowest costs?

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- We compute the optimal subsidy level to fuelwood consumption that makes it possible to achieve the French biomass energy consumption target.
- In this view, we model the competitions and trade-offs between the consumption of fuelwood for heat (FW-H) and the consumption of fuelwood for power generation (FW-E).
- To do so, we couple a forest sector model with an electricity simulation model and we test different scenarios combining FW-H and FW-E that account for contrasted potential rise in carbon price and potential reduction in the number of nuclear plants.
- We assess the implications of these scenarios on (1) the budgetary costs for the Government, (2) the industrial wood producers' profits, (3) the costs savings in power sector for the different scenarios tested and (4) the carbon balance.
- We show that the scenario with the highest carbon price and the lowest number of nuclear plants is the less expensive from a budgetary perspective. Indeed, when associated with a high carbon price, co-firing may increase FW-E demand with lower subsidy level, which enables reducing the cost of reaching the target. However, in this case, FW-E crowds-out part of FW-H which may cause political economy issues.
- From a carbon balance perspective, a FW-H only scenario better performs than any other scenario that combines FW-H and FW-E due to the relatively low emissions factors of alternative technologies for electricity generation, in particular nuclear energy.

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This paper was presented at the 23rd EAERE Annual Conference (June 2017, Athens, Greece), and at 3rd restitution day of the chair "Forêts pour demain" from AgroParisTech and Office National des Forêts (February 2016, Paris, France).
This research is part of the Agriculture and Forestry research program by the Climate Economics Chair. The authors want to thank the Climate Economics Chair for financial support.

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The Laboratory of Forest Economics contributes to the Labex ARBRE ANR-11-LABX-0002-01

1. Introduction

In 2011, renewable energy represented about 15.3% of the total production of French primary energy, *i.e.* about 21.2 Mtoe. European directive 2009/28/EC has set the objective of increasing the share of renewable energy in French energy mix by 23% in 2020. Meanwhile, France is a leading exporter in the EU's electricity markets, having its electricity produced primarily from nuclear power which was largely supported by the Governments during the last decades. However, the "Law on energy transition" has recently been voted. This law aims at reducing the proportion of nuclear power by 2025 while reaching 27% of the total power produced using renewables. In France, where forest resources are abundant — France has the fourth largest forest cover among of the 25EU countries — solid biomass energy is expected to play a major role in achieving these objectives (Sergent, 2014; Caurla *et al.*, 2013). All the more so because, given the recent trends, France appears to be far behind the national target for biomass use while being the biggest energy consumer in the EU in absolute terms (Proskurina *et al.*, 2016).

Several programs to stimulate the consumption of energy wood have been implemented so far. The overall objective of these programs is to increase fuelwood consumption by + 20 hm^3 in 2020 compared to 2006 (Dupuis *et al.*, 2008). They aim at increasing the consumption of wood for heat production in domestic and collective installations (hereafter FW-H) or for power production into electricity plants (hereafter FW-E). In particular, the ability of power producers to increase the FW-E consumption with no investments, through the co-firing of biomass in coal plants, gives to biomass a strong interest. The technical potential for FW-E from co-firing in France has been estimated by Hansson *et al.*, (2009) to 1.24-2.63 TWh/yr (where the highest value assumes the use of all plants $\leqslant$40 years old and the lowest assumes the use of plants $\leqslant$30 years old). In this view, five generations of national public tenders have been launched to fund biomass projects in energy. Meanwhile, on FW-H markets, France has recently made considerable progress *via* increased use of wood pellets, after the introduction of a specific support program for wood pellet equipment (Proskurina *et al.*, 2016).

Technically, the programs to stimulate the use of energy wood, either FW-E or FW-H, take the form of subsidies to increase harvesting, to develop commercial channels, to foster the storage of harvested products and their final consumption through investments in electricity plants and heat collective/domestic boilers. They result in a reduced perceived price of fuelwood for the final consumers of fuelwood, either the domestic households that use FW-H or the power generator owners that consume FW-E.

Yet the impacts of a subsidy on the consumption of FW-E are likely to be different than those on the consumption of FW-H, both in terms of economic outcomes and in terms of carbon implications. Indeed, fuelwood is not used with the same technologies and do not compete with the same products on heat and power markets.

On the one hand, FW-H demand has been estimated as rather inelastic. Couture *et al.* (2012) estimate the price elasticity of fuelwood demand for French households when wood is the main source of heating energy to be −0.42. Wood can be seen as a necessary good for these consumers, as the choice of wood as the main source of heating energy is negatively linked to income, which seems to confirm the energy ladder theory according to which wood is much more widely used by the lowest-income categories in society (Couture *et al.*, 2012). In addition, using wood as domestic, collective or even industrial source of heating involves additional technological costs which result in a form of lock-in situation for consumers, which even increases the inelasticity of the demand on medium and long terms.

On the other hand, in the electricity sector at national scale, the use of FW-E depends on the dispatching of different technologies in the fleet, which follows merit-order logic. This may induce stepwise variations in FW-E demand, when power plants relying on wood switch places with other ones in the merit order. Accordingly, this makes the use of solid biomass for electricity very dependent on two types of variables: the relative prices of energy sources and the installed capacities of power plants from different technologies. Two parameters are likely to play a major role on these variables: the carbon price, which influences the cost of energy according to their carbon content, and the reduction of the share of nuclear in the electricity mix, which has to be compensated by increased contribution of other technologies including wood-based power generation.[1]

One consequence is that, while a subsidy on total fuelwood consumption is likely to play rather linearly for FW-H, it is expected to play nonlinearly for FW-E, with threshold levels when power plants switch places in the merit order. For the same reasons, the budgetary costs

[1] In France, the electricity mix is largely dominated by nuclear, which represents more than 50% of installed capacity, and around 75% of power generation (76% in 2015, according with RTE, *Statistiques Production Consommation Echanges 2015*). Hence, any reduction of nuclear-based power generation in this country may induce very substantial effects on contribution of wood-based power generation and demand for fuelwood.

of the subsidy are expected to rise with its level, but non-linearly. In addition, the spillover effects of the subsidy over the forest sector in both the two cases are ambiguous since they depend on both the thresholds in the electricity generation and the competition between fuelwood and other wood sectors, such as pulp sector.

Within this context, the first objective of our paper is to compute an optimal level of subsidy on total fuelwood (FW-E+FW-H) consumption accounting for (1) the relative prices of biomass and fuel substitutes in electricity sector (2) the carbon price which impacts the costs of other energy sources, (3) the reduction of nuclear power generation.

The second objective of our study is to compute the impacts of this subsidy over the economy of the entire forest sector. Caurla *et al.* (2013) already deal with such analysis but without considering the trade-offs between FW-H and FW-E production. Yet, the impacts of these programs on the forest sector remain unclear. First, by competing for the same raw products, these projects could strengthen the competition with the pulp, panel and paper sectors and could, therefore, increase the price of these products for the consumers. Second, the costs of this additional consumption and the distribution of these costs among forest sector agents and the French Government are unknown.

A third objective is to provide a carbon balance outcome of the different scenarios, in order to compare them both from their ability to contribute to climate change mitigation.

To do so, we couple two models representing the consumption of fuelwood for heat and the forest sector economy on the one hand (French Forest Sector Model: Lecocq *et al.*, 2011; Caurla *et al.*, 2013) and the consumption of fuelwood for electricity on the other hand (Green Electricity Simulate, Bertrand and Le Cadre, 2015).

In a first section, we review previous studies to position our contribution in the literature. In a second section we present our modeling framework, the coupling procedure. In a third section we present the scenarios tested and the results of our simulations and we conclude in a fourth section.

2. Position of our work in the literature

Four previous studies (Slojie *et al.*, 2010; Kallio *et al.*, 2011; Caurla *et al.*, 2013; Moiseyev *et al.*, 2014) question the optimal level of fuelwood subsidies to reach exogenous targets and assess the impacts of these subsidies over the forest sector. These studies all stem from the forest sector modelling literature.

Dealing with fuelwood for heat in Norway, Slojie *et al.* (2010) show that subsidizing fuelwood by implementing a tax of 60 €/CO_2eq on competing fossil fuels could increase the bioenergy use in district heating installations with almost 4000 GWh/year. The same amount of bioenergy could be used in domestic pellet stoves and central heating systems, but a higher tax is then necessary. A 50% investment grant to district heating installations may also have a large effect on the bioenergy use, but the effect of the subsidies decreases rapidly if applied together with a tax.

Kallio *et al.* (2011) show that, in order to increase fuelwood availability, the industries using sawlogs would need to grow, because the logging residues and stumps are primarily collected from the final fellings driven by the sawlog demand. Thereby, for instance, policies leading to the increased use of wood in construction would support the renewable energy goals as well. Also, the subsidies for CHP-production at sawmills could be beneficial in this respect.

Caurla *et al.* (2013) show that the optimal level, and therefore the costs of the subsidies – either the budgetary costs for the Government or the costs for society- greatly depend on which part of the forest sector is subsidized. They show that subsidizing fuelwood production is more costly for the Government than subsidizing fuelwood consumption. However an upstream subsidy also reduces competition with other sector such as pulp and increase exports levels.

None of the three studies above explicitly deal with both FW-E and FW-H. Moiseyev *et al.* (2014) fill this gap by examining how subsidies for wood-fired heat and power plants influence the use of wood biomass for power production in the short (2020) and medium (2030) term in the EU (European Union). Moreover, they investigate the effect of burning wood in coal power stations under co-firing. The authors show that even a relatively modest subsidy or bonus of 30 €/MWh for electricity generation used in just a few EU member countries leads to a substantial increase in the use of industrial wood use for energy. To do so they model coal, gas and wood-based power and heat for the existing technologies in the aggregated form (one technology for each fuel type for each country). This allows them to consider the competition between coal, gas and wood for the electricity production.

