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## Deepening the territorial Life Cycle Assessment approach with partial equilibrium modelling: First insights from an application to a wood energy incentive in a French region

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1 **Deepening the territorial Life Cycle Assessment approach with partial**  
2 **equilibrium modelling: first insights from an application to a wood energy**  
3 **incentive in a French region**

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29 **Acronyms and symbols**

- 30 CGE : Computable General Equilibrium
- 31 CLCA : Consequential Life Cycle Assessment
- 32 EEIO: Environmental Extended Input Output
- 33 FEE: Full Eco Efficiency
- 34 FFSM: French Forest Sector Model
- 35 HW: Hardwood
- 36 IO: Input Output
- 37 LCA: Life Cycle Assessment
- 38 LCI: Life Cycle Inventory
- 39 MFA: Material Flow Analysis
- 40 PE: Partial Equilibrium
- 41 PEE: Partial Eco Efficiency
- 42 SW: Softwood

43 **Region names and correspondence**

- 44 The following regions used in the model are combinations of the Eurostat NUTS2 level regions in the
- 45 NUTS2016 standard.
- 46 AQ: Aquitaine + Poitou
- 47 AL: Auvergne + Limousin
- 48 BFC: Bourgogne Franche Comté
- 49 BRE: Bretagne + Pays de la Loire
- 50 CEN: Centre
- 51 GE: Grand Est
- 52 LP: Languedoc Roussillon + Provence Alpes Côte d'Azur
- 53 MP: Midi Pyrénées
- 54 N-IDF: Nord + Picardie + Ile de France
- 55 NOR: Normandie
- 56 RA: Rhône Alpes

## 57 Abstract

58 An innovative modeling framework and metrics are developed to assess the economic and  
59 environmental performances of regional incentives in the wood energy sector. Our approach is based on  
60 the coupling between a partial equilibrium economic model of the forest sector with Life Cycle  
61 Assessment (LCA). Its originality relies on the computation of regional eco-efficiency ratios while  
62 taking account of diverse direct and indirect spatial and market interactions. Several adaptations were  
63 implemented to ensure consistency between the two modeling approaches in terms of process yields and  
64 flow balances. These adaptations make it possible to produce both economic and environmental  
65 indicators with a consistent perimeter. Finally, we used two kinds of eco-efficiency indicators to  
66 compare bioenergy policies. On the one hand, Partial Eco-Efficiency (PEE) combines the economic  
67 surplus induced by an incentive on the energy wood sector with its potential environmental impacts. On  
68 the other hand, Full Eco-Efficiency (FEE) adds the environmental impacts avoided by substitution  
69 between wood-energy and fossil fuels, compared to a business-as-usual (BAU) scenario. The proposed  
70 adaptations were applied to a case study in the French Grand Est region that compared the eco-efficiency  
71 of scenarios with or without a subsidy to wood energy consumption. Results show that subsidy increases  
72 the eco-efficiency of the forest-based sector using both PEE and FEE while keeping competition with  
73 the other regions to a minimum. However, most benefits come from the consideration of avoided  
74 impacts, with FEE far exceeding PEE. Using FEE, the scenario with the subsidy is 5% to 50% more  
75 eco-efficient than the BAU despite an increased consumption of wood products, due to economic gains  
76 and avoided impacts. These outcomes show the importance of considering potential trade-offs when  
77 assessing the economic and environmental performance of regional policies in favor of the bioeconomy.

78 **Keywords:** model coupling, partial equilibrium, territorial life cycle assessment, multi-sector  
79 interactions, eco-efficiency, bioenergy

## 80 Highlights

- 81 1) A forest sector economic model was coupled with Life Cycle Assessment
- 82 2) Adaptations were made to ensure consistency between the two approaches
- 83 3) Two types of eco-efficiency ratios were developed, including or not avoided impacts.
- 84 4) We tested this framework with a fuelwood subsidy in the French Grand Est Region
- 85 5) The subsidy increases Eco-efficiency for the 3 endpoint indicators, by 5 to 50%

## 86 1 Introduction

87 Territorial units, understood as any space ranging from local communities to first-level subnational  
88 administrative divisions, are receiving increasing attention as relevant scales for implementing solutions  
89 for the transition to sustainable societies. Indeed, these meso-scales are adapted to the integration of  
90 spatial specificities in sustainability assessments as they lie at the intersection between micro and macro  
91 level (Smetana et al., 2015). Assessing territorial units requires detailed modeling of complex systems,  
92 while taking into account local specificities, whether natural or geographical characteristics (Wohlfahrt  
93 et al., 2019) and social or economic features (Bezama et al., 2019). In addition, these geographical scales  
94 correspond to relatively homogenous political levels that may facilitate sustainability transitions  
95 (Hansen and Coenen, 2015), with the identification of context-specific conflicts (Gibbs and O'Neill,  
96 2017), or the implementation of dedicated governance structures (Hoppe and Miedema, 2020). These  
97 characteristics are currently resulting in a set of policies and initiatives supporting the transition towards  
98 sustainability at meso-scale. Local and regional initiatives are promoted by international agreements  
99 such as the local Agenda 21 (Barrutia et al., 2015), or by European authorities for green and circular  
100 economy strategies (European Commission, 2018; Pitkänen et al., 2016).

101 The interest in regional sustainable development policies is particularly marked in the case of the  
102 bioeconomy (Bennich et al., 2021), which encompasses activities relying on natural resources such as  
103 the forest-based sector. The diversity observed in European bioeconomy clusters, oriented towards  
104 bioenergy and materials, highlights the importance of designing specific regional strategies while  
105 avoiding “one fits all” solutions (Stegmann et al., 2020). However, while public stakeholders may seek  
106 to articulate local environmental stakes with regional economic dynamics aiming at both environmental  
107 and economic benefits, bioeconomy plans are not inherently sustainable (Székács and Hu, 2017). The  
108 forest and wood sector highlights these stakes, as it crystallizes issues and expectations that are  
109 sometimes contradictory, and often evaluated separately, for which synergies or trade-offs may exist.  
110 For instance, bioeconomy strategies could have a positive impact on the economy and on climate change  
111 mitigation, while threatening the biodiversity (Fritsche et al., 2020). The existence of these trade-offs  
112 must be made explicit through multicriteria assessments. In addition, implementing local initiatives to  
113 foster bioeconomy may indirectly affect regions or economic sectors not initially targeted by these  
114 policies (Dandres et al., 2011). It is hence required to take into account the environmental and economic  
115 consequences of meso scale decisions at different levels.

116 The assessment of bioeconomic measures oriented towards the development of energy uses of wood has  
117 been the subject of work on the economic consequences for the agents of the wood sector (Caurla et al.,  
118 2013a), the dynamics of the wood resource or the carbon in the forest (Valade et al., 2018). Nevertheless,  
119 no method has yet focused on the joint evaluation of environmental and economic impacts. In terms of  
120 policy analysis, this underlines the need for multicriteria quantitative assessment tools adapted to the  
121 intermediate meso-scale, taking account of local and global drivers (O’Keeffe et al., 2016; Smetana et  
122 al., 2015).

