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

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Abstract

- We compute the optimal subsidy level for fuelwood consumption that makes it possible to achieve the French biomass energy consumption target.
- For this purpose, we model the competition and trade-offs between the consumption of fuelwood for heat (FW-H) and the consumption of fuelwood for electricity (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 contrasting potential increases in the carbon price and the potential reduction in the number of nuclear plants.
- We assess the implications of these scenarios on (1) the budgetary costs for the government, (2) industrial wood producers' profits, (3) cost savings in the 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 least expensive from a budgetary perspective. Indeed, when associated with a high carbon price, co-firing may increase FW-E demand with a lower subsidy level, which makes it possible to reduce the cost of reaching the target. However, in this case, FW-E crowds out part of FW-H, which may cause political and economic issues.
- From a carbon balance perspective, an FW-H-only scenario performs better than any other scenario that combines FW-H and FW-E due to the relatively low emissions factors of alternative technologies for electricity generation and, in particular, nuclear energy.

Keywords: Forestry sector, Bioenergy, Biomass-based electricity, Carbon pricing, Nuclear power.

JEL codes: Q41, Q48, Q23

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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 the French energy mix by 23% in 2020. In France, where forest resources are abundant—France has the fourth largest forest cover of the 25 EU countries—solid biomass energy is expected to play a major role in achieving this objective (Sergent, 2014; Caurla et al., 2013). More precisely, this objective results in an overall additional biomass consumption target of + 20 hm^3 in 2020 compared with 2006 (Dupuis et al., 2008).

Several programs to stimulate the consumption of energy wood have been implemented to date in order to reach this biomass consumption target. They aim to increase the consumption of wood for heat production in domestic and collective installations (hereinafter referred to as FW-H) or for power production in electricity plants (hereinafter referred to as FW-E). In particular, the ability of power producers to increase FW-E consumption with no investment through the co-firing of biomass in coal plants has led to a strong interest in biomass. The technical potential for FW-E from co-firing in France has been estimated by Hansson et al. (2009) to be 1.24-2.63 TWh/yr (where the highest value assumes the use of all plants ⩽40 years old and the lowest assumes the use of plants ⩽30 years old). With this in mind, five generations of national public tenders have been launched to fund biomass projects for energy production. Meanwhile, France has recently made considerable progress in FW-H markets via the increased use of wood pellets following 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 to heat collective/domestic boilers. They result in a reduced perceived price of fuelwood for the final consumers, either domestic households that use FW-H or power generator owners that consume FW-E.

However, the impact of a subsidy on the consumption of FW-E will probably be different from those on the consumption of FW-H, in terms of both economic outcomes and carbon implications. Indeed, fuelwood is not used with the same technologies, and it does not compete with the same products in heat and power markets.

On the one hand, FW-H demand has been estimated as being quite 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 considered a necessary good for such consumers since 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 among the lowest-income categories of society (Couture et al., 2012). In addition, using wood as a domestic, collective, or even industrial source of heating involves additional technological costs that result in a type of lock-in situation for consumers, which actually increases the inelasticity of demand in the medium and long term.

On the other hand, the use of FW-E in the electricity sector at the national scale depends on the dispatching of different technologies in the energy pool, 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 variables: (1) the relative prices of energy sources and (2) the installed capacities of power plants that use different technologies. Two parameters are likely to play a major role with respect to these variables: carbon prices, which influence the cost of energy according to the carbon content, and the reduction of the share of nuclear energy in the electricity mix, which has to be compensated for by an increased contribution of other technologies, including wood-based power generation[1,2].

One consequence is that while a subsidy for total fuelwood consumption will probably play a rather linear role for FW-H, it is expected to play a non-linear role for FW-E, with threshold levels when power plants switch places in the merit order. For the same reasons, the

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[1] Other drivers can play a role in the use of biomass for electricity. Among them, the GES model considers variables, parameters, and constraints such as the constraint regarding the share of renewables in power generation, the availability of different power technologies, cross-border trade in electricity, and differences in cost and technical parameters for different technologies (see section 3.2.). Beyond this, there are other drivers that are not in the scope of this paper. In particular, the existing infrastructure capacity for fossil fuel use and the preferences of society for renewables and biomass are likely to play a role in the use of biomass for electricity. We discuss their implications in section 6.

[2] In France, the electricity mix is largely dominated by nuclear energy, which represents more than 50% of the installed capacity and about 75% of the power generation (76% in 2015, according to RTE, Statistiques Production Consommation Echanges 2015). Hence, any reduction in nuclear-based power generation in France may induce very substantial effects on the contribution of wood-based power generation and the demand for fuelwood. In particular, the recently passed "Law on energy transition" aims to reduce the proportion of nuclear power by 2025, while obtaining 27% of the total power produced using renewables. This is likely to affect the fuelwood sector.

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

Within this context, our paper simulates a subsidy to total fuelwood (FW-E+FW-H) consumption that represents that stipulated in the current national programs implemented to increase fuelwood consumption by + 20 hm^3 in 2020 compared with 2006.
Our first objective is to compute the optimal level of this accounting for (1) the relative prices of biomass and fuel substitutes in the electricity sector; (2) the carbon price, which affects the costs of other energy sources, and (3) the reduction of nuclear power generation.
The second objective of our study is to compute the impact of this subsidy on the economy of the entire forest sector. Caurla et al. (2013) have already conducted such an analysis but without considering the trade-offs between FW-H and FW-E production. Nevertheless, the impact of such programs on the forest sector remains unclear. First, by competing for the same raw products, these projects could increase competition with the pulp, panel and paper sectors and thus increase the price of these products for the consumer. 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 for the different scenarios in order to compare them both in terms of their ability to contribute to climate change mitigation.

To do so, we coupled two models that represent the consumption of FW-H 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 FW-E on the other (Green Electricity Simulate Model: Bertrand and Le Cadre, 2015).

In the first section, we review previous studies to situate our contribution in the literature. In the second section, we present our modeling framework and the coupling procedure. In the third section, we present the scenarios tested, and we present the results of our simulations in the fourth section. We then provide conclusions in the fifth section.

2. Position of our work in the literature

Several studies have previously question the optimal policies to reach exogenous wood biomass targets.

A first group of studies, stemming from the forest sector modeling literature, addresses the impact of fuelwood subsidies on the forest sector.

In this group of studies, Sløjie et al. (2010) show that subsidizing fuelwood by implementing a tax of €60/CO_2eq on competing fossil fuels could increase bioenergy use in district heating installations by 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 bioenergy use, but the effect of subsidies rapidly decreases if they are applied together with a tax.

Kallio et al. (2011) show that to increase fuelwood availability, industries using sawlogs would need to expand because logging residues and stumps are primarily collected from final fellings driven by sawlog demand. Consequently, policies leading to the increased use of wood in construction could also possibly support renewable energy goals. Moreover, subsidies for combined heat and power production at sawmills could be beneficial in this respect.

Caurla et al. (2013) show that the optimal level and therefore costs of 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 costlier for the government than subsidizing fuelwood consumption. However, an upstream subsidy also reduces competition with other sectors, such as that of pulp, and increases export levels.

A second group of studies focus on the consequences of climate policies for the use of wood biomass in co-firing.

In this vein, Johnston and Van Kooten (2015) couple a mathematical programming model of the electricity grid with a transportation model of wood pellets for Canada in order to compare the impact of a carbon tax with those of feed-in tariffs on the rate of conversion of coal plants to co-fire. They show that there is an upper threshold on a carbon tax after which retrofitting of coal plants is less efficient than increasing natural gas-generating capacity.

Kangas et al. (2009) explore the consequences of feed-in laws (either feed-in premiums or feed-in tariffs) and emission trading on biomass utilization in co-firing. They study two different power plants that are located in two different European electricity market areas and show that feed-in tariffs can lead to an unexpected situation where the wood share in co-firing decreases when the emission credit price increases.

Neither of these two groups of studies above explicitly addresses both FW-E and FW-H. This gap is filled by Kangas et al. (2011), who compare three policies (namely, an investment subsidy, an input subsidy, and a production subsidy) to support biofuel production in the pulp and paper sector. Their model explicitly concerns both electricity and heat production within a bio-refinery but without accounting for the trade-offs between them. They show that any of them could better perform depending on the policy target (cost effectiveness, pulp production profitability, harvest residue use).

Moiseyev et al. (2014) also contribute to filling 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. 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 (IW) use for energy. To do so, they model coal-, gas-, and wood-based power and heat for 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 electricity production.

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

Our paper precisely aims to fill these gaps. We use a modeling framework that represents the fuelwood demand from both the heating market, on the one hand, and electricity, on the other[3]. Trade-offs between the FW-H and FW-E markets are therefore made possible by the coupling procedures. In addition, we model the dispatching decisions for power generation

[3] This approach is close to that of Johnston and Van Kooten (2015), who couple an electricity grid model with a wood transportation model.

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 the decommissioning or prolongation of old units. Hence, the structure of the French electricity park is made flexible, which allows us to analyze any change in the electricity mix in favor of biomass with a degree of flexibility that depends on relative prices and technological and legal aspects. Eventually, we investigate the effect of the exogenous reduction of nuclear power generation, in line with provisions enacted in the French energy transition law of 2015.

3. Methodology and materials

3.1. French Forest Sector Model

The French Forest Sector Model (FFSM) is a recursive bio-economic 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), which comprises 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 account for natural growth and mortality and wood removals from anthropic harvesting.

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 so, the MK module solves a partial equilibrium problem by accounting for the costs of transportation from one region to another, according to Samuelson's (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 agent surpluses.
The model represents the demand of six processed products according to the demand function below (Eq. 1): sawnwood (hard and softwood), plywood, FW-H, pulp, and panels. All these products are sold in a "final" market that targets either domestic users or second-transformation industrials.

$$D_{i,t} = D_{i,t-1}\left(\frac{P_{i,t}}{P_{i,t-1}}\right)^{\sigma} \qquad (1)$$

where:

• $D_{i,t}$ and $D_{i,t-1}$ represent the demand for the processed product in region i in year t and $t-1$.

• $P_{i,t}$ and $P_{i,t-1}$ stand for the prices of the processed product in region i in year t and $t-1$.

• σ is the price elasticity of demand.

On the upstream part of the forest sector, the model represents the supply of three raw products according to the supply function below (Eq. 2): roundwood (hard and softwood) and IW. Wood suppliers are either forest owners or forest managers on behalf of forest owners. The model considers sawmills and harvest residues to be 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.

$$S_{i,t} = S_{i,t-1}\left(\frac{P_{i,t}}{P_{i,t-1}}\right)^{\sigma} \quad \left(\frac{F_{i,t}}{F_{i,t-1}}\right)^{\beta} \qquad (2)$$

where:

• $S_{i,t}$ and $S_{i,t-1}$ represent the supply for the raw product in region i in year t and $t-1$.

• $P_{i,t}$ and $P_{i,t-1}$ stand for the prices of the raw product in region i in year t and $t-1$.