One significant shortcoming in the aforementioned literature is that either electricity is not taken into account (Slojie *et al.*, 2010; Kallio *et al.*, 2011; Caurla *et al.*, 2013), or, when it is accounted for (Moiseyev *et al.*, 2014), this only relies on representative approach that sets aside consequences for fuelwood demand when power plants switch places in the merit order. Additionally, Moiseyev *et al.* (2014) only consider existing power generation capacities, without investigating consequences of modifications in the fleet, with new investments and possible decommissioning or prolongation of old units.

Our paper precisely aims at filling these gaps. We use a modeling framework that represents the fuelwood demand from heating market, on the one hand, and from electricity, on the other hand. Trade-offs between FW-H and FW-E markets are therefore made possible by the coupling procedures. We model the dispatching decisions for power generation, based on a merit order logic, which may induce non-linearity in FW-E demand. We also consider possible modifications in the electricity park, through investments in new power stations and decommissioning or prolongation of old units. Hence, the structure of the French electricity park is made flexible, which allows analyzing any change in the electricity mix in favor of biomass with a degree of flexibility that depends on relative price but also on technological and legal aspects. Eventually, we investigate the effect of exogenous reduction of nuclear power generation, in line with provisions enacted in the French energy transition law of 2015.

3. Methodology and material

3.1. French Forest Sector Model

FFSM is a bio-economic recursive model of the French forest sector. The version used in this article is FFSM 1.0 (Caurla *et al.*, 2013a, Caurla *et al.*, 2013b, Lecocq *et al.*, 2011). This version is composed of two modules: an inventory-based dynamics forest module (FD) and a partial equilibrium market module (MK). The FD module represents the dynamics of the French forests that accounts for natural growth and mortality and wood removals from anthropic harvest.

The optimal harvest level is computed by the MK module on a yearly and regional basis, starting from 2006 as the base year. To do this, the MK module solves a partial equilibrium problem taking the costs of transportation from one region to another into account, according to Samuelson (1952) spatial price equilibrium framework. The equilibrium is computed *via* the maximization of an objective function defined as the sum of consumers, producers, processing industries and trade agents' surpluses.

The model represents the demand of processed products: sawnwood (hard and softwood, respectively hereafter referred to as hsw and ssw), plywood (pw), fuelwood for heating (FW-H), pulp and panels (pn). All these products are sold on a "final" market which can refer to domestic users or second-transformation industrials. On the upstream part of the forest sector, the model represents the supply of three raw products: roundwood (hard and softwood, respectively hereafter referred to as HRW and SRW) and industrial wood (IW). The model considers sawmills and harvest residues as by-products of primary activities competing with IW to produce fuelwood, pulp and panels. A Leontief function represents the transformation of raw products into processed products.

While interregional trade is modeled through the spatial price equilibrium framework, international trade is computed through an Armington framework assuming that domestic and foreign products are not fully substitutable (Armington, 1969). The international trade is modeled using exogenous international prices derived from the FAO (2013) and elasticities of substitution between local and international products specifically estimated for FFSM in (Sauquet, 2011).

3.2. Green Electricity Simulate

Green Electricity Simulate (GES) is a simulation model that is designed to investigate questions related to biomass-based electricity in the European countries, with a special focus on the biomass co-firing in coal plants. It is a dynamic cost-minimization model for production and investment decisions in the power sector. The model is implemented under the General Algebraic Modeling System (GAMS), and it considers yearly time periods. For each year in the considered time interval, GES determines the power generation mix (dispatch of generation capacities) and investment decisions, so as to meet electricity demand at the least cost. Furthermore, the model identifies which are the out-of-lifetime power plants at the beginning of each year (*i.e.* age > theoretical lifetime), which ones are decommissioned, and which one are refurbished and prolonged.

We use in this work the 1.0 version of GES (Bertrand and Le Cadre, 2015), which considers different country modules that can be run separately. To carry out the analysis of this paper, we have adapted the French module in a static framework. This allows implementing recursive feedbacks in equilibrium calculations of GES and FFSM. This is further discussed in section 3.3.

3.3. Coupling procedure

In order to recursively adapt the computation in one model, based on results of the other model, we run iteratively the two models with one time lag between FFSM and GES in each iteration. This is illustrated in Fig. 1.

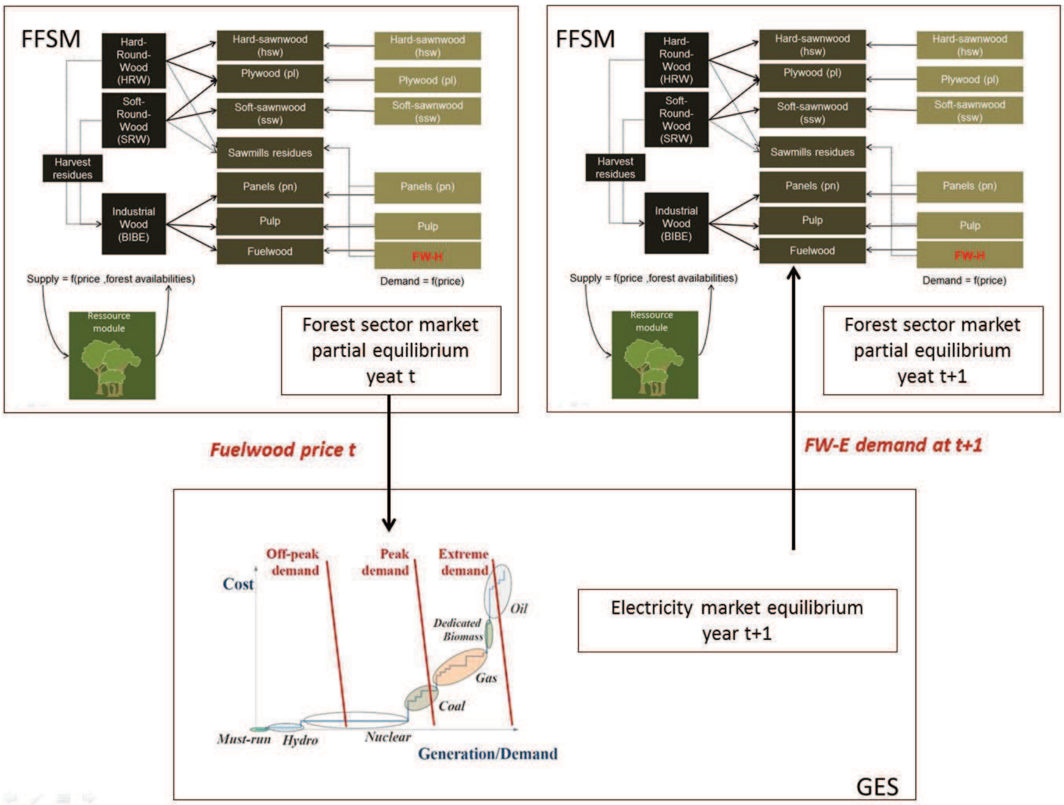

Figure 1: Coupling procedure between FFSM and GES for year *t* and *t+1*.

FFSM first computes a partial equilibrium for forest markets for period *t*. This equilibrium is associated to equilibrium supply and demand quantities and to an equilibrium price for each forest product. In particular, FFSM compute the optimal FW-H demand and the optimal fuelwood equilibrium market price (for both FW-H and FW-E) for period *t*. The optimal fuelwood market price is then given to GES as the market fuelwood price in the electricity sector for period *t*+1. Given this price, as well as prices for other energy sources, electricity market equilibrium is computed in GES for year *t*+1. This market equilibrium is associated to an optimal demand of FW-E.[2] This demand is then translated into FFSM as an exogenous "additional demand" of fuelwood (*i.e.* additional to the endogenous FW-H demand) to compute the *t*+1 equilibrium in FFSM. This allows computing a new fuelwood equilibrium price, which will reflect the market conditions with the new FW-E demand and the endogenous trade-offs between production of FW-H and production of FW-E. The new fuelwood equilibrium price is next considered by GES as the reference price for period *t*+2 that will determine new FW-E demand of *t*+2. So forth for following iterations.

In FFSM, the supplementary demand coming from electricity in every region i ($LDelecBE_i$) is directly introduced in the material balance (Eq. 1) and into the economic surplus related to fuelwood consumption.

$$LDelecBE_i + LD_i + \sum_j e_{i,j} = S_i + \sum_j e_{j,i} \quad (1)$$

where:

- $LDelecBE_i$ represents the amount of fuelwood consumed by electric plants in region i.
- LD_i stands for the amount of fuelwood consumed in region *i* for heat production.
- $\sum_j e_{i,j}$ is the amount of fuelwood exported by region *i* to other regions.
- S_i is the production of fuelwood in region *i*.
- $\sum_j e_{j,i}$ is the amount of fuelwood imported from other regions to region i.

[2] GES computes the optimal dispatch of generation capacities in intra-annual hourly time slices with unequal power demand. This reflects different load levels associated with more or less electricity demand. Different pairings between seasons and load curve segments are considered (*e.g.* summer-base or winter-peak hours) with unequal levels of power demand, and different fractions of the annual electricity demand (Bertrand and Le Cadre, 2015). Hence, power plants that are brought on line first (during hours with low demand for electricity), because of lower marginal costs, continue to run during hours with higher electricity demand. By contrast, the power plants with high marginal costs are only brought on line during the few hours with high demand for electricity, which results in lower fuel demand for the associated fuel input. In this way, the model computes equilibrium demands for each type of fuels, including fuelwood, on the basis of fuel and carbon prices (which are assumed to be exogenous) and some technical or legal constraints (*e.g.* the share of RES in power generation).

We also add the Government surplus ($LDelecBE_i \times P_i$) in the objective function (Caurla et al. 2010; Eq.15, p.9) where P_i is the domestic fuelwood price in region i.

We assume $LDelecBE$ is distributed among the 22 French administrative regions through a range of $LDelecBE_i$ taking into account the available forest resource stock in each region computed on a *pro rata* basis. This assumption can be seen as a simplified but not unrealistic vision of reality in which public power plants favor harvests in high forest-production areas to limit over-harvesting in low production ones.