123 Initially designed to assess the environmental impacts of a product or a service, Loiseau et al. adapted  
124 the Life Cycle Assessment (LCA) framework to focus on a territory as a whole (Loiseau et al., 2013).  
125 The developed methodology, called “territorial LCA” relies on the quantification of an eco-efficiency  
126 metric to compare multifunctional land planning scenarios in a life cycle perspective. As initially defined  
127 by the World Business Council for Sustainable Development (WBCSD), “eco-efficiency is achieved by  
128 the delivery of competitively priced goods and services that satisfy human needs and bring quality of  
129 life, while progressively reducing ecological impacts and resource intensity throughout the life cycle to  
130 a level at least in line with the Earth’s estimated carrying capacity” (Stigson et al., 2006). Eco-efficiency  
131 allows identifying potential trade-offs between the economy and the environment to support decision-  
132 making (Huppés and Ishikawa, 2005; Levidow et al., 2016; Mo et al., 2018). Compared to methods such  
133 as vector optimization or multi-criteria assessment based on the addition of indicators, it allows a full  
134 integration in a single indicator without going through criteria weighting (Huguet Ferran et al., 2018).  
135 When implemented at the product level, eco-efficiency has been the subject of an international standard  
136 since 2012 (ISO, 2012) , and requires LCA to assess its environmental impacts. Seppälä et al. (2005)

137 proposed to broaden the use of this metric by defining eco-efficiency at a regional level as the ratio of  
138 services provided by the territory under study and the corresponding environmental impacts. (Loiseau  
139 et al., 2014) used the territorial LCA to compute eco-efficiency ratios on a French case study. However,  
140 methodological developments are still needed to quantify the socio-economic services provided by  
141 regional policies and to integrate their consequences on other regions or other economic sectors (Loiseau  
142 et al., 2018).

143 Beaussier et al. (2019) review existing works that combine economic approaches and environmental  
144 assessment tools to evaluate the performances of subnational incentives. The authors show that most of  
145 them have been developed since the early 2000s, and rely on a combination between Input-Output (IO)  
146 modeling or on Partial Equilibrium (PE) and Computable General Equilibrium (CGE) models (Irwin et  
147 al., 2010; Loveridge, 2004; Partridge and Rickman, 2010) for the economic part and LCA or  
148 carbon/ecological footprint (Loiseau et al., 2012) for the environmental part. Compared to traditional  
149 environmental assessment models, one major advantage of such a coupling is to take the effects of a  
150 decision on competition or synergies between economic sectors into account, thus integrating indirect  
151 effects in the environmental assessment of different economic development strategies. This integrated  
152 assessment has been mobilized in the LCA community to adopt a consequential approach for  
153 meso/macro-level decision support (European Commission - Joint Research Centre, 2010) as supported  
154 by the JRC. In Consequential Life Cycle Assessment (CLCA), the system boundaries are expanded to  
155 consider effects induced by a change in the product system on other economic sectors. A significant part  
156 of CLCAs are based on couplings using one or more of the aforementioned economic models (Le Luu  
157 et al., 2020; Roos and Ahlgren, 2018). It has been applied to diverse sectors such as agriculture  
158 (Vázquez-Rowe et al., 2013), forestry (Earles et al., 2013), biofuels (Albers et al., 2019), or energy  
159 systems (Igos et al., 2015, 2014).

160 However, these approaches have three main limitations for meso-level decision support (Beaussier et  
161 al., 2019). First the main focus is on the computation of environmental impact indicators, yet a broader  
162 assessment of sustainability requires socio-economic as well as environment indicators, in order to  
163 identify trade-offs and win-win solutions (Guinée et al., 2011). Second, market interactions such as  
164 competitions or synergies between regions or with other global sectors are not always considered. Third,  
165 the coupling between the models can lead to overlaps or inconsistency in of physical flows accounting.  
166 To address these three limitations, this paper aims at developing an innovative methodological  
167 framework based on a coupling between the territorial LCA framework and a partial equilibrium (PE)  
168 model.

169 The choice of a PE model is a compromise between different options (Beaussier et al., 2019). IO models  
170 are easy to use and include detailed information on products and industries. However, they are based on  
171 static accounts of value in given economic sectors. Equilibrium models – CGE and PE – offer a  
172 representation of market interactions between supply and demand, allowing to compute endogenous  
173 prices. Consequently, they assess gain or loss of economic wealth in response to a policy or a shock  
174 while including feedbacks from price variations. Among equilibrium models, PE is preferred to CGE  
175 because it allows for more detailed modeling of sectors and at finer geographic scales. CGE allows a  
176 complete representation of interactions between sectors, as they incorporate other markets than the  
177 original sector of study into the analysis. In a general equilibrium model, feedback from other markets  
178 is taken into account to model the way exogenous shocks in other markets affect the sector in question.  
179 However, it usually models products at a more aggregated level, with broader geographical regions (Le  
180 Luu et al., 2020). Other models such as multi-agent or system dynamics can be considered for this scale.  
181 However, their use to model economic phenomena is more experimental. At the meso scale, they are  
182 generally used to produce simpler economic indicators than equilibrium models, without endogenous  
183 price formation mechanisms (Beaussier et al., 2019).

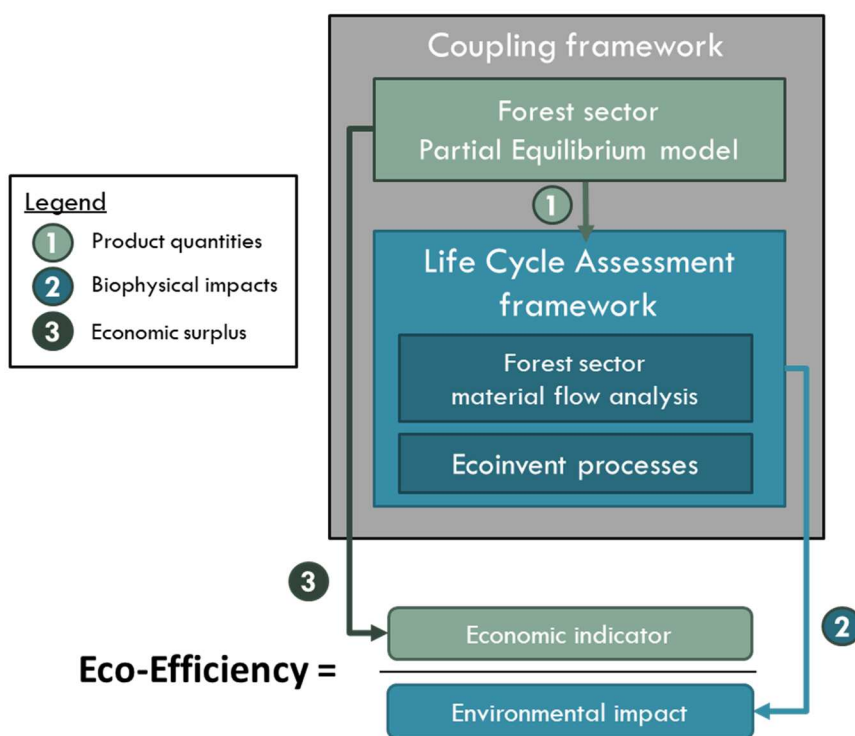
184 The methodological framework developed aims at identifying potential trade-offs generated by the  
185 implementation of regional bioeconomy strategies, namely between different dimensions of  
186 sustainability and between economic sectors or geographical areas. Its originality relies on the  
187 computation of regional eco-efficiency ratios. In addition, special attention will be paid to the  
188 consistency between the two modeling approaches in terms of process yields and flow balances. The