• σ is the price elasticity of the raw product supply.

• $F_{i,t}$ and $F_{i,t-1}$ are the available amounts of timber to be potentially harvested in region i in year t and $t-1$.

• β stands for the elasticity of the supply to stock.

While interregional trade is modeled through the spatial price equilibrium framework, international trade is computed through an Armington framework under the assumption that domestic and foreign products are not fully substitutable (Armington, 1969). International trade is modeled by using exogenous international prices and elasticities of substitution between local and international products specifically estimated for the FFSM in Sauquet et al. (2011).

A complete description of the FFSM is available on the following project website: https://ffsm-project.org/.

3.2. The Green Electricity Simulate Model

The Green Electricity Simulate (GES) Model is a simulation model that is designed to investigate questions related to biomass-based electricity in European countries, with a special focus on 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, the GES model determines the power generation mix (i.e., the dispatch of generation capacities) and investment decisions necessary to satisfy electricity demand at the lowest cost. Furthermore, the model identifies the out-of-lifetime power plants at the beginning of each year (i.e., age > theoretical lifetime)—those that are decommissioned and those that are refurbished and prolonged.

We used the 1.0 version of the GES model (Bertrand and Le Cadre, 2015) in this study, which considers different country modules that can be run separately. To carry out the analysis in this paper, we adapted the French module in a static framework. This allowed us to implement recursive feedbacks in equilibrium calculations of the GES model and the FFSM. This is further discussed in Section 3.3.

3.2.1. Description of the model

The model minimizes the overall cost of electricity (generation and investment), over the 2010-2030 time interval with a range of economic, technical, and legal aspects while taking into account the capacity constraints (generation ≤ available capacity), market clearing for the electricity market, constraints regarding the share of renewables in power generation (as given by the EU Climate and Energy Package), biomass co-firing in coal plants, cross-border trade in electricity, biomass availability (here computed by the FFSM), cost and technical parameters for all the power technologies (operation and maintenance costs, lifetime, investment costs, refurbishment costs, efficiency rates, etc.), and so forth. The complete mathematical formulation and other information regarding the model are provided as supplementary materials (see Appendix G).

For each year in the considered time interval, the model determines the power generation mix (based on a merit order logic) and investment decisions so as to meet the electricity demand with the lowest cost. It computes the optimal dispatch of generating capacities into intra-annual hourly time slices with unequal power demand. This reflects different load levels associated with more or less electricity demand. The model also considers cross-border trades for electricity, with electricity prices (for different pairings between seasons and load curve segments) and transfer capacities evolving over the years. In this work, we did not investigate the consequences for the use of biomass in power when modifying the drivers of electricity trades between France and its border countries. Such investigations would necessitate that we run sensibility analyses on the electricity trade variables (i.e., electricity prices and transfer capacities), which would add more interactions and complications with other scenarios. Cross-border trades in electricity are unlikely to have a very significant impact on the French biomass consumption from power, since the power plants that are exporting electricity from France are primarily base-load units that do not burn biomass. Accordingly, we do not analyze such effects.

In the case of co-firing, we include a constraint in the model to cap the quantity of biomass that can be co-fired in coal plants. We assume that the biomass share cannot exceed 25% (on an energy basis) of the overall fuel (biomass and coal) blend. This corresponds to biomass with medium quality, such as wood pellets, which provides an intermediate solution between the lower (i.e., raw materials, such as agricultural residues or untreated wood chips) and the higher (i.e., pellets of torrefied biomass) quality of biomass fuels. We assume here that the intermediate quality reflects the composite fuelwood product that is considered by the FFSM. This is in line with technical literature on co-firing, which reports that when no investment is implemented to retrofit a coal plant, the biomass rate can reach up to 10% for raw materials, 20-25% for wood pellets, and 50% for torrefied biomass (Ecofys, 2010; IEA-IRENA, 2013)[4].

To account for a possible increase in the generation cost related to co-firing, we model a reduced efficiency rate for coal plants that are run under a co-firing configuration. Thus, η^{cf} is the reduced efficiency rate (MWh_{elec}/MWh_{prim}) of coal plants under co-firing due to

[4] We do not consider investments to retrofit coal plants so as to increase the percentage of co-fired biomass. This is a common approach in the economic literature on co-firing, which mainly focuses on what can be implemented without investment rather than investigating the potential of more ambitious co-firing projects that need retrofitting. We can mention here the contributions of Hansson et al. (2009), Kangas et al. (2009), Kangas and Lintunen (2010), Bertrand et al. (2014), Xian et al. (2015), and Mei and Wetzstein (2017). All these studies consider the biomass percentage to be about 15-25% for co-firing without retrofitting. Notably, both Xian et al. (2015) and Mei and Wetzstein (2017) assume a maximal biomass rate of 25% for co-firing with wood pellets in coal plants that have not been retrofitted (which is the focus of our work).

possible loss with biomass (because of an increase in moisture content or the presence of air). In this case, $\eta^{cf} < \eta^{nocf}$, where η^{nocf} is the efficiency rate of coal plants under the classical configuration when coal is the only input. Following Ecofys (2010), we assume a linear relationship between the efficiency losses and the incorporation rate (i.e., the percentage of biomass in the blend). Then, we express η^{cf} as follows:

$$\eta^{cf} = \eta^{nocf} - \rho\, inc \qquad (3)$$

where ρ is the loss coefficient measuring possible decreases in the efficiency rate of coal plants under co-firing with biomass and inc represents the incorporation rate (Bertrand et al., 2014; Bertrand and Le Cadre, 2015). For the purpose of this work, we assume a single representative type of fuelwood with $\rho = 0.01$ and $inc = 0.25$. In this case, assuming coal plants with a 38% efficiency rate ($\eta^{nocf} = 0.38$), we get $\eta^{cf} = 0.3775$. This is in line with Baxter (2005), who indicates that the efficiency loss associated with co-firing may represent a 0-10% loss in conversion efficiency.

The modeling framework can also be used to investigate the consequences of modifications in generating capacities through investments in new power stations and decisions regarding decommissioning or prolongation of old units that have exceeded their theoretical lifetime. Price trends for fuels and carbon are taken into account in such decisions. Investments rely on comparisons between the levelized lifetime cost of electricity (LLCOE) of different power technologies, such that in each period, the model considers the present and the future values of the LLCOEs for all technologies, which depend on the price trends for fuels and carbon in the future. However, the model has been adapted from a dynamic to a static framework for this work in order to implement iterations between the FFSM and the GES model (see Section 3.3). Then, with the static and iterative approach that we use in this work, the LLCOEs are still modified through time as prices evolve, but investment decisions consider only the current values that are based on prices that prevail in the period at hand. That is, investments depend on price evolutions, but the decisions are based on a myopic approach.

3.2.2. Main data

The dataset for the power system is based on a literature review providing representative values for cost and technical parameters associated with different power technologies of varying vintages, including efficiency rates of power plants, load factors, fixed and variable operation and maintenance costs, refurbishment costs, decommissioning costs, and theoretical lifetimes (depending on whether stations have been prolonged) (see Appendix G).

The model has been calibrated to actual market data for the base year (i.e., 2010). We focused on reproducing the observed yearly generation by fuel through iterative adjustments of availability and marginal costs so as to best replicate the French power generation mix as given by RTE (2011).

Coal (bituminous), gas, oil, and carbon prices are based on the Current Policy Scenario (CPS) from IEA (2012), and other fuel prices are derived from the literature review. In all cases, the model considers price trends that are indexed on the Average Annual Growth Rates (AAGRs) from the IEA-CPS scenario as well as other projections (from different references) reflecting specific evolutions in other fuel industries (e.g., uranium, lignite, and biogas; see Fig. 1 below).

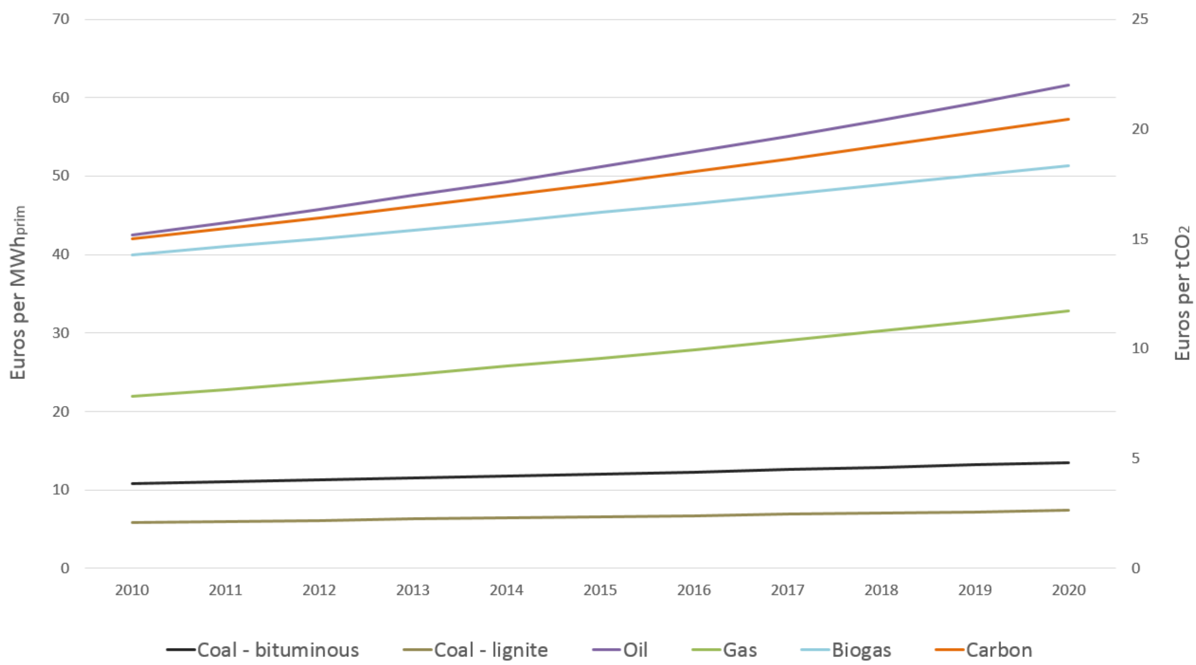

Figure 1: Main fuel and carbon prices.

The annual electricity demand is obtained from the 2010 ENTSO-E values to which we apply the AAGRs from the IEA-CPS scenario to compute projections over the time interval[5]. The resulting yearly demands are then disaggregated on hourly levels by using weighting

[5] See Power Statistics on www.entsoe.eu.

coefficients reflecting intra-annual time slices of varying length and power load (Bertrand and Le Cadre, 2015).

Regarding the installed capacities for power plants, the model uses data from the World Electric Power Plants (WEPP) database by Platts, which provides a global inventory of electric power stations with information such as location, year of commissioning, and size.

3.3. Coupling procedure

To recursively adapt the computation in one model based on the results of the other model, we iteratively ran the two models with one time lag between the FFSM and the GES model in each iteration. This is illustrated in Fig. 2.