4. Which forest and energy policies influence fuelwood consumption? Scenarios presentation

We consider two kinds of policies susceptible to influence the overall fuelwood consumption. Forest sector policies directly influence fuelwood consumption, while energy sector policies have an indirect impact. As of forest sector policies, we simply consider a consumer subsidy aiming to reduce the perceived price by fuelwood consumers. Concerning energy sector policies, we assess the impact of two policy instruments: a carbon price and a reduction of nuclear power in the energy mix.

4.1. Forest sector instrument to stimulate fuelwood consumption

In order to increase total fuelwood consumption by +20 hm^3 in 2020, we introduce a consumer subsidy to purchase fuelwood. Consumer subsidies decrease the fuelwood price paid by consumers, which increases its demand (Caurla *et al.*, 2013).[3] We assume the subsidy is implemented in 2010 and remains constant (in relative term) until 2020. This is summarized by Eq. 2.

$$P_t^{sub} = P_t \ (1 - sub) \tag{2}$$

where:

[3] Note that, in reality, a consumer subsidy may also represent indirect policies that reduce the price paid by consumers (implementation of fuelwood distribution facilities, for example).

- P_t stands for the unsubsidized price of fuelwood in year t.
- sub is the rate of subsidy for fuelwood.
- P_t^{sub} represents the final purchase price of fuelwood with subsidy sub.

The calibration is made by a trial and error process, as the overall objective can be achieved either by increasing FW-H only, or for both FW-H and FW-E. Results are presented in section 4.3.

4.2. Energy sector policies: carbon price and importance of nuclear power

We consider two parameters that can have a key role in influencing FW-E consumption: the carbon price and the share of nuclear power in the electricity mix.

A key factor that determines the quantities of FW-E consumed is the switching price at which fuelwood becomes desirable for co-firing in coal power stations. In the case of dedicated biomass units, the carbon price also influences the contribution, but the effect is indirect because we assume biomass is carbon-neutral. Hence, a higher carbon price may increase contribution of dedicated, by improving their relative competitiveness compared with units that have costly CO_2 emissions.

Therefore, we first investigate the extent to which a high carbon price can help reaching the +20 hm^3 consumption objective with a lower subsidy level. Indeed, an increase of the carbon price is expected to produce a significant impact on the FW-E demand. Being considered carbon neutral, an increase in the carbon price would make fuelwood more competitive, which may trigger substantial FW-E demand in a context of high carbon constraint in the European power sector.[4] To account for rising carbon price, we consider two different price path computed with the IEA (2012) *Current Policy Scenario* (CPS) as reference: *Carbon Base* (CPS carbon price path, which corresponds to a 3% Average Annual Growth Rate (AAGR), *Carbon Plus* (increased carbon price path compared with the CPS, which

[4] Since the beginning of the EU ETS (European Union Emission Trading Scheme) in 2005, a constant feature of the scheme has been to impose to electricity the main part of the emission abatement effort. It is justified by the high potential of short-term carbon abatement in this sector compared to other covered industries. Another explanation relies on the non-exposition of this sector to international competition from regions without carbon pricing. Hence, the electricity sector accounts for more than half of both emissions and allowance allocations under the EU ETS. Furthermore, since the beginning of the Phase 3 in 2013, it is the only sector that has to deal with a 100% auction allocation regime (Solier, 2014).

corresponds to a 10% AAGR). The resulting carbon price paths are depicted on the carbon switching price graphics for co-firing in Appendix B (Fig. 6 and 7). Note that these paths do not objectively reflect what have been observed in the EU ETS during the last few years. However, it is not a problem in our case, since our aim is not to produce an ex-post analysis based on actual past market conditions, but rather to investigate the fuelwood demand response to high levels of carbon price that would prevail in the future.

Second, the share of nuclear power in the electricity mix is another element that can impact the fuelwood demand. Any reduction of nuclear-based power generation has to be compensated by an increased contribution of other technologies that would be substituted to nuclear. Thus, the share of fuelwood from dedicated biomass units (biomass co-firing, resp.) in the electricity mix is expected to increase, if the carbon price (carbon switching price, resp.) is high (low, resp.) enough. Then, the interaction between the carbon price and the decrease in nuclear power is crucial: the redistribution of electricity sources resulting from the decrease of nuclear power is more likely to be favorable to fuelwood if the carbon price is larger. In order to analyze this, an additional constraint is added to the electricity model, which sets for each year a maximal percentage of nuclear power in the overall power generation. This percentage is gradually decreased to reach 50% in 2020. [5] Table 1 summarized the different scenarios tested.

[5] First possible decommissioning of French nuclear plants identified by the model (*i.e.* the first nuclear plants that are identified as out-of-lifetime power plants, with age strictly higher than theoretical lifetime) takes place after 2020, whereas the +20hm^3 fuelwood consumption target has to be reached in 2020. Hence, in order to analyze the effect of a reduced nuclear power generation, we add a constraint about the maximal share of nuclear in the overall power generation. This allows assessing the impact of reduced nuclear power generation on the level of fuelwood subsidy to reach the consumption target. Note that the France's energy transition law that has been adopted by the French Parliament (*loi sur la transition énergétique pour la croissance verte*, enacted on July 2015), provides similar restrictions to reduce the share of nuclear in the French power generation by 2025.

Scenario name	Policy ingredient
BAU	Fuelwood for heat only No subsidy to fuelwood consumption
Heat Only	Fuelwood for heat only Subsidy to fuelwood consumption to reach +20 hm3 by 2020
Elec Carbon Base	Fuelwood for heat & electricity Subsidy to fuelwood consumption to reach +20hm3 by 2020 Carbon Base trajectory for the carbon price No constraint on power generation from nuclear
Elec Carbon Plus	Fuelwood for heat & electricity Subsidy to fuelwood consumption to reach +20 hm3 by 2020 Carbon Plus trajectory for the carbon price No constraint on power generation from nuclear
Elec Carbon Base Nuclear Reduction	Fuelwood for heat & electricity Subsidy to fuelwood consumption to reach +20hm3 by 2020 Carbon Base trajectory for the carbon price Constraint to cap power generation from nuclear
Elec Carbon Plus Nuclear Reduction	Fuelwood for heat & electricity Subsidy to fuelwood consumption to reach +20hm3 by 2020 Carbon Plus trajectory for the carbon price Constraint to cap power generation from nuclear

Table 1: Scenarios.

Four types or results are analyzed hereafter. First, we consider how the energy sector instruments influence the level of the forest sector instrument necessary to achieve the 2020 objective. Second, we assess how they impact the composition of the fuelwood use. Third, we explore the economic impacts in the forest sector. Fourth, we focus on carbon assessment.

5. Results

5.1. Subsidy levels

We compute the subsidy levels required to reach the +20 hm^3 target in each scenario. Results are presented in Table 2 together with the respective shares of FW-E and FW-H in each scenario.

Scenario	Fuelwood subsidy level in% of the perceived price	Share of fuelwood for power (FW-E) in % of the +20hm^3 objective	Share of fuelwood for heat (FW-H) in % of the +20hm^3 objective
Heat Only	74	0	100
Elec Carbon Base	36	87	13
Elec Carbon Plus	34	86	14
Elec Carbon Base Nuclear Reduction	25	99	1
Elec Carbon Plus Nuclear Reduction	16	101	-1

Table 2: Subsidy levels and share between heat and power.

First, results in Table 2 show that taking fuelwood as a potential source of electricity production is proven to be crucial from a cost-effectiveness perspective: the required level of subsidy necessary to achieve the +20hm^3 target is twice smaller when electricity production is introduced to the system, even without an increased carbon price or nuclear reduction (from 0.74 in “Heat only” to 0.36 in “Elec Carbon Base”).

Second, the interaction between the carbon price and the reduction of nuclear power has an important impact on the subsidy rate: when reducing nuclear power, the required subsidy level decreases by another 30 % (from 0.36 to 0.25). Moreover, the impact of an increase in the carbon price is more significant when nuclear power is reduced (from 0.25 to 0.16), than when it is not (from 0.36 to 0.34). Overall, as expected, the impact of a carbon price has to be considered, but more importantly, the interaction between the nuclear power and the carbon price is crucial.

5.2. Composition of the fuelwood use

Heat or electricity?

As shown in columns 3 and 4 in Table 2, when the power sector is included in the fuelwood consumption target, the majority of the +20 hm3 target is consumed as FW-E. In that case, any variation in the FW-H consumption is due to the trade-off between two opposite effects: (1) the subsidy effect: the subsidy to fuelwood consumption reduces the perceived price to FW-H consumers, which tends to increase their demand; and (2) the scarcity effect: the increase from the electric sector increases the fuelwood price, which tends to reduce FW-H demand. In our scenarios, the first effect always dominates the second, except for the "Elec Carbon Plus Nuclear Reduction" scenario. In this last case, the scarcity effect overrides the subsidy effect and part of FW-H consumption is crowded out by FW-E demand. This crowding-out appears as being sensitive to the nuclear capacity, while the carbon price has very little if any impact.

Dedicated biomass units or co-firing?