189 forestry sector being a strategic sector for the bioeconomy, the methodology will be implemented to  
 190 assess the environmental and economic performance of regional incentive measures in favor of  
 191 bioenergy in the Grand Est region, one of the most dynamic regions regarding the development of forest  
 192 biomass activities in France. This case study will allow to test the feasibility and the interest of such a  
 193 coupling to provide objective elements of decision support.

194

## 195 2 Material and Methods

196 The overall approach is based on the coupling of the French Forest Sector Model (FFSM) (Caurla et al.,  
 197 2013b; Lobianco et al., 2015; Sauquet et al., 2011), a partial equilibrium economic model of the forest  
 198 sector, with territorial LCA (Loiseau et al., 2018). The economic model provides data on quantities of  
 199 products (arrow 1 in Figure 1), which are used as input flows by LCA to assess their environmental  
 200 impacts (arrow 2). This approach can be categorized as a “soft” coupling, following the definition  
 201 proposed by Salou et al. (2019) or Beaussier et al. (2019) as no other interactions between the two  
 202 modelling approaches are considered. The partial equilibrium model also provides economic indicators,  
 203 namely economic surpluses (arrow 3), which account for the profits made by the producers and the  
 204 welfare derived by the consumers. More details are provided in section 2.5. Economic and  
 205 environmental indicators are combined to compute eco-efficiency ratios, allowing to compare the  
 206 performance of different economic measures at a regional level.



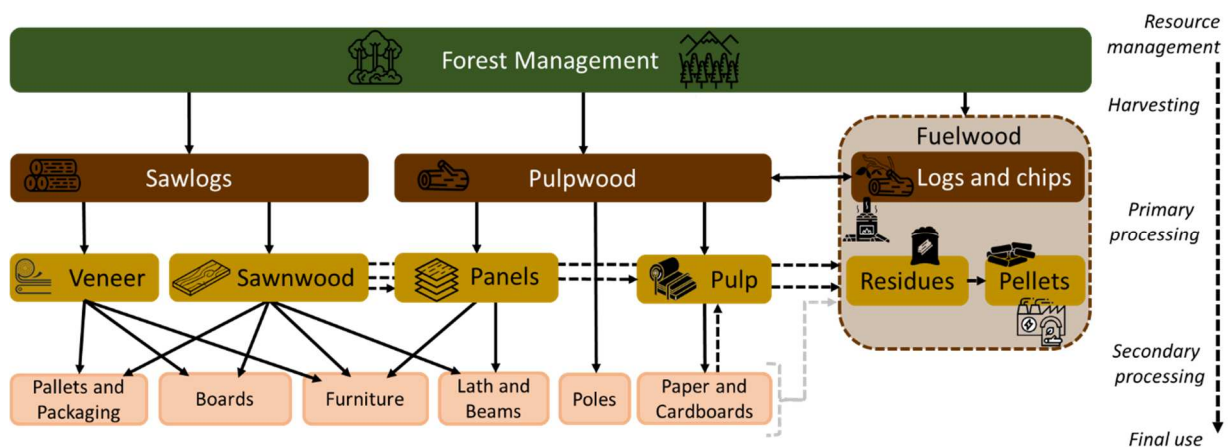
207

208 *Figure 1- Overview of the soft-coupling procedure between the economic model and the LCA framework*  
 209 *carried out to assess the performance of regional economic measures*

210 In this section, the general methodology is described with particular attention to three points, i) the  
 211 definition of the boundaries of the system studied and the flows taken into account in the assessment, ii)  
 212 the data collection and interfacing between the two models, and iii) the indicators assessed. To illustrate  
 213 the proposed methodological developments and the interest of this coupling, they are applied to a case  
 214 study described in the first part, i.e. the forest sector of the Eastern France. The economic model chosen  
 215 is also presented at the beginning of this section.

216 2.1 Case study

217 The forestry sector in France has a strong potential for the development of bioeconomy strategies both  
 218 as a lever for the transition to a low-carbon economy through biomass and wood products and for  
 219 developing economic activities in rural areas. In this sense, the forestry sector in the Grand Est region  
 220 is one of the most dynamic in France and represents a significant activity in the regional economy. In  
 221 this region, the sector represents 12% of the jobs and 18% of revenues of the French forest sector, as  
 222 well as 12% of the French forest area (Institut National de la Statistique et des Etudes Economiques,  
 223 2019; MAAF, 2016). The forest-based sector covers a wide range of activities, from forest management  
 224 and harvesting to various processing industries such as sawmills, paper production, construction  
 225 materials or furniture production downstream, as depicted in Figure 2 below.



226  
 227 *Figure 2- Structure of the forest and wood industries sector, considering 4 stages: 1) forests and forest*  
 228 *management (green), 2) primary wood products (brown) obtained from harvesting, 3) first level*  
 229 *processed products (yellow) obtained from primary processing, 4) second level processed products*  
 230 *(beige), obtained from the secondary processing. Dotted lines indicate waste and residues flows. Based*  
 231 *on MFA data of the French forest-based sector (Lenglet et al., 2017) and FAOSTATS (FAOSTAT-*  
 232 *Forestry Production Statistics.)*

233 2.2 Partial equilibrium modelling: the French Forest Sector Model (FFSM)

234 2.2.1 Main principles

235 FFSM is a bioeconomic model representing the French forest sector in both its biophysical resource and  
 236 its economic dimensions (Caurla et al., 2013b; Lecocq et al., 2011; Lobianco et al., 2015). It is mainly  
 237 based on a forest resource module simulating forest growth and management on the one hand, and an  
 238 economic module simulating market supply and demand on the other hand. The market module is a  
 239 partial equilibrium model. Policy scenarios are implemented by modifying a given parameter – fuelwood  
 240 price in our case study – and then comparing the outcome to a Business As Usual (BAU) scenario. One  
 241 major advantage of a partial equilibrium model yields in its capacity to simulate market dynamics with  
 242 endogenous prices and quantities at a disaggregated level. A classical shortcoming with partial  
 243 equilibrium models compared to a general equilibrium framework is the absence of constraints related  
 244 to the factors of production and their movement across sectors (labor, capital, land). This hypothesis is  
 245 acceptable in the forest sector for a time horizon of 30 years, as capital movement is slow and land use  
 246 change is strictly controlled.