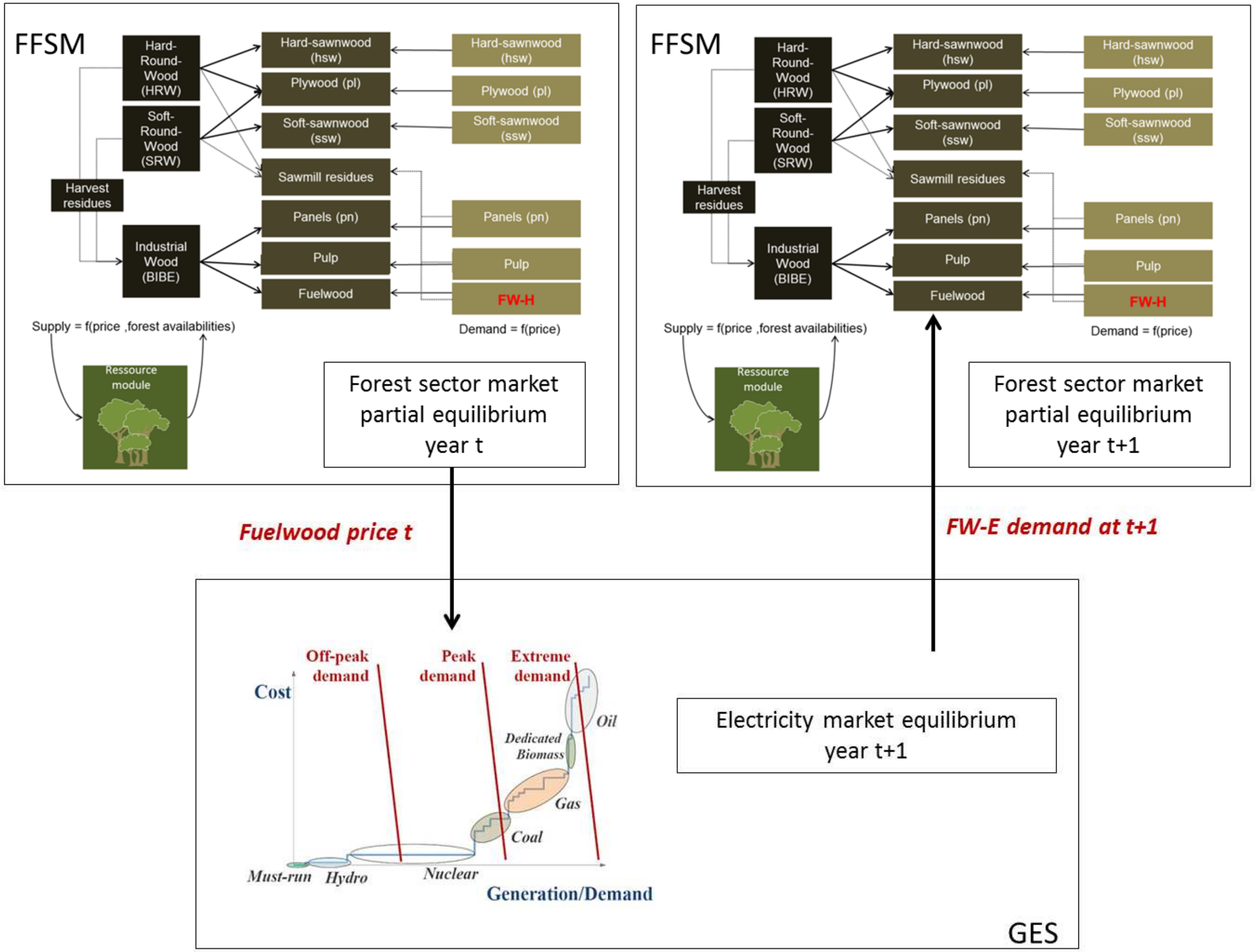

Figure 2: Coupling procedure between the FFSM and GES model for year *t* and *t+1*.

The FFSM first computes a partial equilibrium for forest markets for period *t*. This equilibrium is associated with the equilibrium supply and demand quantities and with an equilibrium price for each forest product. In particular, the FFSM computes the optimal FW-H demand and the optimal FW-H equilibrium market price for period *t*. This optimal FW-H market price is then given to the GES model as a proxy for the FW-E market price in the electricity sector for period *t*+1. Given this price, as well as prices for other energy sources, the electricity market equilibrium is computed in the GES model for year *t*+1. This market equilibrium is associated with the optimal demand of FW-E (see Section 3.2.1). This demand is then translated into the FFSM as an exogenous "additional demand" of fuelwood (i.e., additional to the endogenous FW-H demand) to compute the *t*+1 equilibrium in the FFSM. In this way, we can compute a new fuelwood equilibrium price, which will reflect the market conditions with the new FW-E demand and the endogenous trade-offs between the production of FW-H and the production of FW-E. The new fuelwood equilibrium price is then considered in the GES model as the reference price for period *t*+2, which will determine the new FW-E demand of *t*+2 and so on for the following iterations.

In the FFSM, the supplementary demand from electricity in every region i ($LDelecBE_i$) is directly introduced into the material balance (Eq. 4) and into the economic surplus related to fuelwood consumption.

$$LDelecBE_i + LD_i + \sum_j e_{i,j} = S_i + \sum_j e_{j,i} \qquad (4)$$

where:

- $LDelecBE_i$ is the amount of fuelwood consumed by electric plants in region *i*.
- LD_i is 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*.

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 that $LDelecBE$ is distributed among the 22 French administrative regions through a range of $LDelecBE_i$, while accounting for the available forest resource stock in each region computed on a *pro rata* basis. This assumption can be considered a simplified but not unrealistic vision of reality in which public power plants favor harvests in high forest-production areas in order to limit over-harvesting in low production ones.

4. Which forest and energy policies influence fuelwood consumption? Presentation of different scenarios

We considered two types of policies that are capable of influencing overall fuelwood consumption. Forest sector policies directly influence fuelwood consumption, while energy sector policies have an indirect impact. Regarding forest sector policies, we simply considered a consumer subsidy aimed at reducing the price perceived by fuelwood consumers. Concerning energy sector policies, we assessed 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

To increase the total fuelwood consumption by +20 hm^3 in 2020, we introduced a consumer subsidy to purchase fuelwood. Consumer subsidies decrease the fuelwood price paid by consumers, which increases its demand (Caurla et al., 2013)[6]. We assumed that the subsidy was implemented in 2010 and that it remained constant (in relative terms) until 2020. This is summarized by Eq. 5.

$$P_t^{sub} = P_t \ (1 - sub) \qquad (5)$$

where:

- 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 since the overall objective can be achieved either by increasing FW-H only or by increasing both FW-H and FW-E. The results are presented in Section 4.3.

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

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

We considered two parameters that can play 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 that biomass is carbon neutral[7]. Hence, a higher carbon price may increase the contribution of dedicated biomass units by improving their relative competitiveness compared with units that have costly CO_2 emissions.

Therefore, we first investigated the extent to which a high carbon price can help a country reach the +20 hm^3 consumption objective with a lower subsidy level. Indeed, an increase in the carbon price is expected to produce a significant impact on 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 the context of high carbon constraints in the European power sector[8]. To account for rising carbon prices, we considered two different price paths computed with the IEA (2012) CPS as a reference: *Carbon Base* (CPS carbon price path, which corresponds to a 3% AAGR) and *Carbon Plus* (an increased carbon price path compared with the CPS, which corresponds to a 10% AAGR). The resulting carbon price paths are depicted on the carbon switching price graphs for co-firing in Appendix B (Figs. 7 and 8). Note that these paths do not objectively reflect what has been observed in the EU ETS over the last few years. However, this is not a problem in our case since our aim is not to produce a prediction based on actual past market conditions but, instead, to investigate the fuelwood demand response to high levels of carbon prices.

[7] We provide an in-depth discussion of carbon neutrality in Appendix F.
[8] Since the beginning of the EU ETS (European Union Emission Trading Scheme) in 2005, a constant feature of the scheme has been to impose the main part of the emission abatement effort on electricity. This is justified by the high potential of short-term carbon abatement in this sector compared with the other industries covered. Another explanation relies on the non-exposure 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 Phase 3 in 2013, it is the only sector that has to deal with a 100% auction allocation regime (Solier, 2014).

Second, the share of nuclear power in the electricity mix is another element that can affect the fuelwood demand. Any reduction of nuclear-based power generation has to be compensated for by an increased contribution of other technologies that would be substituted for nuclear power. 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 sufficiently high (low, resp.). Consequently, the interaction between the carbon price and the decrease in nuclear power is crucial: the redistribution of electricity sources resulting from the decrease in nuclear power would probably be favorable to fuelwood if the carbon price is higher. To analyze this, an additional constraint is added to the electricity model, with a maximal percentage of nuclear power in the overall power generation for each year. This percentage is gradually decreased to reach 50% in 2020[9]. Table 1 summarizes the different scenarios tested.

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

[9] The 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 ages strictly greater than the theoretical lifetime) will take place after 2020, whereas the +20 hm^3 fuelwood consumption target has to be reached in 2020. Hence, to analyze the effect of reduced nuclear power generation, we add a constraint regarding the maximal share of nuclear power in the overall power generation. In this way, we can assess the impact of reduced nuclear power generation on the level of the fuelwood subsidy to reach the consumption target. Note that 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 power in overall French power generation by 2025.

	Carbon plus trajectory for the carbon price No constraint on power generation from nuclear power plants
Elec Carbon Base Nuclear Reduction	Fuelwood for heat & electricity Subsidy for fuelwood consumption to reach +20 hm3 by 2020 Carbon base trajectory for the carbon price Constraint to cap power generation from nuclear power plants
Elec Carbon Plus Nuclear Reduction	Fuelwood for heat & electricity Subsidy for fuelwood consumption to reach +20 hm3 by 2020 Carbon plus trajectory for the carbon price Constraint to cap power generation from nuclear power plants

Table 1: Scenarios.

Four types or results are analyzed below. 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 affect the composition of fuelwood use. Third, we explore the economic impact in the forest sector, and fourth, we focus on carbon assessment.

5. Results

5.1. Subsidy levels

We computed the subsidy levels required to reach the +20 hm^3 target in each scenario. The 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 +20 hm^3 objective	Share of fuelwood for heat (FW-H) in % of the +20 hm^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, the results in Table 2 show that considering fuelwood to be a potential source of electricity production is crucial from a cost-effectiveness perspective: the required level of subsidy necessary to achieve the +20 hm^3 target is twice as low when electricity production is introduced into 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 a considerable 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 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 hm^3 target is consumed as FW-E. In this case, any variation in the FW-H consumption is due to the trade-off between two opposite effects: (1) the subsidy effect, where the subsidy for fuelwood consumption reduces the price perceived by FW-H consumers, which tends to increase their demand; and (2) the scarcity effect, where the increase from the electricity 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 to be sensitive to the nuclear capacity, while the carbon price has very little if any impact.