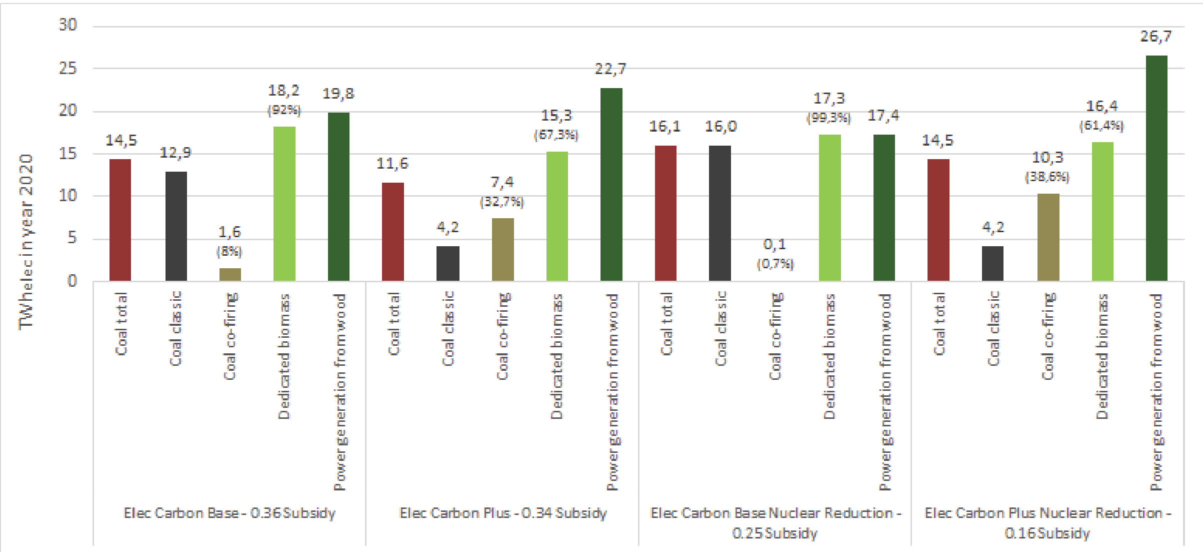

Figure 2: Power generation from coal and biomass dedicated stations under different scenarios with calibrated subsidy levels.

Regarding FW-E sector, it appears that the fuelwood demand is more located on biomass dedicated power plants than on coal stations under co-firing with wood. This is explained by the investments in dedicated biomass power plants (among other RES technologies) triggered by the 27% constraint about the share of RES in the French power generation for 2020 (MEEDDM, 2008), whereas there is no investment for coal in neither of the scenarios.[6] This

[6] Generation capacities for dedicated biomass units evolve from 58 MW in 2010 to 3058 MW (2020 in Elec Carbon Base with 0.36 subsidy), 2565 MW (2020 in Elec Carbon Plus with 0.34 subsidy), 2915 MW (2020 in

makes the dedicated unit demand more stable and less sensitive to price variations in our scenarios, compared with co-firing (which is not recognized as a RES). Moreover, fuelwood constitutes the single fuel source of biomass dedicated units, whereas it is only part of the overall fuel entering in coal plants under co-firing. Hence, even with a higher power generation from co-firing compared with dedicated units, it is possible to have a greater fuelwood demand from dedicated units. In all cases, this tends to increase the wood demand from dedicated units more than from co-firing.

When comparing the effects associated with different policy instruments, we first observe that co-firing seems to be more sensitive to the carbon price, and less to the subsidy, whereas the opposite occurs with dedicated units. This is illustrated in Fig. 2, which shows that increasing the carbon price generates, in all cases, a straight rise in co-firing, whereas it is more ambiguous for dedicated units (which are more impacted by simultaneous decrease in the level of subsidy to reach the +20 Mm^3 target).[7] In fact, increasing the carbon price has a direct effect on co-firing as it makes it more profitable than coal only configurations (*i.e.* when coal is the only input). By contrast, in the case of dedicated, this only has indirect effect (because dedicated units are assumed carbon neutral as biomass is their only input), by increasing the relative competitiveness of investments in these units.
Inversely, when considering variations of the subsidy level, this produces a relatively greater effect on dedicated, because the subsidy impacts the whole fuel input in this case, whereas this only affects a part with co-firing.

Looking at the impacts of reducing nuclear, Fig. 4 in Appendix A shows that, for a fixed level of the subsidy, this contributes to increase wood-based power generation and therefore FW-E demand. As a consequence, reducing the nuclear capacity allows for reducing the level of the subsidy to reach the same +20 hm^3 target. In our scenarios, because the subsidy level is simultaneously decreased, reducing nuclear appears to produce greater increase for co-firing, which is less dependent on the subsidy, compared with dedicated (Fig. 2). However, when we remove the effect of simultaneous decrease of subsidy, the opposite occurs, with stronger

Elec Carbon Base Nuclear Reduction with 0.25 subsidy) or 2750 MW (2020 in Elec Carbon Plus Nuclear Reduction with 0.16 subsidy).

[7] In order to disentangle the nested effects of carbon price increase and simultaneous decrease in subsidy (which counteract with each other in our scenarios), we run the models with fixed levels of subsidy (neglecting the +20 hm3 target). Results are presented in Appendix A.

increase of dedicated when nuclear is reduced, due to investments in dedicated units to fill the nuclear gap (see Appendix A).

5.3. Impacts on the forest sector economy

Scenario	Fuelwood perceived price in €/m3 (% of the BAU price)	Fuelwood market price (without subsidies) in €/m3(% of the BAU price)	Pulp price in €/m3 (% of the BAU price)	Industrial wood producers surplus gains compared to Business-As-Usual in M€	Budgetary costs in M€
Heat only	23 (-64%)	88 (+39%)	181.5 (+27%)	1017	798
Elec Carbon Base	52.5 (-17%)	82 (+30%)	171.5 (+20%)	721	684
Elec Carbon Plus	53 (-17%)	80 (+26%)	168.5 (+18%)	643	513
Elec Carbon Base Nuclear Reduction	63 (-1%)	83 (+33%)	174.5 (+22%)	836	406
Elec Carbon Plus Nuclear Reduction	64.5 (+2%)	77 (+21%)	163.5 (+14%)	523	261

Table 3: Economic implications of the forest sector in 2020.

Table 3 summarizes the results from FFSM. Three main results stem from this table.
First, as shown in column 2, the different scenarios show contrasting impacts on fuelwood price perceived by consumers. This is because two opposite forces drive the price. On the one hand, the subsidy to fuelwood consumption reduces the perceived price; on the other hand, the FW-E demand from electricity sector withdraws a certain amount of fuelwood which increases scarcity and, as a result, the market price. The first effect usually dominates the second with a fuelwood market price lower with the introduction of forest and energy sector policies compared to the baseline. However, it appears that, when a high carbon price is combined to a reduction of nuclear potential (scenario “Elec Carbon Plus Nuclear Reduction”), the second effect becomes dominant and the fuelwood price in this scenario exceeds the business-as-usual one by 2%. One consequence is a moderate crowding-out effect as FW-H consumption slightly decreases compared to business-as-usual (-0.6%). One possibility to counteract this effect would be to implement a higher subsidy to FW-H consumption than to FW-E consumption.

Second, in column 4 of Table 3 we present the pulp price as a competition index. Although pulp price increases in all scenarios, the inclusion of FW-E globally limits this impact compared to the “Heat Only” scenario. This is directly linked to the value of fuelwood market price: the higher the fuelwood market price is, the higher the pulp price and the stronger the competition.[8] Fuelwood market price increases with both the subsidy (price) effect and scarcity (quantity) effect (Scarcity effect refers to the additional FW-E consumption which crowds out part of the FW-H).[9] Since these two effects do not always go in the same direction, this leads to “non-linear” results regarding one effect in particular. For instance, while the subsidy is higher in “Elec Carbon Plus” than in “Elec Carbon Base Nuclear Reduction”, fuelwood market price is higher in the latter due to an increased scarcity effect. In this case, the combination of subsidy and scarcity effects leads to a lower level of competition in “Elec Carbon Plus” than “Elec Carbon Base Nuclear Reduction”, despite the higher subsidy level.

Third, budgetary costs depend on the levels of subsidy applied. Therefore, scenarios which depend on the subsidy effect are more expensive than those relying more on the alternative carbon price and nuclear reduction policies. In addition, the budgetary costs of the subsidy include an important windfall effect: consumers that would have purchased fuelwood anyway (*i.e.* in the BAU) also receive the subsidy. Favoring nuclear reduction and carbon price instead of direct fuelwood subsidy is therefore a political mean to reduce this windfall effect.

5.4. Carbon impacts

FW-H and FW-E are substitutes to different energy alternatives and the proportions of FW-H and FW-E differ between our 5 scenarios.[10] We therefore expect than the overall carbon implications will be different for the 5 scenarios.

In order to compute the carbon balance, we first assess the “substitution” coefficient for FW-H and FW-E, in each scenario. For FW-H, we compute the amount of CO_2 that is saved using wood instead of alternatives energy sources for heating purposes (see Appendix D for the detailed calculation). For FW-E, we first compute the CO_2 content of power for each scenario using data presented in Appendix E. Then, subtracting it to the CO_2 content of the baseline

[8] This is due to modeling assumptions in FFSM: in the model both pulp, panels and fuelwood are made with the same raw material, namely Industrial Wood (IW). If the market price of one of these transformed products increases, here fuelwood, this raises the attractiveness of IW suppliers for this particular transformed product. Meanwhile, consumers are subsidized for their fuelwood consumption, i.e. their perceived price is lower than market price. Overall, when maximizing the total surplus, the model allocates more IW to the fuelwood sector, which crowds out part of the pulp and panels sectors, increasing the competition.

[9] Scarcity effect refers to the additional FW-E consumption which crowds out part of the FW-H.

[10] Moreover, the overall energy mix for power generation depends on the assumptions about carbon price and nuclear, which makes the carbon outcomes of the “energy alternative” to FW-E ambiguous.

power mix (*i.e.* Carbon Elec Base with zero subsidy for fuelwood, line 2 Table 4), we get the amount of CO_2 saved or increased using an alternative energy mix for power production.