247 2.2.2 FFSM market module structure

248 FFSM endogenously computes, on a yearly basis, and for 12 French regions, the quantities produced,  
 249 consumed and exchanged as well as the prices of 9 groups of wood products. On the supply side,  
 250 3 primary wood products are produced, i.e. i) softwood roundwood, ii) hardwood roundwood, and iii)



251 an aggregated product gathering low-diameter woods and residues suitable for fuelwood and pulpwood.  
 252 They are processed to the demand side into 6 processed products, i.e. iv) softwood and v) hardwood  
 253 sawnwoods, vi) plywood, vii) fuelwood, viii) panels, ix) paper pulp (Lecocq et al., 2011). Three types  
 254 of relationships make these products dependent on each other: first, primary wood products are  
 255 processed into first-level processed products, according to fixed coefficients e.g., sawnwoods and  
 256 plywood are derived from roundwood. Second, some processed products compete for the same raw  
 257 materials: e.g., paper pulp, panels and fuelwood all compete for pulpwood and residues. Third, some  
 258 products are jointly produced: e.g., sawnwood production comes with a production of residues that is  
 259 added to the total of pulpwood and residues, according to a coefficient. We updated all the upper  
 260 mentioned coefficient using Material Flow Analysis (MFA) results for the forest sector built with a data  
 261 reconciliation method (Courtonne and Wawrzyniak, 2019; Lenglet et al., 2017). The updated links  
 262 between the primary wood products and processed products are presented in Table 1 below.

263 *Table 1- Transformation coefficients matrix used to convert primary wood products into processed*  
 264 *products.*

<b>Output</b>	Hardwood sawnwoods	Softwood sawnwoods	Pulpwood/ residues/ fuelwood coproduction	Plywood	Fuelwood	Panels	Paper Pulp
<b>Input requirement</b>							
Softwood roundwood		2 <sup>a</sup>	a : +1	2			
Hardwood roundwood	2.5 <sup>b</sup>		b:+1.5	2			
Pulpwood and raw fuelwood					1	1	2

265 *Reading key: For each unit of Hardwood Sawnwood, 2.5 units of Hardwood roundwood are required.*

266 *<sup>a</sup>: for each unit of softwood sawnwood produced, 2 units of softwood roundwood are consumed and 1 additional*  
 267 *unit of pulpwood/raw fuelwood is co-produced*

268 *<sup>b</sup>: for each unit of hardwood sawnwood produced, 2.5 units of hardwood roundwood are consumed and 1.5*  
 269 *additional unit of pulpwood/raw fuelwood is co-produced*

270 All products are exchanged from one region to another following Samuelson's spatial price theory  
 271 (Samuelson, 2008). In addition, exports of primary products and imports of processed products are  
 272 represented through the Armington theory of imperfect substitutability, representing trade with the rest  
 273 of the world, all foreign countries aggregated together (Armington, 1969).

274 Samuelson's theory considers wood products to be homogeneous and perfectly substitutable according  
 275 to their region of origin or destination. Product flows between French regions are thus determined by  
 276 the price gradient between regions, including transport costs (Samuelson, 2008). While this model is  
 277 legitimate for representing trade between homogeneous regions such as the French administrative  
 278 regions, it raises questions for the modeling of trade between French regions and the rest of the world  
 279 for three reasons. First, domestic and foreign products may have heterogeneous physical characteristics.  
 280 Second, a foreign industry that is well established in a given domestic market produces goods that are  
 281 more substitutable with domestic products than a less well-established foreign firm, which can be  
 282 explained, in particular, by informational factors (better knowledge of consumption habits and a better  
 283 supply network for raw materials). Finally, the presence of administrative and commercial barriers, the  
 284 presence of trade unions or of powerful consumer associations can influence consumption habits in a  
 285 country (political reasons). In order to better take into account the imperfect substitutability between  
 286 products from different countries, we mobilize the Armington model to represent wood trade between  
 287 France and the rest of the world (Armington, 1969). The principle of this model is to consider that goods  
 288 produced in different places are imperfectly substitutable between them. Representing these two

289 different exchange behaviors allows representing more precisely the impact of a regional incentive on  
290 the other French regions and on the import and export of products from and to the rest of the world  
291 (Sauquet et al., 2011).”

292 As a complement to these main principles used in this study, full details, figures and equations describing  
293 the model and modules are provided in Appendix A and online (French Forest Sector Model (FFSM++),  
294 2021).

## 295 2.3 Goal and scope definition

### 296 *2.3.1 Goal of the study*

297 The aim is to develop a modelling framework dedicated to the combined assessment of the economic  
298 and environmental performance of regional economic incentives in the forest sector. As a proof of  
299 concept, the developed framework is applied to assess the performance of the implementation of a  
300 subsidy in the region Grand Est to increase final demand for fuelwood among domestic households,  
301 district heating or industrial facilities. This type of policy is in line with past and current trends in the  
302 French and European forest bioeconomy strategies (European Commission, 2018; Ministère de  
303 l’Agriculture et de l’Alimentation, 2018). French guidelines place particular emphasis on the  
304 development of local biomass markets and regional energy wood supply chains, setting regional biomass  
305 production targets (Ministère de la Transition Ecologique et Solidaire, 2018, 2020). Economic  
306 incentives for wood energy demand mostly consist in tax expenditures towards individual households  
307 (fuelwood tax expenditures have stood at €130M per year since 2006) and in subsidies from the  
308 government budget towards heating networks for communities and industries (€6M per year towards  
309 wood biomass units since 2006). Two scenarios will be compared, i.e., i) a BAU scenario where no  
310 incentive policy is implemented and ii) a scenario where a subsidy accounting for 50% of the fuelwood  
311 price is applied in the region Grand Est to increase fuelwood consumption, starting in 2020 and ending  
312 in 2050.

313 By definition, these two scenarios do not provide the same services, particularly in economic terms. The  
314 basis of comparison will therefore not be the functional unit as in a conventional LCA. According to  
315 territorial LCA, the starting point is the definition of the studied systems, here a regional forest sector  
316 and policy scenarios. Then, several functions can be defined for these scenarios, notably in terms of  
317 wealth creation and welfare for the various stakeholders in the forestry sector, including producers and  
318 consumers. These functions will be quantified through economic surpluses. Economic surpluses are  
319 generally considered as reliable and relevant indicators compared to national (or regional) incomes  
320 (Harberger, 1971). Consumer surplus is based on the difference between the market equilibrium price  
321 of a given product and the consumers’ willingness-to-pay for that product, which corresponds to the  
322 demand curve and depends on both endogenous variables and initial parameters. It can be seen as a  
323 proxy of consumer welfare (Willig et al., 1976). Producer surplus is based on the difference between the  
324 market equilibrium price and production costs for a given product and reflects producers profit. Thus, a  
325 change in consumer (producer) surplus is used to measure the gain or the loss in consumer welfare  
326 (private profits).