Dedicated biomass units or co-firing?

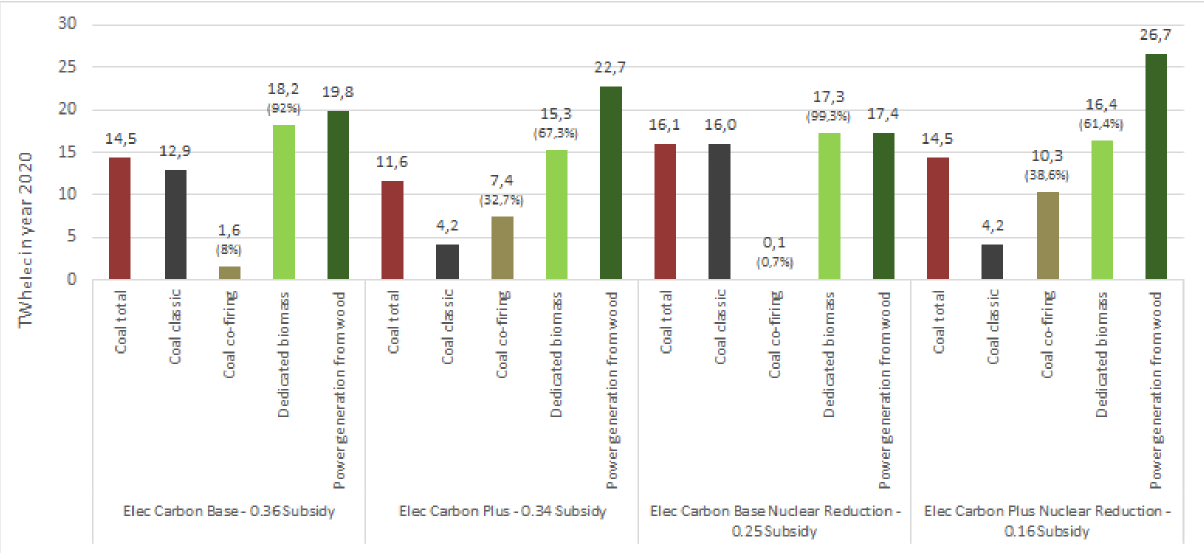

Figure 3: Power generation from coal and biomass dedicated stations under different scenarios with calibrated subsidy levels.

Regarding the FW-E sector, it appears that fuelwood demand is more concentrated 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 regarding the share of RES in the French power generation for 2020 (MEEDDM, 2008), whereas there is no investment for coal in either of the scenarios[10]. This 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 dedicated biomass units, whereas it is only part of the overall fuel entering 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 sensitive to the subsidy, whereas the opposite occurs with dedicated units. This is illustrated in Fig. 3, which shows that increasing the carbon price generates a straight increase in co-firing in all cases, whereas it is more ambiguous for dedicated units (which are more affected by the simultaneous

[10] Generation capacities for dedicated biomass units will evolve from 58 MW in 2010 to 3058 MW (2020 in Elec Carbon Base with a 0.36 subsidy), 2565 MW (2020 in Elec Carbon Plus with a 0.34 subsidy), 2915 MW (2020 in Elec Carbon Base Nuclear Reduction with a 0.25 subsidy), and 2750 MW (2020 in Elec Carbon Plus Nuclear Reduction with a 0.16 subsidy).

decrease in the level of the subsidy to reach the +20 Mm^3 target)[11]. In fact, increasing the carbon price has a direct effect on co-firing since it makes it more profitable than coal-only configurations (i.e., when coal is the only input). In contrast, in the case of dedicated units, this has only an indirect effect (because dedicated units are assumed to be carbon neutral since biomass is their only input) by increasing the relative competitiveness of investments in such units.

Inversely, when considering variations in the subsidy level, this produces a relatively greater effect on dedicated units because the subsidy affects the whole fuel input in this case, as opposed to only a part of it with co-firing. This result is in line with that of Johnston and Van Kooten (2015), who show that up to an upper carbon price threshold, a carbon tax is likely to retrofit coal plants to co-fire with biomass, which is not the case with a feed-in tariff, as it specifically targets biomass energy, the same way that our subsidy does.

Regarding the impact of reducing the contribution of nuclear power, Fig. 5 in Appendix A shows that for a fixed level of the subsidy, this contributes to increasing wood-based power generation and thus the demand of FW-E. Consequently, reducing the nuclear capacity makes it possible to reduce the level of the subsidy to reach the same +20 hm^3 target. In our scenarios, because the subsidy level is simultaneously decreased, reducing the contribution of nuclear power appears to produce a greater increase in co-firing, which is less dependent on subsidies—compared with dedicated biomass units (Fig. 3). However, when we remove the effect of the simultaneous decrease of subsidies, the opposite occurs, with a greater increase in dedicated biomass units when the nuclear contribution is reduced due to investments in dedicated units to fill the nuclear gap (see Appendix A).

5.3. Impact on the forest sector economy

Scenario	Perceived fuelwood 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 with 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

[11] To disentangle the nested effects of carbon price increases and the simultaneous decrease in subsidies (which counteract with each other in our scenarios), we ran the models with fixed subsidy levels (neglecting the +20 hm3 target). The results are presented in Appendix A.

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 the FFSM. Three main results can be observed from this table.

First, as shown in column 2, the different scenarios show contrasting effects on fuelwood prices as perceived by consumers. This is because two opposite forces drive the price. On the one hand, the subsidy for fuelwood consumption reduces the perceived price; on the other hand, the FW-E demand from the electricity sector eliminates a certain amount of fuelwood, increasing scarcity and thus the market price. The first effect usually dominates the second, with a fuelwood market price that is lower with the introduction of forest and energy sector policies compared with the baseline. However, it appears that when a high carbon price is combined with 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 since FW-H consumption slightly decreases compared with the business-as-usual scenario (-0.6%). One possibility to counteract this effect would be to implement a higher subsidy for FW-H consumption than for FW-E consumption.

Second, in column 4 of Table 3, we present the pulp price as a competition index. Although the pulp price increases in all scenarios, the inclusion of FW-E globally limits this impact compared with the "Heat Only" scenario. This is directly linked to the value of the fuelwood market price: the higher the fuelwood market price, the higher the pulp price, and the stronger the competition[12]. The fuelwood market price increases with both the subsidy (price) effect and the scarcity (quantity) effect[13]. 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," the fuelwood market price is higher in the latter case due to an increased scarcity effect. In this case, the combination of subsidy and scarcity effects leads to a lower level of

[12] This is due to modeling assumptions in the FFSM: in the model, pulp, panels, and fuelwood are made with the same raw material, namely, IW. If the market price of one of these transformed products increases—fuelwood in this case—the attractiveness of this particular transformed product for IW suppliers increases. Meanwhile, consumers are subsidized for their fuelwood consumption, i.e., their perceived price is lower than the 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 panel sectors, increasing competition.

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

competition in "Elec Carbon Plus" than in "Elec Carbon Base Nuclear Reduction," despite the higher subsidy level.

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

5.4. Carbon impact

FW-H and FW-E are substitutes for different energy alternatives, and the proportions of FW-H and FW-E differ between our five scenarios. We therefore expect that the overall carbon implications will be different for the five scenarios.

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 by using wood instead of alternative 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 by using data presented in Appendix E. Then, by subtracting this value from the CO_2 content of the baseline power mix (i.e., Carbon Elec Base with a zero subsidy for fuelwood; line 2, Table 4), we obtain the amount of CO_2 saved or increased by using an alternative energy mix for power production.

Scenarios	Fuel	MWh_{prim}	Emissions ($MtCO_2$)	Total emissions ($MtCO_2$)	Emissions saved compared with 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 differences from the baseline.

Table 4 shows that all of the scenarios except "Elec Carbon Base Nuclear Reduction" lead to carbon savings compared with the initial emission 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 fossil fuels for nuclear fuel also depends on the carbon price, which is lower in the "Elec Carbon Base Nuclear Reduction" scenario 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). Notably, the carbon price level in this case is not sufficiently high to generate co-firing, whereas co-firing is implemented in the "Elec Carbon Plus Nuclear Reduction" scenario (see Figs. 3 and 7). Therefore, in the "Elec Carbon Base Nuclear Reduction" scenario, not only is the power generation from coal and gas increased but the coal stations are run with coal as a single input. This explains the increased CO_2 emissions in this case.

Scenarios	FW-H (hm^3)	Emissions avoided 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 purposes clearly leads to the best carbon outcome. This is because the alternative 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: (1) the high proportion of nuclear energy (carbon-free) in the overall French electricity mix; (2) the carbon neutrality assumption for wood biomass. In our case, carbon neutrality is based on a biophysical principle that assumes that the biogenic carbon released by burning wood is recovered by growing trees. As extensively explained in Appendix F, this assumption holds only if forests that provide energy wood are in an *at-equilibrium steady state* and are managed in a sustainable way—i.e., harvested trees are replaced by new growing ones. Since the carbon released is not instantly recovered by growing trees, the carbon-neutrality assumption is not valid for short-term horizons. We therefore consider the system for 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) IW producers' profits, and (3) cost savings in the power sector for the different scenarios tested in 2020. They are presented on a histogram in Fig. 4.

Cost savings in the power sector refer to the savings due to the fuelwood subsidy, and they are presented in Table 4. These cost savings are non-linearly correlated with the level of subsidy since they account for the costs of all energy sources, not only those from fuelwood.

IW sector surplus gains and budgetary costs of the subsidy were taken from Table 3 in Section 4.5.

Scenario	Power generation cost savings compared with 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: Cost savings due to subsidies in the power sector in 2020.