Scenarios	Fuel	MWh_{prim}	Emissions ($MtCO_2$)	Total emissions ($MtCO_2$)	Emissions saved compared to baseline ($MtCO_2$)
Elec Baseline	Coal	37 878 170	13.12	25.25	0.00
	Gas	56 470 906	11.52		
	Oil	2 289 039	0.61		
	Wood	1 426 991	0		
Elec Carbon Base 0.36 subsidy	Coal	36 841 402	12.75	24.87	0.38
	Gas	56 470 906	11.52		
	Oil	2 268 175	0.61		
	Wood	53 800 536	0		
Elec Carbon Plus 0.34 subsidy	Coal	25 580 403	8.93	21.06	4.19
	Gas	56 470 906	11.52		
	Oil	2 283 575	0.61		
	Wood	49 094 697	0		
Elec Carbon Base Nuclear Reduction 0.25 subsidy	Coal	42 154 999	14.64	27.25	-2.00
	Gas	58 821 586	12.00		
	Oil	2 269 233	0.61		
	Wood	49 889 236	0		
Elec Carbon Plus Nuclear Reduction 0.16 subsidy	Coal	31 312 612	10.87	23.20	2.05
	Gas	57 458 172	11.72		
	Oil	2 273 350	0.61		
	Wood	54 068 777	0		

Table 4: Carbon emissions from power generation and difference with baseline. Values in columns 4 and 5 appear in red (green) when increased (reduced) compared with baseline.

Table 4 shows that all scenarios except "Elec Carbon Base Nuclear Reduction" lead to carbon savings compared to the initial emissions volume. Reducing nuclear power actually entails higher contributions from coal to fill the gap, which tends to increase CO_2 emissions. However, the actual substitution of fossils to nuclear also depends on the carbon price, which is smaller in the "Elec Carbon Base Nuclear Reduction" than in the "Elec Carbon Plus Nuclear Reduction" scenario. This translates into substantial increases in the contributions of coal and gas in the "Elec Carbon Base Nuclear Reduction" scenario, with resulting higher CO_2 emissions (lines 5 and 6, Table 4). It is worthwhile to note that the carbon price level in this case is not high enough to generate co-firing, whereas co-firing is implemented in the

“Elec Carbon Plus Nuclear Reduction” scenario (see Figures 2 and 6). Hence, in the “Elec Carbon Base Nuclear Reduction” scenario, not only the power generation from coal and gas is increased but also the coal stations are run with coal as single input. This explains the increased CO_2 emissions in this case.

Scenarios	FW-H (hm^3)	Avoided emissions due to FW-H ($MtCO_2eq$)	Total emissions saved due to FW-H and FW-E (see Table 4) ($MtCO_2eq$)
Elec Carbon Base 0.36 subsidy	2.6	1.37	1.75
Elec Carbon Plus 0.34 subsidy	2.8	1.48	5.67
Elec Carbon Base Nuclear Reduction 0.25 subsidy	0.2	0.11	-1.90
Elec Carbon Plus Nuclear reduction 0.16 subsidy	-0.2	-0.11	1.94
Heat only	20.0	10.57	10.57

Table 5: Carbon emissions saved.

As shown in Table 5, using wood for heat purpose clearly leads to the best carbon outcome. This is because the alternatives heating sources have a higher emission factor (0.209 $kgCO_2eq$ kWh^{-1}, see Appendix D) than any other energy mix for electricity production in the different scenarios. This result can be explained by two reasons: first the high proportion of nuclear energy (carbon free) in the overall French electricity mix and second, the carbon neutrality assumption for wood biomass. This assumption both lies on an accounting principle and a biophysical principle. The IPCC carbon accounting principle stipulates that the emissions from fuelwood combustion are reported in the Agriculture, Forestry and Other Land-Use (AFOLU) sector at harvesting time. Once fuelwood enters the Energy sector, its carbon content is therefore null. The biophysical principle assumes that the biogenic carbon released by burning wood is recovered by growing trees. This assumption only holds if forests which provide energy wood is managed in a sustainable way, i.e. harvested trees are replaced by new growing trees. As the carbon released is not instantly recovered by growing trees, the carbon-neutrality assumption therefore implies to consider the system on the long term, once the carbon debt has been repaid.

5.5. Intersectoral and multi-criteria comparison

In this section, we summarize and compare the implications on (1) the budgetary costs, (2) the industrial wood producers' profits, (3) the costs savings in power sector and (4) the social benefit of mitigation (SBM) for the different scenarios tested in 2020. We present them on a histogram in Fig. 3.

Costs savings in power sector refer to the savings due to the fuelwood subsidy, they are presented on Table 4. These costs savings are non-linearly correlated to the level of subsidy as they account for the costs of all energy sources, not only fuelwood.

The social benefit of mitigation (SBM) is computed as the Social Cost of Carbon (SCC) by the total amount of carbon saved compared to baseline in each scenario. SCC 2020 values come from Nordhaus (2017) and are given with 4 alternative discount rates (17€/tCO_2, 31€/tCO_2, 66€/tCO_2, 106€/tCO_2 with resp. 5%, 4%, 3%, 2.5%). Industrial wood sector surplus gains and budgetary costs of the subsidy come from Table 3 in section 4.5.

Scenario	Power generation costs savings compared to a scenario with the same energy mix but without a subsidy (in M€)
Elec Carbon Base	169
Elec Carbon Plus	169
Elec Carbon Base Nuclear Reduction	123
Elec Carbon Plus Nuclear Reduction	162

Table 4: Costs savings due to subsidy in the power sector in 2020.

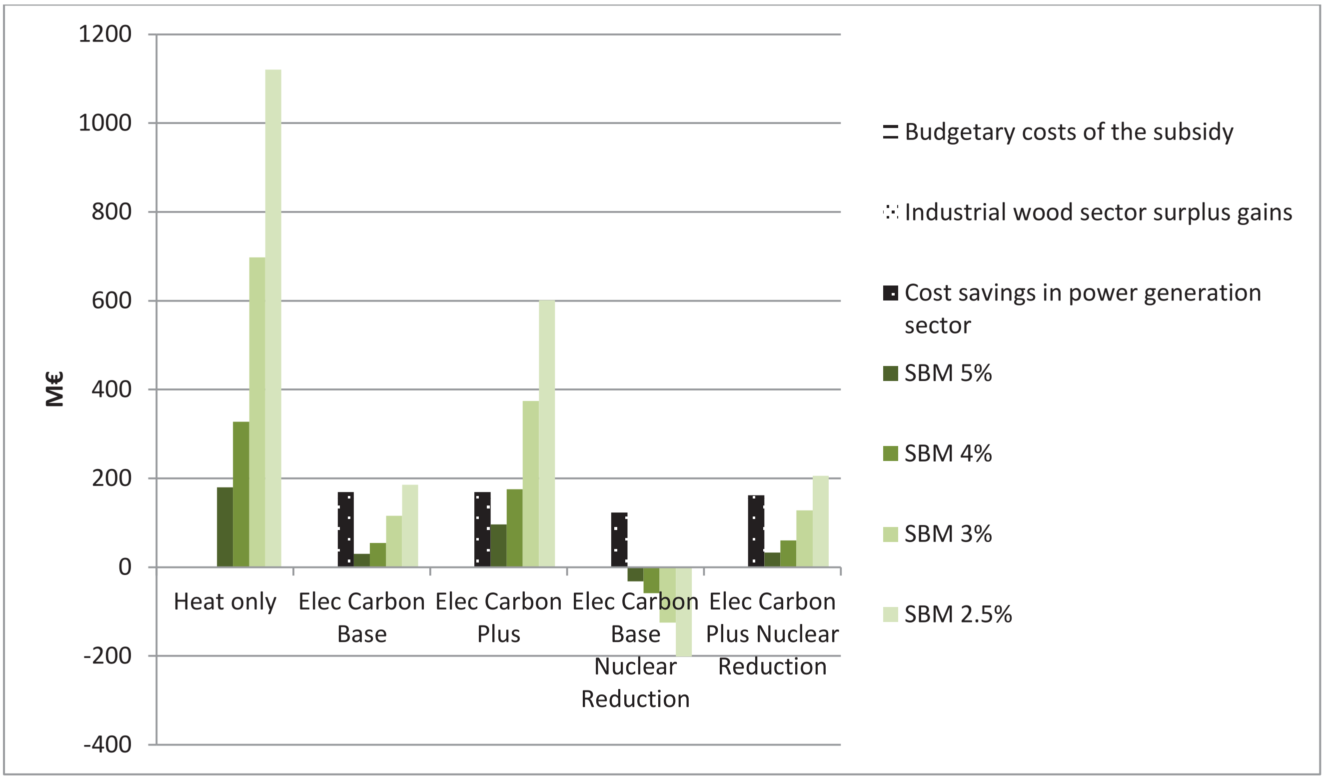

Figure 3: Comparison of the different costs for each scenario in 2020.

Looking at Fig. 3, there is a great temptation to sum up the benefits (for the forest and power sectors and for the society) and to remove the total budgetary costs in order to get cost-benefit outcomes. However, one has to remind that we only provide a small range of the puzzle pieces here. In particular, feedbacks on the rest of the Economy are not accounted for as we use partial equilibrium models. This keeps many costs and benefits aside from our analysis.

Nevertheless, three key findings stem from this graph.

First, it appears that the introduction of FW-E with a combination of a high carbon price and a reduced number of nuclear plants is the less expensive option from a budgetary perspective. Meanwhile, as mentioned above, this is also the only scenario in which FW-E crowds-out FW-H which questions the political feasibility of reaching the target within this option. More generally, the reduction of nuclear, by reducing the level of subsidy necessary to reach the target, appears as a cost-effective option.