### 327 *2.3.2 System boundaries*

328 System boundaries are set from cradle to gate, including all the Grand Est forest-based sector from forest  
329 management and harvesting to the processed products obtained from primary processing: sawnwoods,  
330 plywood, panels, paper pulp. All upstream processes (energy supply, machine tools, chemicals  
331 production, etc.) are also accounted for. Fuelwood is modelled to the point of use, including impacts  
332 related to its combustion for heat production. Disposal of waste produced from paper pulp production  
333 (in the form of pulp residues used for energy production and fertilization) were considered. Other  
334 disposal issues were not included. These choices follow the structure of the economic model FFSM,

335 which does not represent second level processed products (beyond secondary processing in Figure 2).  
336 Thus, the downstream supply chain is not included to maintain consistency between economic and  
337 environmental modelling.

338 In terms of environmental accounting, the impacts of the upstream processes are allocated to the region  
339 where the processed product is consumed (e.g., if sawnwoods are produced and consumed in region B  
340 with wood from region A, the impacts allocated to region B include those related to sawmills,  
341 transportation, and forest management). The only exceptions are raw wood products exported to the  
342 rest-of-the-world, in which case the impacts related to forest management are accounted in the  
343 production region. This corresponds to the principle of territorial responsibility (Eder and  
344 Narodoslowsky, 1999), a hybrid approach between consumer and producer accounting. This approach  
345 is relevant when focusing on the impacts of a given region, in a context where a consistent global  
346 accounting is not sought after.

347 To perform an exhaustive assessment, consequential effects must also be considered (Beaussier et al.,  
348 2019). Consequently, the system boundaries should also include different types of interactions between  
349 economic sectors at different geographic and temporal scales (see Figure 3).

350 First, the whole forest-wood sector in the case-study region is considered. Intra-sectoral interactions,  
351 i.e. flow exchanges between wood products due to competition or synergy effects, are taken into  
352 account in the approach and are represented by arrows 1 in Figure 3.

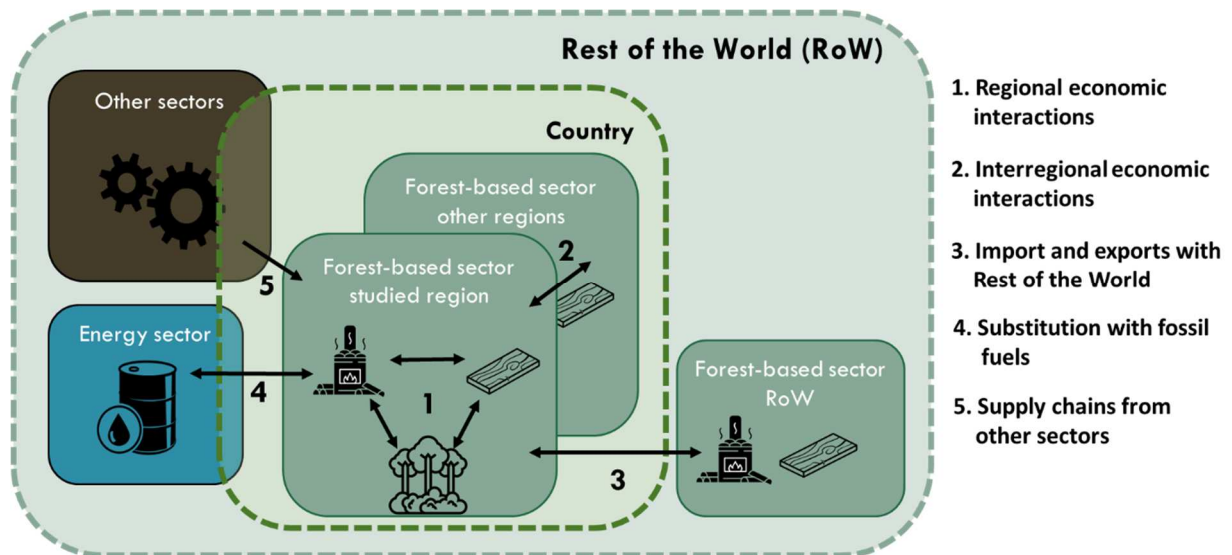
353 Second, flow exchanges with wood sectors of other French regions are included in the study, e.g., a  
354 decision taken in a given region can affect the supply and demand for wood products in other regions.  
355 These are inter-regional interactions and are represented by arrow 2 in Figure 3.

356 Third, arrow 3 represents the exchanges between the forest sector of any French region and a generic  
357 forest sector for the Rest of the World (RoW). This allows accounting for variations in wood products  
358 export/import following a change in the regional supply and demand for wood products.

359 Fourth, wood energy is part of the global energy system and a subsidy to wood energy is likely to affect  
360 other energy sources, therefore interactions between a given regional forest-wood sector and the  
361 worldwide energy sector must be accounted for. These flows represented by arrows noted 4 stand for  
362 both the effects of competition induced by the worldwide energy sector on the regional forest-wood  
363 sector and the energy flows imported by the regional forest-wood sector for its operations. To be  
364 comprehensive, the model must also include avoided impacts induced by the increase in fuelwood  
365 consumption compared to the BAU scenario, under the assumption that additional fuelwood  
366 consumption replaces fossil fuel consumption.

367 Other exchanges between the studied regions and the rest-of-the-world economy are represented by  
368 arrows 5 in Figure 3 and stand for the life cycle perspective. It includes for instance sawmill or harvesting  
369 machinery and equipment.

370 Finally, all these interactions must be studied dynamically, and an annual time step has been chosen to  
371 take into account this temporal dynamic. The time horizon was set at 2020-2050, as this period is long  
372 enough to observe the consequences of dynamic interactions between sectors related to forest products.



373

374 *Figure 3 - System boundaries, flows, interactions, and temporal dynamic in the coupled modelling*  
 375 *framework. Arrows indicate flows between regions*

376

## 377 2.4 Data inventory: connecting economic modelling outputs with Life Cycle Inventories (LCI)

378 In order to build an exhaustive inventory of the environmental flows associated with a given scenario,  
 379 we have to associate LCI data to each quantity of wood products produced and consumed as computed  
 380 in FFSM. These FFSM outputs are provided at a scale where they are too aggregated to be directly  
 381 connected in process LCA databases, while too disaggregated with regard to products found in  
 382 Environmental Extended Input Output databases such as Exiobiase (Merciai and Schmidt, 2018). This  
 383 issue arises when dealing with meso-scale objects, and hybrid approaches can be adopted to compute  
 384 data (Peters, 2010). As our study deals with few products, we developed a process-based procedure to  
 385 connect FFSM outputs with LCI datasets to ensure wood product representativeness. This procedure  
 386 requires special attention to maintaining a balanced material account between the two approaches.