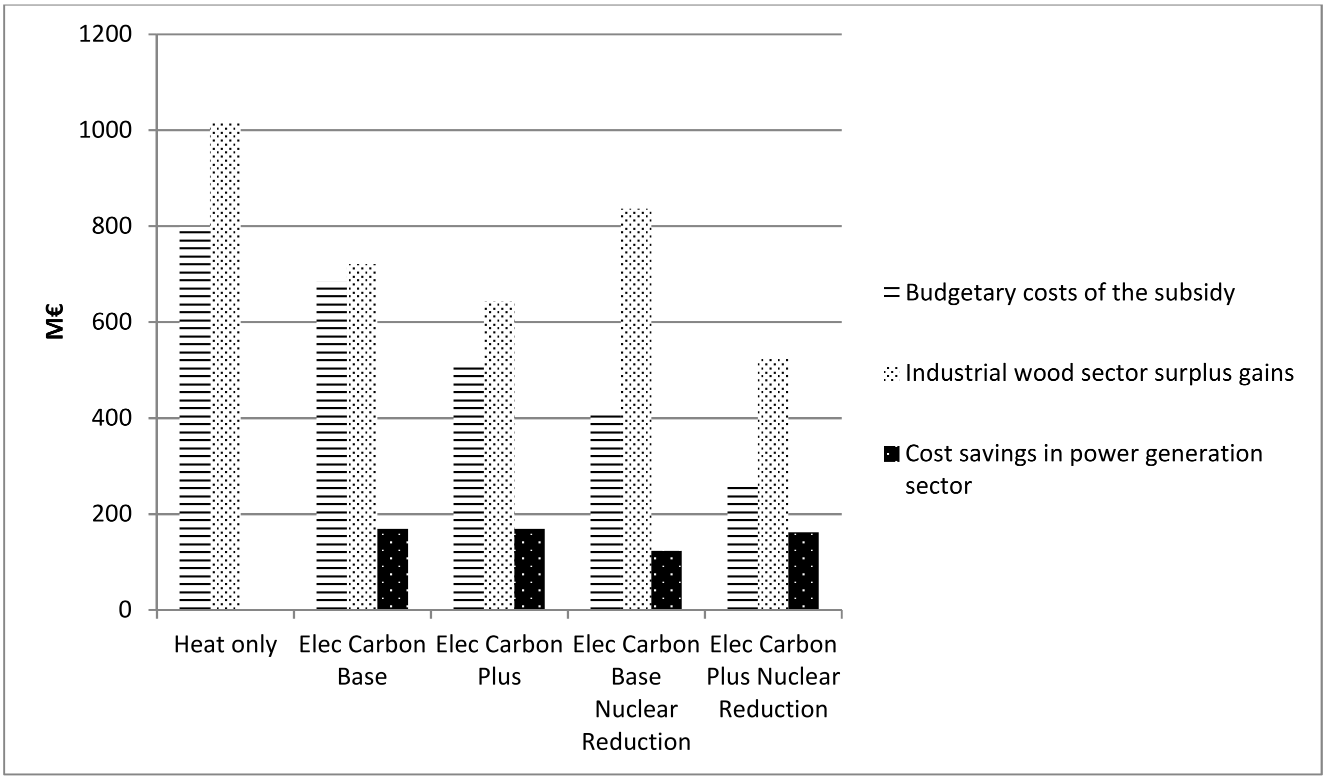

Figure 4: Comparison of the different costs for each scenario in 2020.

Two key findings emerge from Fig. 4.

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 least 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 raises questions about the political feasibility of reaching the target within this option. More generally, the reduction of the nuclear contribution appears to be a cost-effective option by reducing the level of subsidy necessary to reach the target.

Second, and in contrast, the Heat Only scenario is the most expensive, partly because of the windfall effect, which benefits consumers who have already used FW-H as a heating source without a subsidy and who are now subsidized for doing so. This windfall effect also occurs in the power sector (FW-E, which was used without a subsidy is now subsidized), but the consumption increases by about +3500% for FW-E (see Table 4), while it increases only by about 60% for FW-H compared with the baseline without a subsidy, making the windfall have far less of an effect in the electricity sector than in the heating sector[14].

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

6. Discussion and conclusion

The reduction of the contribution of nuclear power to the energy mix is at stake in many countries. Moreover, reducing the carbon intensity of energy production is another and possibly contradictory objective. In France, the electricity sector has historically relied on nuclear power, which makes France one of the least carbon-intensive among EU countries in terms of electricity. The national "law on energy transition" was recently passed, which aimed to reduce the proportion of nuclear power by 2025[15]. Meanwhile, renewable targets have been set at both European and national levels. For the electricity sector, it can therefore be expected that part of the nuclear reduction will be offset by an increase in 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 regarding what would be the most cost-efficient way to increase total fuelwood consumption. This question provided the general guidelines for our work.

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

To address these implications, we combined two partial equilibrium models through a soft-coupling procedure and simulated the impact of direct subsidies for biomass consumption with alternative carbon prices and nuclear capacities in order to reach the overall +20 hm^3 biomass target. This analysis framework has the huge advantage of making it possible to simulate all the synergies, competitions, and technologies within the sectors represented. Moreover, regarding our scope, we do aim not to provide a prediction on a 2020 time horizon but to provide more of a projection of "*what would have happened if.*" In other words, the strength of our analysis lies more in its comparison between the different scenarios in which we test different values for different variables than in the absolute values computed by the models. We think that our coupling procedure underlines the economic determinants of a

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

particular phenomenon, as it points out orders of magnitude and highlights the sensitivity of key parameters. In this vein, five key results emerged from our analysis:

(1) Two opposite effects affect the consumption of FW-H: the subsidy effect, which reduces the price perceived by FW-H consumers, and the scarcity effect, which results from increasing FW-E consumption. In our scenarios, the subsidy effect always dominates the scarcity effect except when nuclear capacity is reduced and the carbon price is high. In such a case, the level of subsidy required to reach the target is very low, and the additional fuelwood consumption is entirely captured by the electricity sector.

(2) Dedicated biomass units and co-firing plants do not respond similarly to policy incentives. Compared with each other, dedicated units appear to be more sensitive to direct subsidies, while co-firing benefits more from a rise in carbon prices. In fact, both benefit more from a policy that increases the immediate profitability. Subsidies reduce the FW-E price on which the dedicated units totally rely, whereas the carbon price reduces the cost of co-firing compared with running coal stations with coal as the only input.

(3) Nuclear reduction works in a somewhat different manner, since it initially involves an impact on quantity: reducing the nuclear capacity mechanically translates into an increase in other technologies in order to provide the required quantity of electricity, including biomass—either in dedicated units or co-firing. This rise in biomass consumption automatically reduces the level of subsidies necessary to reach the fixed target. Since dedicated units are relatively more sensitive to subsidies than co-firing, nuclear reduction may then appear, though indirectly, to favor co-firing compared with dedicated units.

(4) This latter effect has a counterintuitive effect on the carbon outcome. If the carbon price remains low, reducing the nuclear capacity may increase the profitability of classic configurations for coal plants, which increases coal emissions. If the carbon price increases, the level of subsidies required diminishes and becomes too low to be able to overcome the scarcity effect for FW-H consumption, which translates into a lower use of wood for heat purposes and thus a worse situation in terms of emissions compared with a case without nuclear reduction.

(5) For the same reasons, the perceived price of fuelwood for FW-H consumers increases in this last case, reducing their economic surpluses, which raises questions regarding

the political economy of such an option. However, reducing the nuclear capacity is logically the least expensive option since it relies less on subsidies and therefore reduces the windfall effect.

Regarding these five groups of results, it appears that the answer to the initial question—"How to reach the fuelwood consumption target at the lowest cost?"—is not straightforward. From a strictly budgetary perspective, the combination of favoring FW-E and relying on nuclear reduction with a high carbon price performs better in our simulations since it limits the level of the subsidy required and the subsequent windfall effect. Moreover, from future capacity development perspectives in the electricity sector, a high carbon price combined with a moderate subsidy level makes it possible to invest in dedicated units. Although it favors co-firing more than dedicated units at first, it can be surmised that the investments lead the way to an increase in overall dedicated capacity. Moreover, the IW sector perspective may favor FW-H compared with FW-E since it requires a higher subsidy to reach the target, thus leading to a higher selling price for IW producers. However, we saw that this result mainly relies on the short-term windfall effect and that it is highly dependent on political decisions. Eventually, from a climate mitigation perspective, using wood for heat production clearly performs better, whereas reducing nuclear capacity may lead to a pernicious effect by increasing GHG emissions compared with the baseline. In addition to these considerations, we are aware that our analysis remains incomplete and that it would benefit from extending the multi-criteria analysis to others sectors. In particular, though fuelwood is assumed to be carbon neutral, it emits other particles, some of which can have huge implications on local pollution and human health. The types and quantities of particles emitted depend on the combustion technologies. Within this context, an additional cost assessment focused on the cost for human health would add value to the work done. One way to do so would be to couple a Life Cycle Analysis of the fuelwood sector with a valuation of air pollution.

Eventually, while our analysis mainly focused on the carbon price and nuclear share as potential drivers of biomass use in electricity generation (in combination with other variables in the electricity model), it would be useful to explore the role of other parameters in future studies. In particular, two groups of parameters are likely to play a significant role in biomass adoption: those related to the existing infrastructure capacity for fossil fuels use and those related to societal preferences for biomass and other renewables[16].

These two groups of parameters are highly subject to the *green paradox* and the *divestment effect*. The green paradox refers to a backfire situation in which the expected depletion and/or expropriation of fossil energies can lead to accelerate the extraction, thus resulting in accelerating greenhouse gases emissions (Riekhof and Bröcker, 2017). The divestment effect works in an opposite way, as it relates to the removal of investment assets involved in extracting fossil fuels for economic, social, or moral reasons. It has recently been demonstrated that the divestment effect could prevail over the green paradox when anticipating strong future climate policies (Bauer et al., 2018). Exploring individuals' preferences in renewable energy investments, as done by Aguilar and Cau (2010) for the U.S., could contribute to calibrating the level of the divestment effect in order to test these two sets of parameters in a further study. Regarding the consequences of the future evolution of infrastructure capacity using fossil fuels, another interesting question concerns plans to shut down coal plants that are under consideration in several European countries. In particular, it would be interesting to investigate the effect of retrofitting coal plants to convert them into units burning only biomass so as to comply with the phasing-out obligations for coal-based electricity. This may be another avenue for future research.

[16] One would also consider alternative price paths for fossil fuels in order to investigate the effect of modifying the relative prices of fuels. Variations in relative prices are accounted for in the case of fuelwood, through there are different prices computed by the FFSM and the two paths that we consider for the carbon price. However, we did not include alternative price paths for other fuels in our analysis. First, although variations in prices of fossil fuels may affect the use of fuelwood, the effect would be indirect and less effective compared with variations in the prices of fuelwood and carbon, which modify the profitability of fuelwood against all the polluting fossil fuels and not only one. Second, a relevant analysis involving variations in relative prices of fossil fuels would need to account for some market events that may justify variations (e.g., effects of shale gas, geopolitical issues in the Middle East, the new policy of the US Trump Administration to promote American mining jobs). Overall, this would complicate the analysis and multiply the number of scenarios, whereas the effects are likely to be small in the case of France, where gas, coal, and oil account for about 5, 4, and 2% of French power generation. Accordingly, we decided to not investigate the effect related to variations in the relative prices of fossil fuels.

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

Carbon price:

Results with 0 and 0.3 fixed subsidy levels appear on Fig. 5. We can observe that moving from a 0 to a 0.3 subsidy produces a stronger effect on dedicated biomass units 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 a 0 or a 0.3 subsidy level. Co-firing directly increases with the carbon price, *ceteris paribus*. Notably, Fig. 5 shows that when the subsidy level is set to zero, modifying the carbon price from *Carbon Base* to *Carbon Plus* may induce a situation where co-firing accounts for almost 70% of wood-based power generation. In our case, by increasing the maximal wood price beyond which co-firing is no longer profitable (i.e., the wood switching price increases; see graphs in Appendix B), a carbon price rise makes it possible to generate 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 a lower subsidy level, making it possible to reduce the cost of the policy. In this way, co-firing may produce a kind of positive externality by making it possible to increase fuelwood demand with a lower subsidy level.