Second, and in contrast, the Heat Only scenario is the most expensive, partly because of the windfall effect which benefits to consumers who already used FW-H as a heating source without subsidy, and who are now subsidized for this. This windfall effect also occurs in the power sector (FW-E which was used without subsidy is now subsidized) but the consumption increases by about +3500% for FW-E (see Table 4) while it only increases by about 60% for

FW-H compared to a baseline without subsidy, making the windfall effect far less impacting in the electricity sector than in the heating sector.[11]

Third, it appears that taking the social benefit of mitigation into account gives another perspective to the analysis. We show in section 5.4. that, due to the higher emissions factors of alternative heat sources compared to alternative power technologies, FW-H had a higher mitigation potential than FW-E. As a consequence, the scenario Heat Only which only relies on FW-H presents the best carbon assessment. Fig. 3 shows the social benefit of mitigation, which represent the change in the discounted value of economic welfare from the quantities of CO2-equivalent emissions saved in each scenario. As Nordhaus (2017) recalls, the discount rate has an important impact on the social cost of carbon, which translates in a wide range of social benefits for mitigation in our scenarios. Despite these uncertainties, Fig. 3 clearly shows that for an "average" discount rate (say 3%), social benefit for mitigation belongs to the same order of magnitude than budgetary costs of the policies in the Heat Only and the Elec Carbon Plus scenario while they are about twice lower in the Elec Carbon Plus Nuclear Reduction and 5 times lower in the Elec Carbon Base. Note here that the Elec Carbon Base Nuclear Reduction is a particular case in which benefits are slightly negative due to the additional carbon emissions compared to the baseline. One consequence is that, without taking the implications in terms of sectoral costs and benefits into account, the net cost for society of putting a subsidy to reduce carbon emissions through the use of fuelwood is almost nil in the Heat Only and Elec Carbon Plus scenarios but remains substantially positive in other scenarios.

6. Discussion and conclusion

The reduction of the importance of nuclear power in the energy mix is at stake in many countries. At the same time, reducing the carbon intensity of energy production is another and possibly contradictory objective. In France, the electricity sector has historically relied on nuclear, which makes the French electricity one of the less carbon-intensive among EU countries. Recently, the national "Law on energy transition" has been voted, which aims at reducing the proportion of nuclear by 2025.[12] Meanwhile, renewables targets have been set at European and national levels. For the electricity sector, one can therefore expect that part of

[11] In 2015, the French FW-H consumption was about 35 hm^3.

[12] LOI n° 2015-992 du 17 août 2015 relative à la transition énergétique pour la croissance verte (accessible from https://www.legifrance.gouv.fr/).

nuclear reduction will be offset by an increase of renewables, among which biomass is expected to play a major role, in particular FW-E. Meanwhile, FW-H demand is still increasing and uncertainties remain as to which would be the most cost-efficient way to increase total fuelwood consumption. This question provided the general guidance for our work.

Traditional top-down energy models working with an input-output framework (Markaki *et al.*, 2013; Yushchenko and Patel, 2016) or general equilibrium model (Capros *et al.*, 2016) deal with this issue from a global perspective, looking at welfare costs and macroeconomic retrofitting but without considering what happens specifically at sectoral scales (in our case either electricity and forest sectors). Yet, the cost sharing among the different economic agents have huge implications for the political economy of these policies.

In order to deal with these implications we combined two partial equilibrium models through a soft-coupling procedure and simulated the impacts of direct subsidies to biomass consumption with alternative carbon prices and nuclear capacities to reach the overall +20 hm^3 biomass target. This analysis framework presents the huge advantage to make it possible to simulate all the synergies and the competitions and the technologies within the sectors represented. Five key results stem from our analysis:

(1) Two opposite effects impact the consumption of FW-H: the subsidy effect which reduces the perceived price for FW-H consumers and the scarcity effect due to the increasing FW-E consumption. In our scenarios, the subsidy effect always dominates the scarcity effect except when nuclear capacity is reduced and carbon price is high. In this case, the level of subsidy required to reach the target is very low and the additional fuelwood consumption is entirely caught by electricity sector.
(2) Dedicated biomass units and co-firing plants do not respond similarly to policy incentives. Compared to each other, dedicated units appear as more sensitive to direct subsidies while co-firing benefit more from a rise in carbon price. In fact, both benefit more from the policy which increases its immediate profitability. Subsidies reduce the FW-E price on which the dedicated units 100% rely while carbon price reduces the cost of co-firing compared to running coal stations with coal as the only input.
(3) Nuclear reduction works in a somewhat different manner as it involves, first, an impact on quantity: reducing the nuclear capacity mechanically translates in increasing

other technologies to provide the required quantity of electricity, of which biomass – either in dedicated units or co-firing. This rise in biomass consumption automatically reduces the level of subsidy necessary to reach the fixed target. As dedicated units are relatively more sensitive to subsidies than co-firing, nuclear reduction then may appear, though indirectly, to favor co-firing compared to dedicated units.

(4) This latter effect has a counterintuitive impact on carbon outcome, whatever the carbon price. If the carbon price remains low, reducing nuclear may increase the profitability of classic configurations for coal plants, which increases emissions from coal. If the carbon price increases, the level of subsidy required diminishes and becomes too low to be able to overcome the scarcity effect for FW-H consumption, which translates in a lower use of wood for heat purpose and, therefore a worst situation in terms of emissions.

(5) For the same reasons, the perceived price of fuelwood for FW-H consumers increases in this last case, reducing their economic surpluses, which poses questions regarding the political economy of such an option. However, reducing the nuclear capacity is logically the less expensive option as it relies less on subsidies and, therefore, reduce the windfall effect volume.

From these five groups of results, it appears that the answer to the initial question "how to reach the fuelwood consumption target at the lowest costs?" is not straightforward. From a strictly budgetary perspective, favoring FW-E and relying on nuclear reduction with a high carbon price better performs in our simulations as it limits the level of the subsidy required and the subsequent windfall effect. Moreover, from future capacity development perspectives in electricity sector, a high carbon price combined with a moderate subsidy level makes it possible to invest in dedicated units. Though it favors co-firing more than dedicated units at first, one may think that the investments lead the way to an increase in overall dedicated capacity. Besides, the industrial wood sector perspective may prefer to favor FW-H compared to FW-E as it requires a higher subsidy to reach the target, which therefore lead to a higher selling price for industrial wood producers. However we saw that this result mainly lies on short term windfall effect and is very dependent on political decisions. Eventually from a social mitigation benefit perspective, using wood for heat production clearly better performs while reducing nuclear capacity may lead to a pernicious effect by increasing GHG emissions compared to the baseline.

Besides these considerations, we are aware that our analysis remains incomplete and would benefit from extending the multi-criteria analysis to others sectors. In particular, though fuelwood is supposed to be carbon neutral, it emits other particles, of which some can have huge implications on local pollution and human health. The types and the quantities of particles emitted depend on the combustion technologies. Within this context, an additional cost assessment directed on the cost for human health would add value to the work done. One way to do this would be to couple a Life Cycle Analysis on fuelwood sector with a valuation of air pollution.

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Appendix A: Carbon price and nuclear effects on FW-E consumption under fixed subsidy

Carbon price:

Results with 0 and 0.3 fixed subsidy level appear on Fig.4. We observe that moving from 0 to 0.3 subsidy produces a stronger effect on dedicated than increasing the carbon price for a fixed subsidy level. Conversely, increasing the carbon price has a relatively stable effect on co-firing, when considering either 0 or 0.3 subsidy level. Co-firing straightly increases with the carbon price, *ceteris paribus*. Notably, Fig. 4 shows that, when the subsidy level is set to zero, modifying the carbon price from *Carbon Base* to *Carbon Plus* may induces situation with co-firing accounting for almost 70% of wood-based power generation. In our case, by increasing the maximal wood price beyond which co-firing is no more profitable (*i.e.* the wood switching price increases, see graphics of Appendix B), a carbon price rise enables generating more fuelwood demand in energy, through co-firing, without increasing the subsidy. Hence, when associated with a high enough carbon price, co-firing may increase fuelwood demand with lower subsidy level, which enable reducing the cost of the policy. In this way, co-firing may produce a kind of positive externality by allowing to increase fuelwood demand with lower subsidy level.

Nuclear reduction:

Looking at the impact of nuclear reduction, we observe that when we remove the effect of simultaneous decrease of subsidy, dedicated benefit more than co-firing (whereas the opposite occurs in the reference scenarios, in which co-firing gains in importance as the subsidy decreases with the nuclear reduction). Indeed, dedicated are more profitable when the subsidy is not reduced, which explains that existing units are more solicited and new investments are implemented to fill the nuclear gap. In this case, investments in dedicated are all the more interesting because they enable filling the need for new generation capacities in a way that helps to comply with the RES constraint, relying in a RES technology that is not subject to the same drawbacks as other RES with intermittency (*e.g.* solar, wind).

Interestingly, with a fixed zero subsidy level, a reduction of nuclear may diminish contribution of co-firing, whereas dedicated is significantly increased (Fig 4). Here again, the RES constraint may be a significant driver. On the one hand, without any subsidy, wood-based power generation is less profitable. However, on the other hand, in the case of dedicated, the RES constraint is an additional driver (compared with co-firing), which makes it possible to simultaneously fill the nuclear gap and comply with RES obligation with a competitive RES technology (see Appendix C). Hence, investments in dedicated triggered by this double effect (reduction of nuclear and RES constraint, Fig. 5), generates a sharp increase of wood demand from dedicated units (without any subsidy), which, in turn, increases the fuelwood price due to scarcity effect in wood market, because of this additional FW-E consumption under zero subsidy. Regarding co-firing, the resulting market price for fuelwood is too high to make it profitable, even with higher carbon price (Carbon Plus). This is illustrated by Fig. 7 of Appendix B, which shows the switching prices for co-firing under zero subsidy.