### 387 2.4.1 A general procedure to provide consistent flow accounting

388 The general procedure is to disaggregate FFSM products into products that match LCI process databases  
 389 such as ecoinvent (Wernet et al., 2016) for the forest management and wood industries. We use data  
 390 from various sources, as presented in Table 2. It is mainly based on the detailed results of a Material  
 391 Flow Analysis (MFA) applied to the French forest sector (Courtonne and Wawrzyniak, 2019; Lenglet  
 392 et al., 2017). In addition, we use information in existing LCI process datasets to disaggregate products  
 393 into more specific items such as sawnwoods split into beams, laths, and boards.

394

395 *Table 2 - Product disaggregation from FFSM to LCI*

<b>FFSM product</b>	<b>LCI process</b>	<b>Proportion</b>	<b>Data sources</b>
Roundwood – softwood (SW) and hardwood (HW)	Raw Sawlog	See Figure 4	Ecoinvent <sup>1</sup> MFA <sup>2</sup>
	Debarked Sawlog		
Pulpwood and raw fuelwood	Pulpwood	See Figure 4	Ecoinvent <sup>1</sup> MFA <sup>2</sup>
	Cleft timber		
	Harvest residues		
	Bark Chips		
	Sawmill residues		
Sawnwood – softwood (SW) and hardwood (HW)	Beam	40%	Ecoinvent, Sawing process Dataset Information <sup>1</sup>
	Lath	45%	
	Board	15%	
Plywood	Plywood	100%	MFA <sup>2</sup>
Fuelwood	Domestic heating	20%	MFA <sup>2</sup>
	District/industrial heating	80%	
Panel	Particle board, indoor	50%	Ecoinvent <sup>1</sup> , FCBA <sup>3</sup>
	Particle board, outdoor	50%	
Paper Pulp	Paper pulp, Sulphate ECF (elemental chlorine-free)	100%	Ecoinvent <sup>1</sup> , FCBA <sup>3</sup>

396 All LCI processes used were adapted to the French Grand Est region context (e.g. scarce use of  
397 mechanical forest harvesters and tree seedlings, French electricity mix for industrial processes, adapted  
398 transportation distance for product imports and exports). Complete details, data and sources are provided  
399 in Table B.2-10 in Appendix B, and modifications are specified in the comments.

400 Still, some discrepancies remain between economic outputs and LCI needs. In particular, economic  
401 models focus on product quantity and price relationships, whereas LCIs focus on elementary flows and  
402 matter conservation. Due to these differences, consistency issues arise regarding several aspects of the  
403 FFSM model structure and LCA modelling stakes such as yields, coproducts, allocations, system limits,  
404 end uses and time dynamics. We detail below how we dealt with these issues.

#### 405 *2.4.2 Material conservation*

406 The first issue is the need to match yields at each transformation process between the two approaches.  
407 By default, FFSM and LCI processes use different yields in terms of input and output quantities at each  
408 step of the supply chain. In FFSM, a transformation coefficient matrix (see Table 1) presented in 2.2.2  
409 connects a given quantity of primary product with a quantity of processed product, both expressed in  
410 Mm<sup>3</sup>. Coefficients are based on MFA results computed with data reconciliation methods (Lenglet et al.,  
411 2017). For instance, for each unit of softwood sawnwoods produced, two units of softwood roundwood  
412 are consumed and one additional unit of industry wood is co-produced. These coefficients are  
413 represented in Figure 4 and correspond to red numbers associated to the left-to-right black arrows.  
414 Meanwhile, in the softwood sawing process in the ecoinvent database, for each unit of softwood  
415 sawnwood, 1.6 m<sup>3</sup> of softwood roundwood are consumed and 330kg in dry mass of residues,

<sup>1</sup> Wernet, G. et al., 2016

<sup>2</sup> Courtonne and Wawrzyniak, 2019; Lenglet et al., 2017

<sup>3</sup> FCBA, 2020

416 corresponding roughly to 0,8 m<sup>3</sup> of industry wood is co-produced. Yields are harmonized by modifying  
417 those in LCI processes, using the same MFA results used for FFSM.

418 However, FFSM does not fully track matter conservation, as co-products are not economically  
419 represented in an independent fashion (no specific supply or demand functions for co-products).  
420 Sawmills and harvest residues are partially accounted for as by-products of sawnwood, for which a fixed  
421 proportion of the quantity of softwood and hardwood sawmill (indicated by coefficients noted with a  
422 star \* in Figure 4) is included in the raw material pool usable for wood energy and pulpwood (bottom-  
423 left box labelled “pulpwood and fuelwood” in Figure 4). Thus, flows between sawmills, panel and paper  
424 pulp industries, and fuelwood, are not accounted for separately but as a whole.

425 Dealing with this second issue leads to an aggregation discrepancy between FFSM and LCI processes.  
426 We build inventories starting from end products fuelwood, panels, and paper pulp (described in detail  
427 in Appendix B – Table B.7a). Despite harvest and sawmill residue quantities not being explicitly  
428 computed, the inventory of products processed from low diameter woods and residues is disaggregated  
429 using MFA data, going upwards in the supply chain, using averages on the ratio of each input used. This  
430 enables us to take into account the quantities and proportions of the various types of pulpwood and  
431 residues used in secondary products: on the LCI side, we distinguish bark chips, sawmill residues,  
432 harvest residues, cleft timber and pulpwood, as shown in Figure 4.