Nuclear reduction:

Looking at the impact of nuclear reduction, we observe that when we remove the effect of a simultaneous decrease of a subsidy, dedicated biomass units 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 units are more profitable when the subsidy is not reduced, which explains why existing units are preferable and new investments are implemented to fill the nuclear gap. In this case, investments in dedicated units are all the more interesting because they make it possible to fill the need for new generation capacities in a way that helps to comply with the RES constraint, relying on an 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 capacity may diminish the contribution of co-firing, whereas dedicated biomass is significantly increased (Fig 5).

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 biomass units, the RES constraint is an additional driver (compared to co-firing), which makes it possible to simultaneously fill the nuclear gap and comply with RES requirements with a competitive RES technology (see Appendix C). Hence, investments in dedicated biomass units triggered by this double effect (reduction of nuclear capacity and the RES constraint; Fig. 6) generate a sharp increase in wood demand from dedicated units (without any subsidy), which, in turn, increases the fuelwood price due to a scarcity effect in the wood market because of this additional FW-E consumption under a zero subsidy. Regarding co-firing, the resulting market price for fuelwood is too high to make it profitable, even with higher carbon prices (Carbon Plus). This is illustrated by Fig. 8 in Appendix B, which shows the switching prices for co-firing under a zero subsidy.

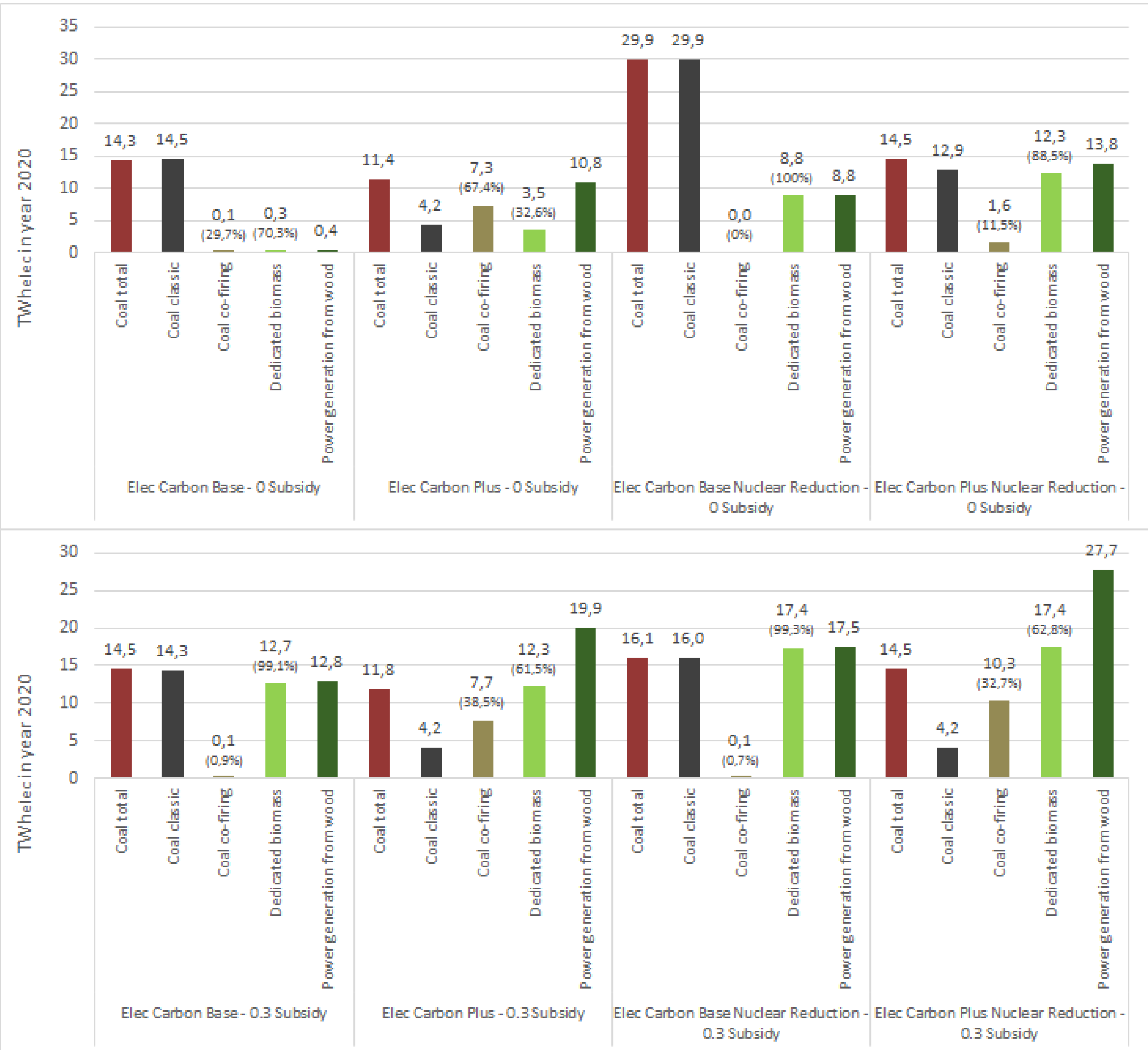

Figure 5: Power generation from coal and dedicated biomass stations under different scenarios and fixed subsidy levels.

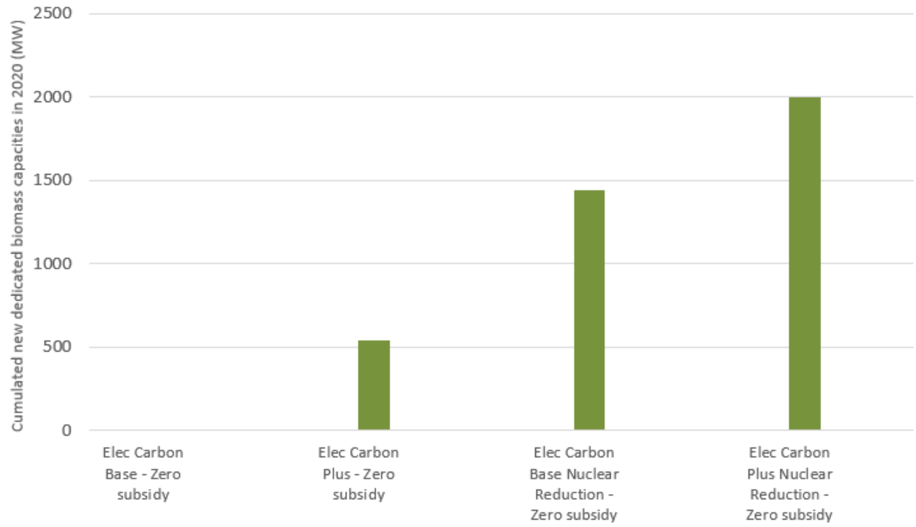

Figure 6: 2020 Cumulated investment in dedicated biomass power under a fixed zero subsidy.

Appendix B: Switching price analysis for co-firing

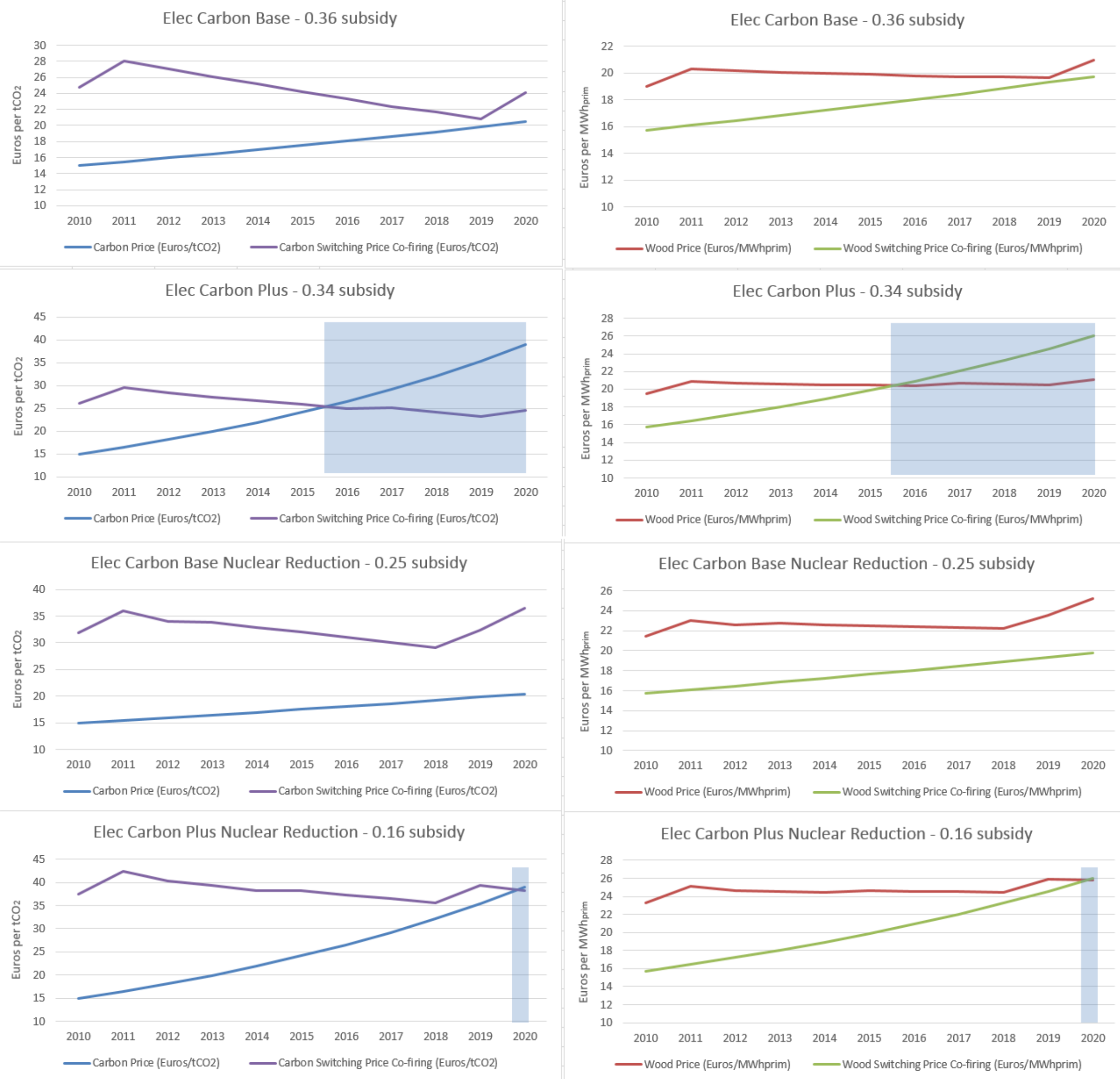

Figure 7: Wood and carbon prices vs. wood and carbon switching prices for co-firing. The computed switching prices reflect co-firing opportunities in hard-coal plants (around 6% of installed capacities in France, whereas lignite stations account for less than 1%). The shaded areas represent situations in which co-firing is profitable.