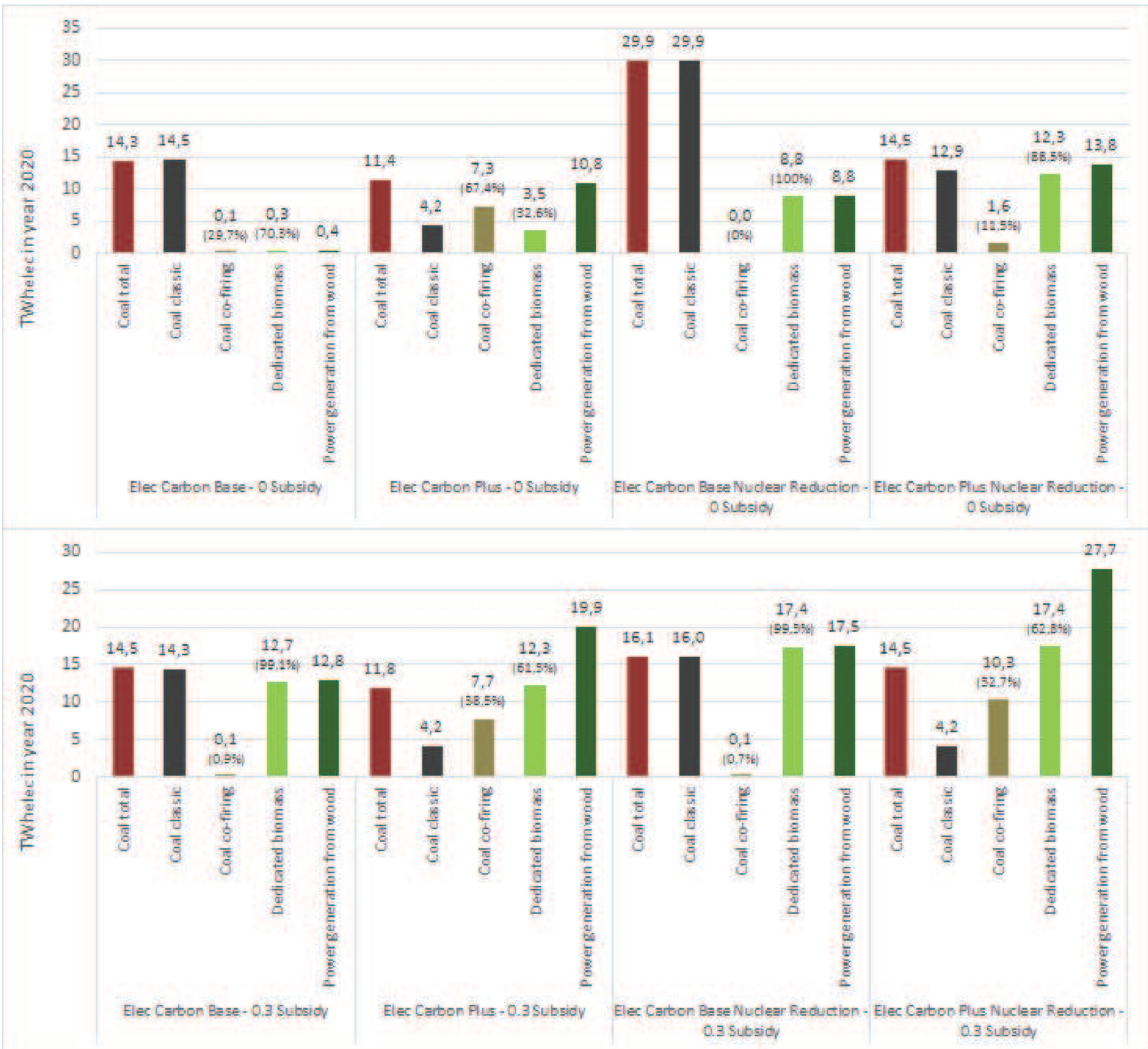

Figure 4: Power generation from coal and biomass dedicated stations under different scenarios and fixed subsidy levels.

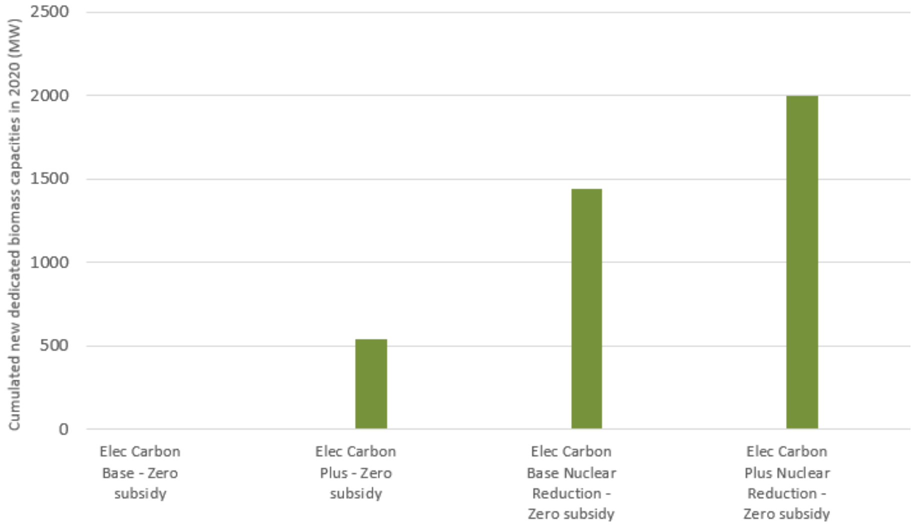

Figure 5: 2020 Cumulated investment in biomass dedicated power under fixed zero subsidy.

Appendix B: Switching price analysis for co-firing

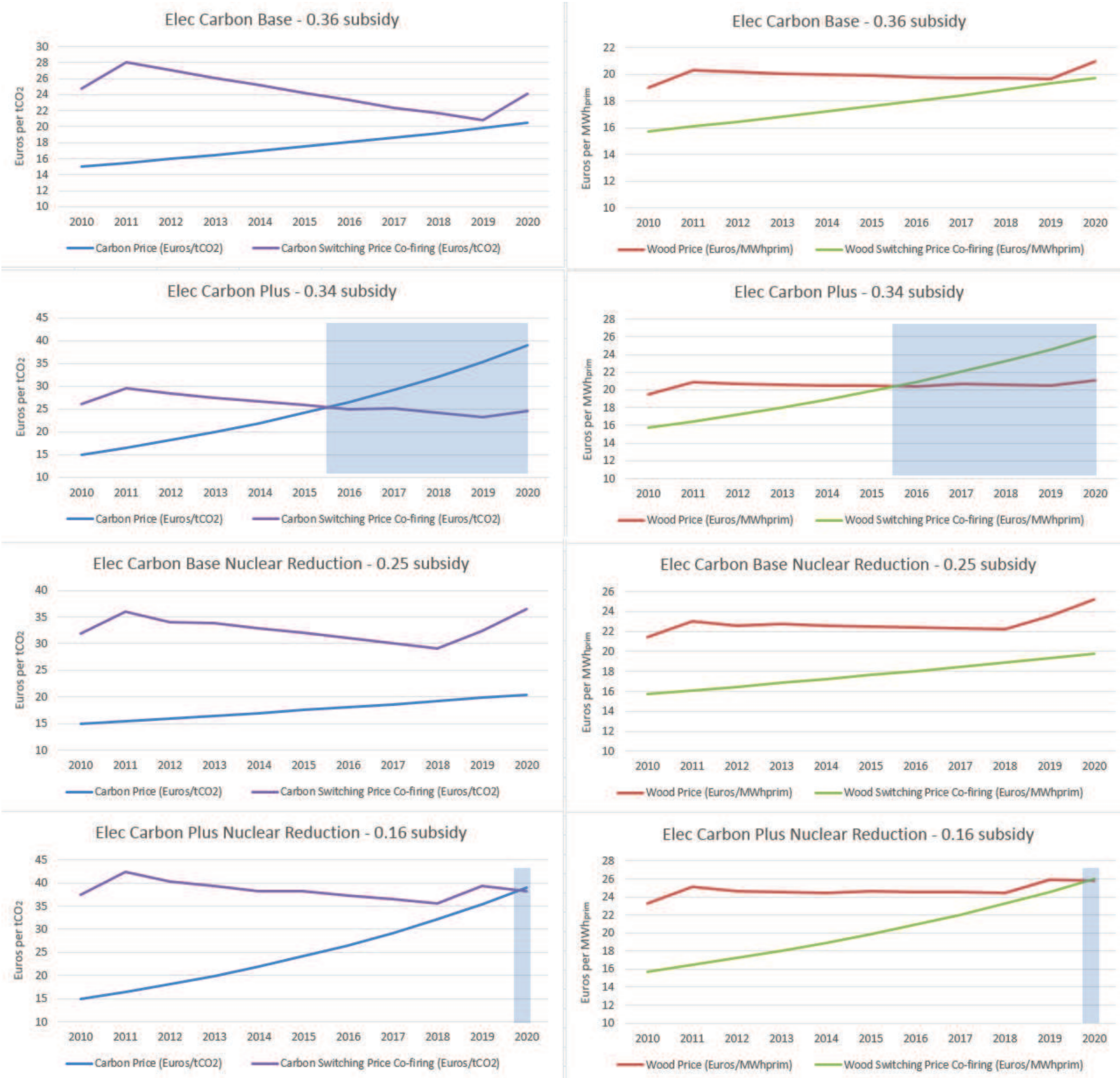

Figure 6: Wood and carbon prices versus wood and carbon switching prices for co-firing. The computed switching prices reflect co-firing opportunities in hard-coal plants (around 6% of installed capacities in France, whereas lignite stations account for less than 1%). The shaded areas represent situations in which co-firing is profitable.