433

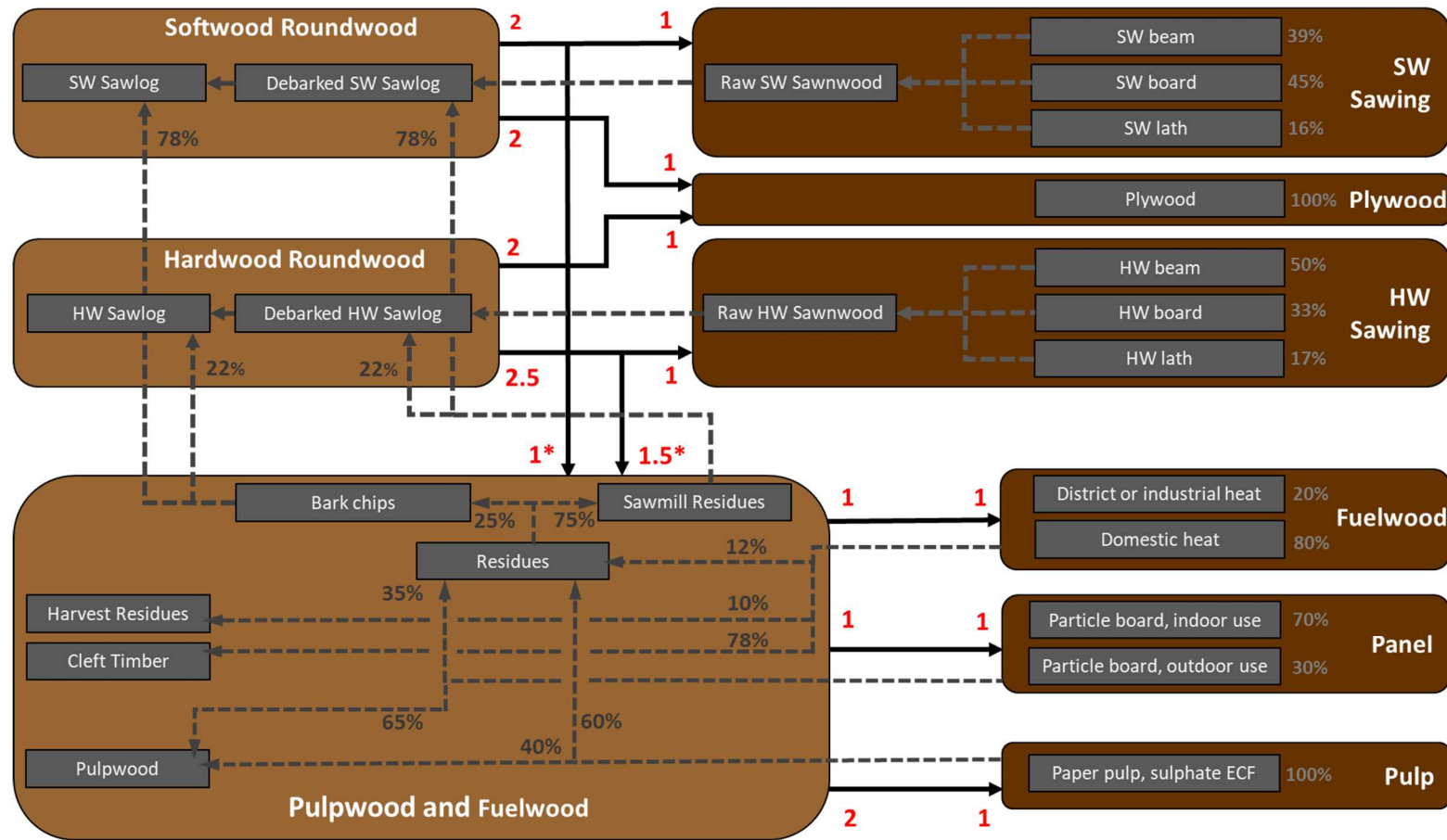
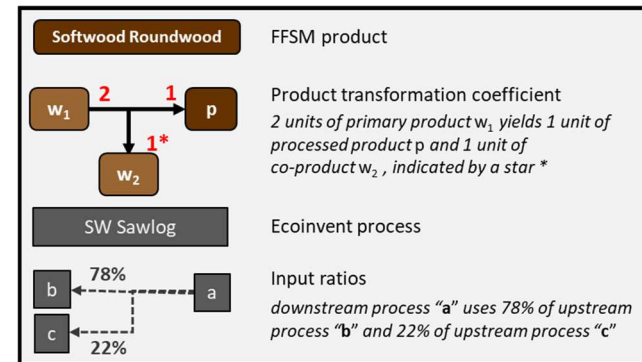


Figure 1 - Yields, LCI disaggregation ratios, and consistency between the FFSM economic model and the LCA framework.

Brown boxes connected by black arrows from left-to-right correspond to the wood product supply chain as modelled in FFSM. Light brown boxes are primary products and dark brown boxes correspond to processed products.

Grey boxes connected by grey dotted arrows from right-to-left represent the wood supply chain modelled from a LCA perspective, modelled upwards from end products to raw materials.

Plywood production residues are eluded for simplicity as the volumes at stake are neglectable.



437 2.4.3 Allocations

438 Both mass allocations and economic allocations were used according to the ecoinvent database (Wernet  
439 et al., 2016). The proportion of each primary forest product – roundwoods, industry wood and fuelwood  
440 – in the total quantity of wood harvested is used to perform a mass allocation for forest harvest processes  
441 and to carry out a carbon balance on all products in the forest-based sector. More details are shown in  
442 Appendix B, Tables B.11 and B.12. In the processes downstream in the supply chain of the harvest,  
443 ecoinvent processes are based on monetary values to perform an economic allocation. This concerns the  
444 allocation of impacts between sawnwood co-products: debarked logs and bark, sawnwoods and sawmill  
445 residues.

446 2.5 Combining indicators in two eco-efficiency metrics

447 We assess the economic and environmental performance of the regional subsidy by comparing the eco-  
448 efficiency ratio of trajectory of the forest sector with and without an incentive. Eco-efficiency is  
449 generally defined as follow (Eq. (1) :

450 
$$Eco - efficiency = \frac{Socio-economic\ service}{Environmental\ impact} \text{ (Seppälä et al., 2005)} \quad (1)$$

451 The indicator of service provided used in the numerator of the eco-efficiency ratio is the total economic  
452 surplus of the forest-based sector, as computed by FFSM. Total economic surplus is the sum of consumer  
453 surplus, producer surplus minus budgetary costs of the policy. Specific producer and consumer surplus  
454 are calculated for any given product by FFSM, then aggregated at the sectoral level, by adding the  
455 producer surplus of the 3 primary products on the one hand, and the consumer surplus of the 6 processed  
456 products on the other hand. We refer to these aggregated producer and consumer surplus, as they  
457 integrate the competition dynamics between wood products, calculated specifically for each region.

458 The environmental indicators used are the Life Cycle Impact Assessment (LCIA) outputs obtained with  
459 the impact assessment method ReCiPe (v1.13, Hierarchist) (RIVM, 2011). LCIA methods provide  
460 midpoint and endpoint impacts. Endpoint impacts translate the environmental impacts into damages on  
461 the three Areas of Protection, namely human health, ecosystems, and resources. Midpoint impacts  
462 quantify a potential impact earlier in this cause-effect chain: for example, Global Warming Potential  
463 expressing additional radiative forcing to assess climate change. We chose the levels of the three  
464 endpoint categories as potential environmental impacts to compute the eco-efficiency indicators.  
465 Midpoint impacts rely on fewer assumptions and are thus more reliable, when endpoint impacts  
466 provide a more easily understandable information to non-specialists (Van Hoof et al., 2013). The choice  
467 of endpoint indicators thus makes it possible to limit the number of criteria used and to reduce the  
468 complexity of the information provided to decision-makers. However, it is still necessary to look at  
469 midpoint effects when interpreting results (Guérin-Schneider et al., 2018).