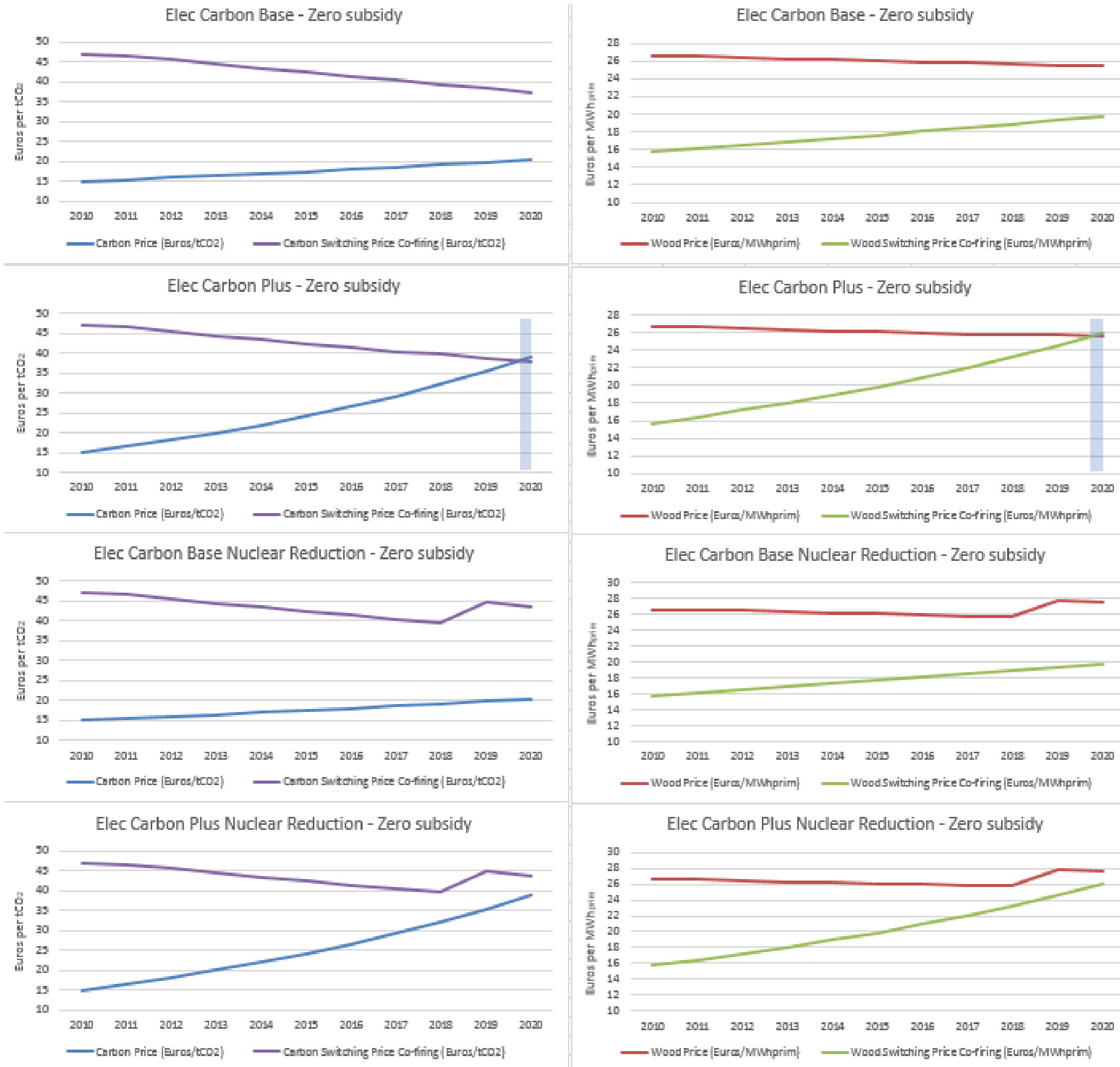

Figure 8: Wood and carbon prices vs. wood and carbon switching prices for co-firing, under a fixed zero subsidy.

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 a 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

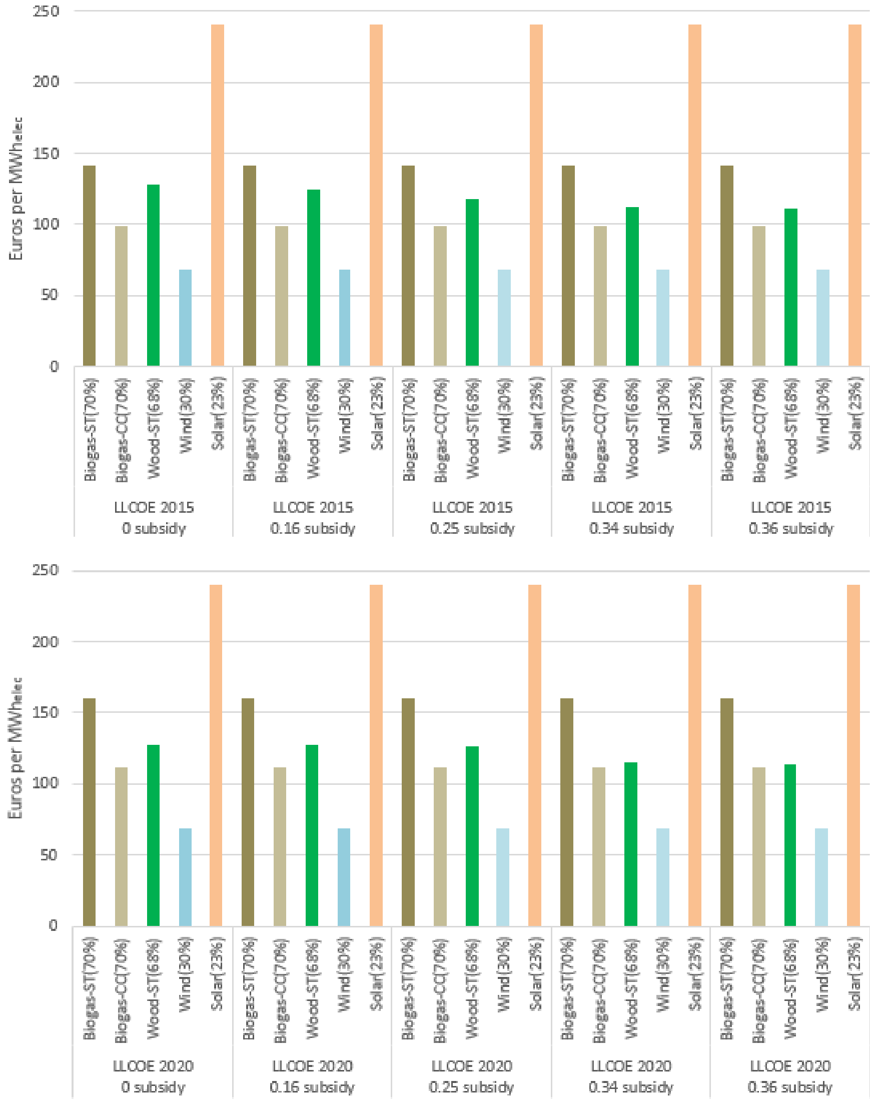

Figure 9: Levelized lifetime cost of electricity computed for the main RES technologies (Biogas-ST = Biogas Steam Turbine; Biogas-CC = Biogas Combined Cycle; Wood-ST = Dedicated biomass Steam Turbine), under different fuelwood subsidies. For each technology, the value in brackets reflects the availability 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 vs. the total lifetime discounted electricity output. This makes it possible to convert all streams of costs (investment, operation and maintenance, fuel, etc.) for each technology into the same unit (Euros/MWh_{elec}), taking all the discounted expenses over the entire operating lifetimes of power plants into account. See IEA (2010) and Bertrand and Le Cadre (2015) for an overview.

Appendix D: Assumptions for FW-H carbon content

We used the assumptions of Lobianco et al. (2016). They used French data from ADEME (2010, Table 37) and obtained 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 assumed that fuelwood had a humidity (w) of 15% (over the wet mass). After including the mass of the water, they computed the gross calorific value of oven-dry hardwood and softwood of French species (5.07 and 5.33 [kWh t−1], respectively). Eventually, they converted 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 FW-H substitution coefficient is the average of these two values.

Appendix E: Emission factor in power generation

Fuel type	Emission 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 to 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.

Appendix F: Carbon neutrality assumption

Sjølie and Solberg (2011) show that carbon neutrality for energy wood can be assumed if either "time conditions" or "spatial conditions" are met. Spatial conditions for carbon neutrality consist of two assertions: (1) "*the system boundaries include the forest area from which timber is harvested*", and (2) "*the annual increment is at least as large as the annual harvest*", i.e., the area's long-term growth. Time conditions also consist of two assertions: "*the system boundaries include the forest growth on the harvested area for at least as long a horizon as the time needed for the forest to grow to the size when harvested*" and "*the discount rate is zero, implying that the points in time when carbon fluxes take place are of no importance*".

For a given point in time t, there is no carbon neutrality since carbon stored in wood used for energy is not re-sequestered immediately. The time lag[17] between the emissions and the re-sequestration, also known as "*carbon debt*" or "*payback time*", is uncertain and depends on many biophysical assumptions (species, fertility, future climate conditions), as well as on harvesting methods (harvesting residues and stumps can postpone it). In order for the carbon

[17] *"As argued by Johnston and van Kooten (2014), biomass burning is only carbon-neutral if there is no urgency in addressing climate change, in which case the timing of the CO2 flux is unimportant. It only matters that over the harvest cycle, the same amount of CO2 is removed from the atmosphere by tree growth as was emitted producing electricity. If there is some urgency to address climate change, however, future removals of CO2 from the atmosphere must be considered as smaller than current emissions, in which case biomass burning can no longer be considered carbon-neutral" (Johnston and Van Kooten, 2015)*

debt to be repaid, we must assume two things: (1) the forest is in a dynamic *at-equilibrium* state (steady state), and (2) the harvest does not outreach *the quantity of biomass – on average and over a long period of time - that would have naturally disappeared without human intervention*. Let us illustrate this through diagrams.