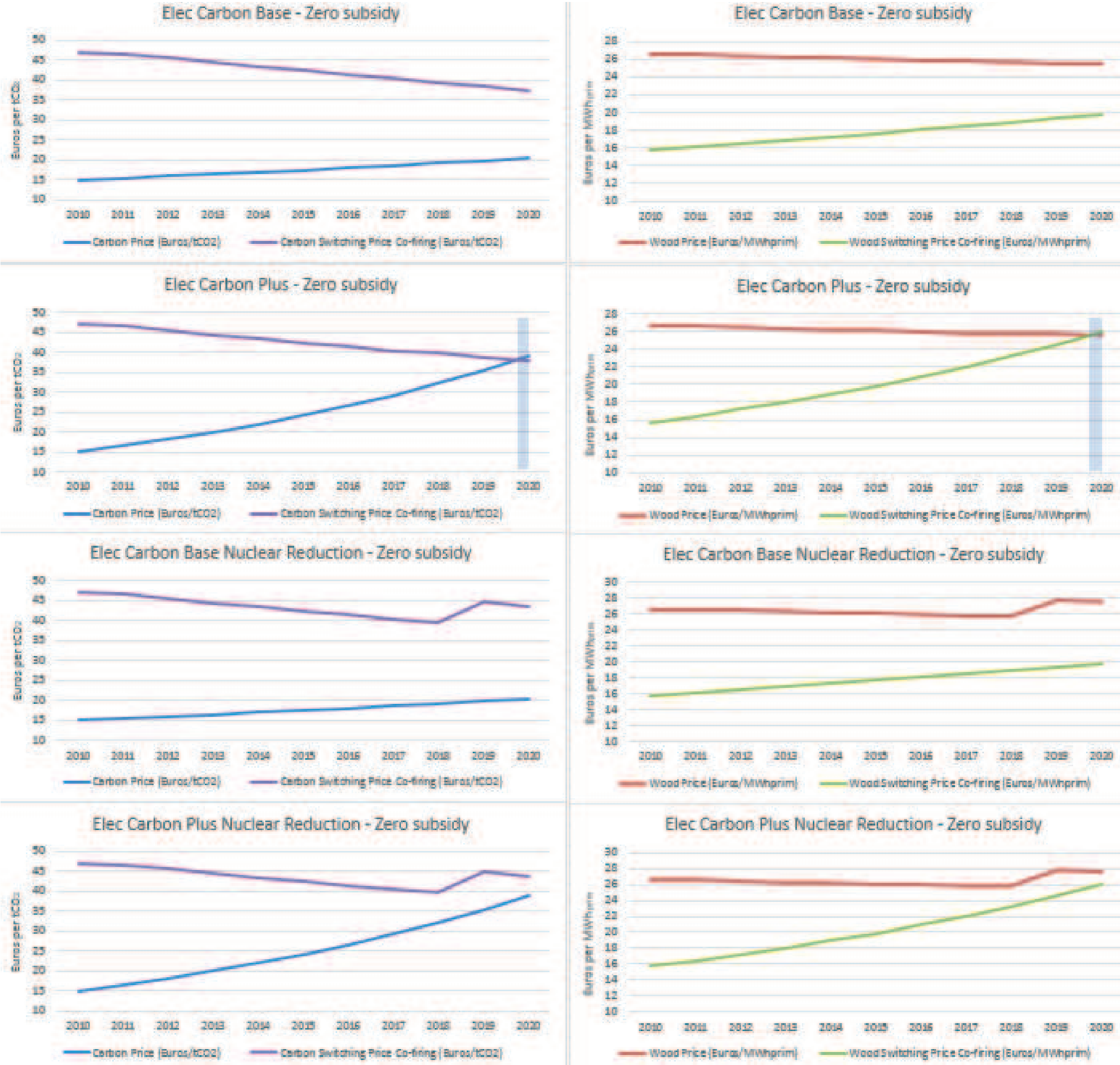

Figure 7: Wood and carbon prices versus wood and carbon switching prices for co-firing, under fixed zero subsidy.

The switching prices correspond to prices that equalize the marginal cost of production of coal plants under classical (*i.e.* when coal is the only input) and co-firing (coal plus wood) configurations. The carbon switching price is the carbon price above which it becomes profitable to run coal plants under co-firing configuration (*i.e.* co-firing is profitable if the carbon switching price is lower than the carbon price of reference). The wood switching price is the wood price beyond which including wood in coal stations is no longer profitable (*i.e.* co-firing is profitable if the wood price of reference is lower than the wood switching price). See Bertrand *et al.* (2014).

Appendix C: Computed LLCOEs for RES technologies for electricity

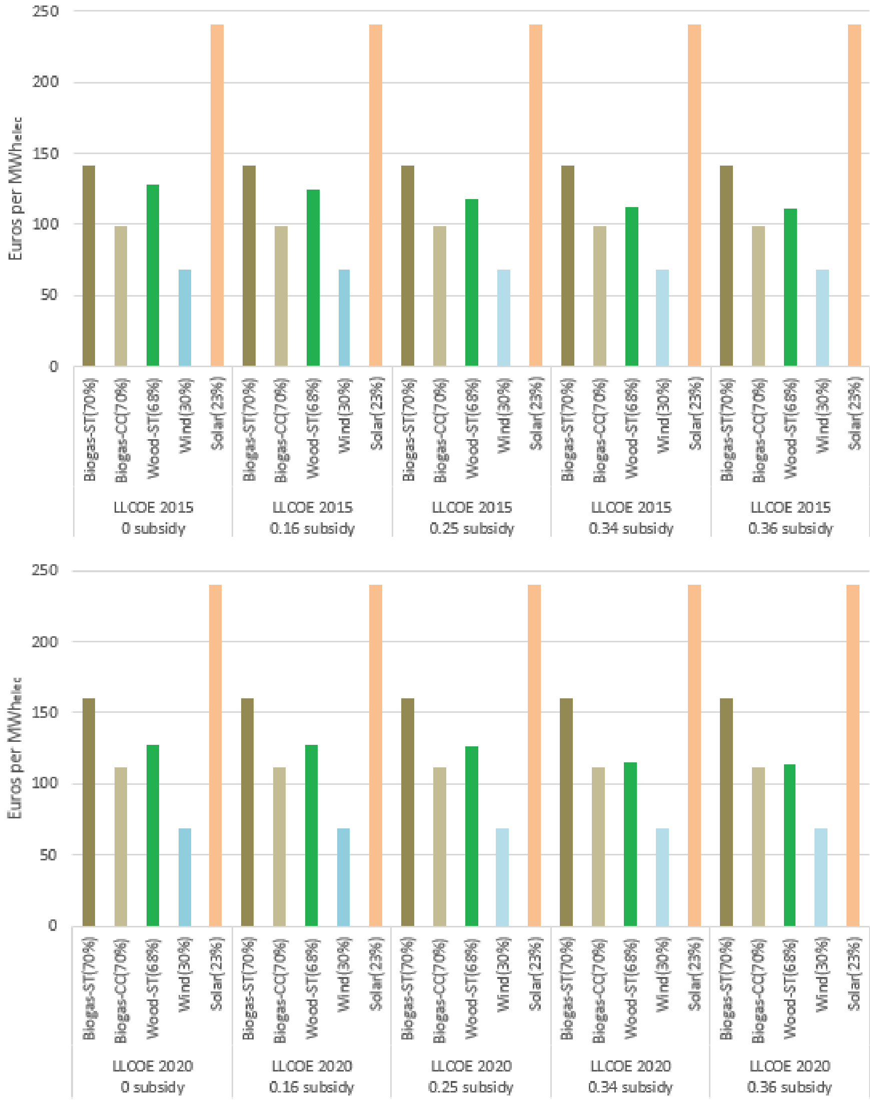

Figure 8: Levelized lifetime cost of electricity computed for the main RES technologies (Biogas-ST = Biogas Steam Turbine ; Biogas-CC = Biogas Combined Cycle ; Wood-ST = Dedicated biomass Steam Turbine), under different fuelwood subsidies. For each technology, the value in bracket reflects the availability factor.

The levelized lifetime cost of electricity (LLCOE) is the usual indicator to evaluate the economic performance of a power system by comparing the whole competitiveness of different technologies. The LLCOE for each unit of electricity generated with a given technology is the ratio of the total lifetime discounted cost versus the total lifetime discounted electricity output. This allows converting all streams of costs (investment, operation and maintenance, fuel, etc) for each technology into the same unit (Euros/MWh_{elec}), taking into account all the discounted expenses over the whole operating lifetimes of power plants. See IEA (2010) and Bertrand and Le Cadre (2015) for an overview.

Appendix D: Assumptions for FW-H carbon content

We use the assumptions of Lobianco *et al.* (2016). They use French data from ADEME (2010, Table 37) and obtain an average carbon emission factor of 0.209 [kg CO2eq kWh^{-1}] for alternative heating sources. To compute the gross calorific power of the wood, they assume fuelwood to have humidity (w) of 15% (over the wet mass). After including the mass of the water, they compute the gross calorific value of oven-dry hardwood and softwood of French species (5.07 and 5.33 [kWh t−1], respectively). Eventually, they convert these values into the gross calorific value obtaining 4.21 and 4.42 [MWh t^{-1}].The gross calorific values for wood are therefore 2.74 and 2.32 [MWh m^{-3}], and the substitution coefficients for hardwood and softwood are 572.07 and 484.72 [kg CO2eq m^{-3}]. The fuelwood energy substitution coefficient is the average of these two values

Appendix E: Emissions factor in power generation

Fuel type	Emissions factors (in tCO_2/MWh_{prim})
Coal – bituminous	0.339
Coal - lignite	0.357
Gas	0.204
Oil	0.268
Wood[a]	0

Table 5: CO2 emission factors from fuels in power generation (IPCC, 2006).

[a] : According with Directive 2003/87/EC (establishing the EU ETS and the related rules) and Decision 2007/589/EC (establishing guidelines for monitoring and reporting greenhouse gas emissions), emissions from burning biomass are exempted from surrendering corresponding allowances in the carbon market. This is equivalent to a zero emission factor applied to wood.

WORKING PAPER

n° 2017-07 • August 2017

DAUPHINE UNIVERSITÉ PARIS

CLIMATE ECONOMICS CHAIR

LATTER ISSUES

Working Paper Publication Director: Philippe Delacote

La Chaire Economie du Climat est une initiative de l'Université Paris-Dauphine, de la Caisse des Dépôts et Consignations et de Total sous l'égide de la Fondation Institut Europlace de Finance

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