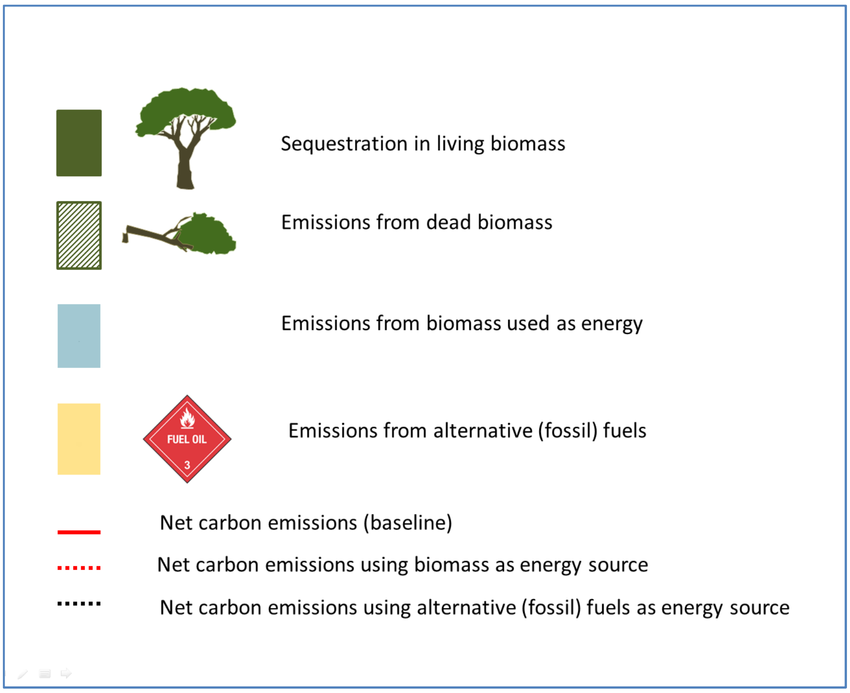

Figure 10: Legend of the diagrams

We present four cases depending on the forest carbon sink assumption. Case A presents a forest in a dynamic “at equilibrium” state or *steady state*. In case B, the forest system is static (no growth, no mortality), which is what happens for any point-in-time. Case C presents a dynamic growing stock case in which biological production exceeds the natural mortality. Case D presents a dynamic declining stock case in which mortality outreaches the biological production. Carbon emissions are counted on the vertical axis as positive when they enter the forest system and negative when they enter the atmosphere.

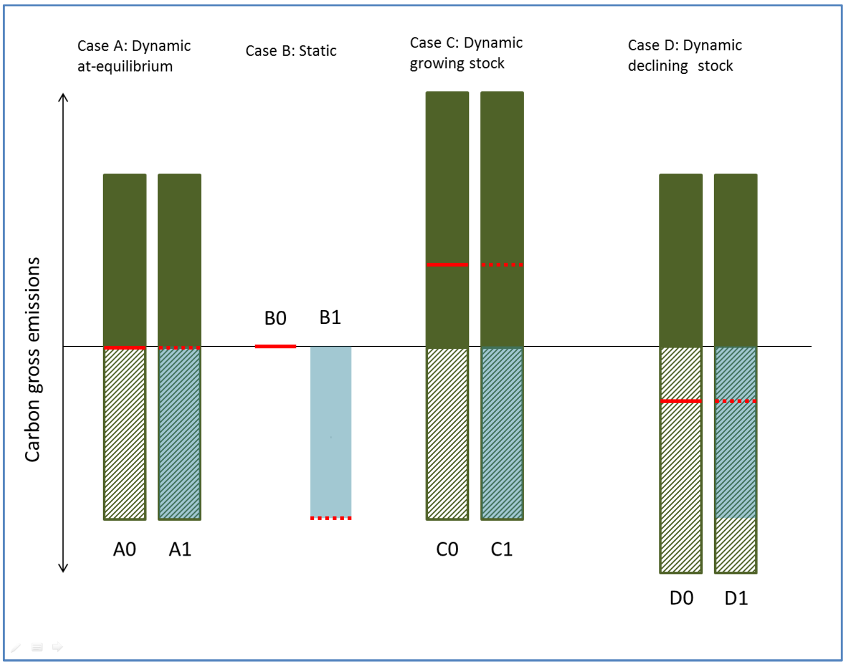

Figure 11: Introducing wood as energy

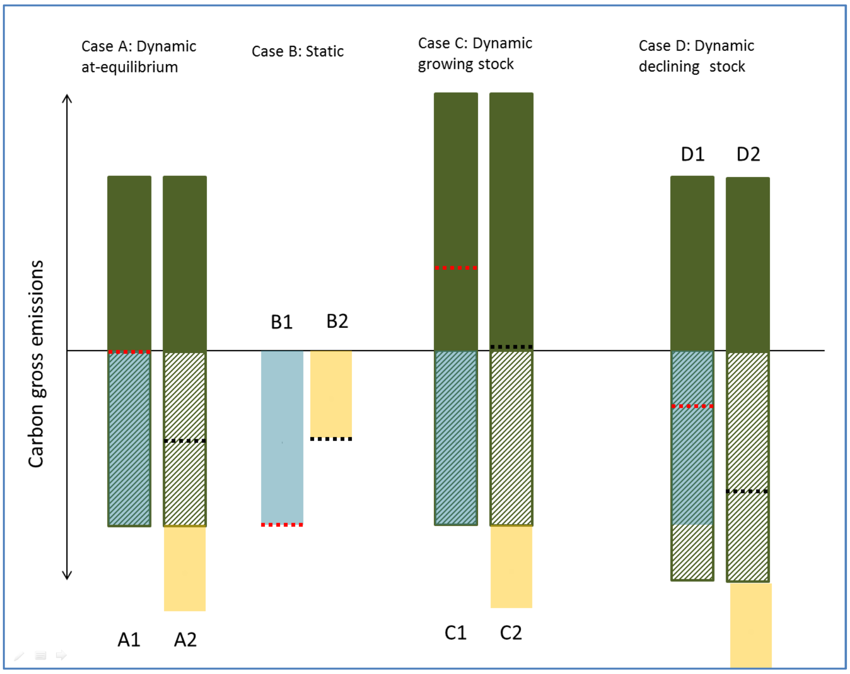

Figure 12: Comparing wood energy and alternative fossil fuel options

Case A shows an overall system "at equilibrium", which means that all the emissions are compensated for by an equivalent sequestration. This is what Odum (1969) described for very old forest, assuming constant biophysical, atmospheric and edaphic parameters. In that case, if wood that would die at some point in time is used as an energy source, the resulting net emissions remain unchanged (diagram A1 on Fig. 12, compared to A0 on Fig. 11). Since we usually harvest living biomass and not dead biomass, we anticipate the end of the biological cycle. However, on average, if we assume that every tree used for energy is replaced by a young tree in the forest, then the overall operation is "neutral" on a time horizon compatible with carbon debt repayment. In this case, carbon neutrality is a biophysical principle and not a political one.

The consequence is that if we compare the net emissions of a fuelwood scenario and the net emissions of an alternative fossil fuel scenario (A1 compared to A2 on Fig. 12), there is a positive *carbon substitution effect*.

Case B is virtual since, in reality, emissions and sequestration processes never stop in time. However we can assimilate it to what happens over a very short period of time. In that case, there is obviously no carbon neutrality since time conditions such as defined by Sjølie and Solberg (2011) are not respected. The consequence is that when adding the emissions from using biomass as energy (diagram B1), the net emissions become negative. Another consequence is that since wood is usually less energy-efficient than other fuel sources (i.e., it emits more than gas, for instance, for the same energetic service), replacing alternative fuels by wood translates into a negative carbon substitution outcome (diagram B1 and B2 on Fig. 12, where the yellow area is voluntarily smaller than the blue one although it represents the same energy service).

Case C describes a forest system that absorbs more carbon than it releases. For instance, it could consist of a forest that is not yet mature (although Luyssaert et al. (2014) recently showed that due to changing environmental conditions, old forests can also continue to store more carbon than they release). In case C, similarly to case A, if harvests do not exceed what would have died on average, then carbon neutrality is possible, with the same restrictions and assumptions as presented before. Nevertheless, a controversy appears when the harvest exceeds the natural emissions without exceeding the total biological sequestration (case C3 on Fig. 13). Indeed, in that scenario, the harvest can still be assumed to be "sustainable" since it does not exceed the biological production (leading to a zero net carbon emission) but is instead an artifact. In fact, the additional forest growing stock, represented in light green on Fig. 13, extends what Sjølie and Solberg (2011) call the system boundaries. In others words, the additional emissions (i.e., those exceeding the natural rate of decline) are no longer compensated for by the additional growth since this additional growth is "out of the system" and should be considered separately. In that case, carbon neutrality is not guaranteed, even if forest management appears to be "sustainable".

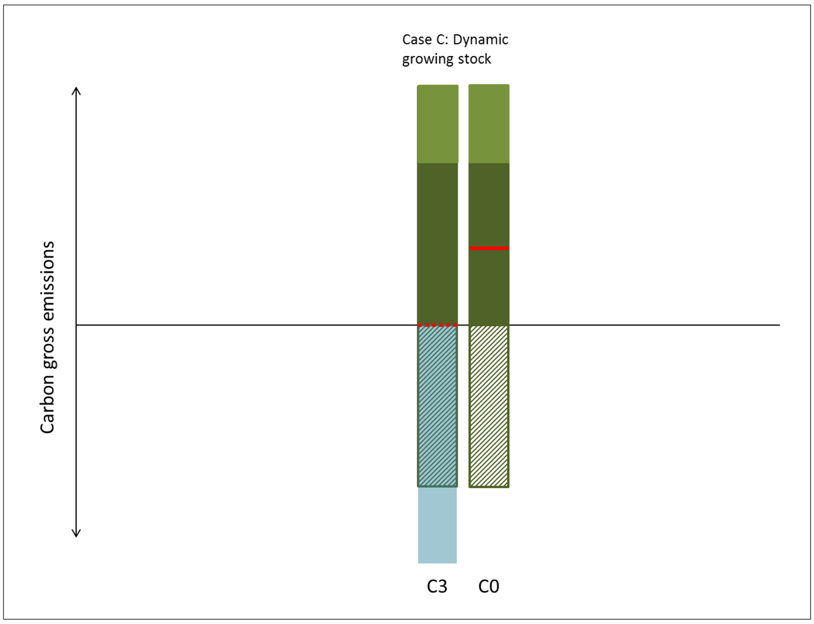

Figure 13: C3 shows a scenario where the harvest appears to be "sustainable" (the net carbon emissions are zero) but the carbon neutrality assumption is violated.

Eventually, case D describes a declining forest system that emits more than it sequesters (because of pathogen invasion, windfall or fire, for instance). Similarly to cases A and C, if harvests do not exceed what would have to die on average, then carbon neutrality is possible, with the same restrictions and assumptions.

All in all, these four cases illustrating four different hypothesis on the forest carbon sink show that the neutrality assumption (1) only holds on a dynamic framework (it does not hold in case B), and (2) only holds if the harvest does not exceed an average of what would have naturally disappeared (does not hold in case C3).

Appendix G: Documentation fort the GES model

More documentation on the GES model is available as supplementary materials. This includes the GAMS codes, the data files, the appendix on treatments for the cost and technical data, and the complete mathematical formulation of the model. More documentation is available on request.