470 Thus, we can define a first eco-efficiency ratio, based on the total economic surplus divided by the  
471 endpoint impacts, leading to three indicators (one for each endpoint category). We define this first  
472 typical eco-efficiency ratio as Partial Eco-Efficiency ratio (PEE) (Eq. (2).):

473 
$$PEE = \frac{Total\ economic\ surplus}{Potential\ endpoint\ impacts} \quad (2)$$

474 Yet, the PEE does not consider the avoided impacts induced by the non-consumption of fossil energy in  
475 the case of the scenario that promotes wood energy with a regional subsidy (arrow 4 in figure 3). In this  
476 scenario, less fossil energy is used compared to the BAU scenario to provide the same level of heating  
477 for final users. We hence propose to define a second ratio of eco-efficiency that integrates the avoided  
478 impacts due to the substitution between fossil and wood energy in the trajectories. It is called Full Eco-  
479 Efficiency ratio (FEE).

480 
$$FEE = PEE \times Impact\ Avoidance\ Ratio \quad (3)$$



481 Direct subtraction of avoided impacts could lead to situations where the denominator would be zero,  
 482 which is mathematically impossible. In order to include the avoided impacts directly in the Full Eco-  
 483 Efficiency indicator, we propose to create a ratio to account for the importance of the avoided impacts  
 484 compared to the potential impacts. We define the Impact Avoidance Ratio (IAR) as follows in Eq. (4):

$$485 \quad IAR = \frac{\text{Potential Environmental Impacts} - \text{Substitution Environmental Impacts}}{\text{Potential Environmental Impacts}} \quad (4)$$

486 We estimate quantities substituted as in Eq. (5), by assuming that the additional consumption of  
 487 fuelwood induced by the subsidy replaces an energy-equivalent quantity of a mix of fossil fuels as in  
 488 Eq. (6).

$$489 \quad Q_{\text{substituted}} = Q_{\text{subsidy}} - Q_{\text{baseline}}, \text{ expressed in Mm}^3 \quad (5)$$

490 Where  $Q_{\text{substituted}}$  is the quantity of fuelwood substituted for the mix of fossil fuels,  $Q_{\text{subsidy}}$  is the  
 491 quantity of fuelwood consumed in the subsidy scenario and  $Q_{\text{baseline}}$  is the quantity of fuelwood  
 492 consumed in the BAU scenario.

493 This simple substitution mechanism implies that the economic effect of the fuelwood sector on energy  
 494 markets is neglected. This assumption is deemed acceptable, as fossil energy is provided by large  
 495 operators which source from international markets when it comes to gas and oil distribution, on which  
 496 the volume of fuelwood produced by the forest sector has no market influence.

497 The quantity of useful energy (heat) measured in MJ, noted  $Energy_{\text{substituted}}$ , is calculated as follows  
 498 in Eq. (6):

$$499 \quad Energy_{\text{substituted}} = Q_{\text{substituted}} \times Useful\ Energy_{\text{Fuelwood}} \quad (6)$$

500 The average useful energy of wood combustion processes was estimated from the existing LCIs in the  
 501 ecoinvent database for installations sizing from individual wood stoves to industrial size furnaces  
 502 (Wernet et al., 2016). These LCIs were carried out taking into account various data such as the lower  
 503 heating values of different types of fuelwood (logs, chips, residues) at common moisture – between 10  
 504 and 30, and the efficiencies of the installations. More details are provided in Appendix B, Table B.7-b.

505 Then, we consider that this heating energy quantity is substituted with a mix of fossil fuels. Based on  
 506 residential heating mix data for the Grand Est region (Ministère de la Transition Ecologique et Solidaire,  
 507 2019), we assume a substituted mix composed of a 0.6 share of gas and a 0.4 share of oil. Coal use is  
 508 negligible for heating purpose, and we consider electricity heating as fixed. Substitution Environmental  
 509 Impacts correspond to the impact of the fossil fuel mix for 1 MJ of useful heat multiplied by the quantity  
 510 of heating energy substituted as shown in Eq. (7):

$$511 \quad \text{Substitution Environmental Impacts} = \\ 512 \quad - Energy_{\text{substituted}} \times (share_{\text{oil}} \times impacts_{\text{oil}} + share_{\text{gas}} \times impacts_{\text{gas}}) \quad (7)$$

513 “Substitution Environmental Impacts” only deal with substitution related to energy. They are negative  
 514 if substitution leads to impacts being avoided (if fuelwood consumption increases), in this case  $IAR > 1$ ,  
 515 and is positive if there are more impacts due to substitution (i.e. if fuelwood consumption decreases), in  
 516 this case  $IAR < 1$ .

517 3 Case study results

518 The results of the implementation of a fuelwood price subsidy are compared to the BAU scenario for  
 519 the year 2050. The effects of the subsidy are broken down into economic and environmental impacts  
 520 and their combination into eco-efficiency metrics. In addition, special attention is paid to the  
 521 contributions of the different consequential effects defined in 2.3.2 and taken into account in the study.

522 3.1 Economic impacts

523 The economic indicators presented are quantities of wood products (consumed, produced, or traded),  
 524 prices (nominal prices and perceived prices which include the subsidy), and the total economic surplus  
 525 calculated as the sum of consumers' surpluses, producers' surpluses and the subsidy cost for the  
 526 government. Results are presented in Table 3. It includes subsidy effects in the region Grand Est where  
 527 the policy is applied, and its indirect effects in other regions. They are also shown in Figure 5.

528 *Table 3 - Economic outputs in 2050, in the subsidy scenario compared to the BAU, in the region*  
 529 *Grand Est and in other regions*

	Grand Est			Other French regions		
	<i>Initial value</i>	<i>variation</i>	<i>% variation</i>	<i>Initial value</i>	<i>variation</i>	<i>% variation</i>
Fuelwood consumption (Mm <sup>3</sup> )	7.9	+3.8	+48%	30.7	-0.8	-3%
Fuelwood production (Mm <sup>3</sup> )	7.1	+0.6	+8%	31.5	+2.4	+7%
Fuelwood imported from other regions	0.8 (Imp.)	+3.2 (Imp.)	+400%	8.5 (Total)	+2.0 (Total)	+24%
Fuelwood price for the consumer(€/m <sup>3</sup> )	25	-12	-48%	25	+1	+5%
<b>Welfare indicators</b>						
Subsidy cost (M€)	-	152	-	-	-	-
Consumer surplus (M€)	1183	+371	+31%	5006	-46	-1%
Producer surplus (M€)	361	+12	+3%	1397	+52	+4%
<b>Total economic surplus (M€)</b>	<b>1543</b>	<b>231</b>	<b>+15%</b>	<b>6403</b>	<b>+6</b>	<b>0%</b>

530 Quantities of fuelwood consumed in Grand Est increase by up to 48% compared to the BAU following  
 531 the price reduction due to the subsidy. In addition, volumes in Table 4 also show that the quantities  
 532 consumed of wood products other than fuelwood are not impacted by the subsidy. This indicates that  
 533 there is no substantial competition between fuelwood, panels, and paper pulp, which are sourced from  
 534 the same primary product markets. This lack of competition is also illustrated by the relative stability of  
 535 paper pulp and panel prices, which increase by only 1-3% in this scenario.

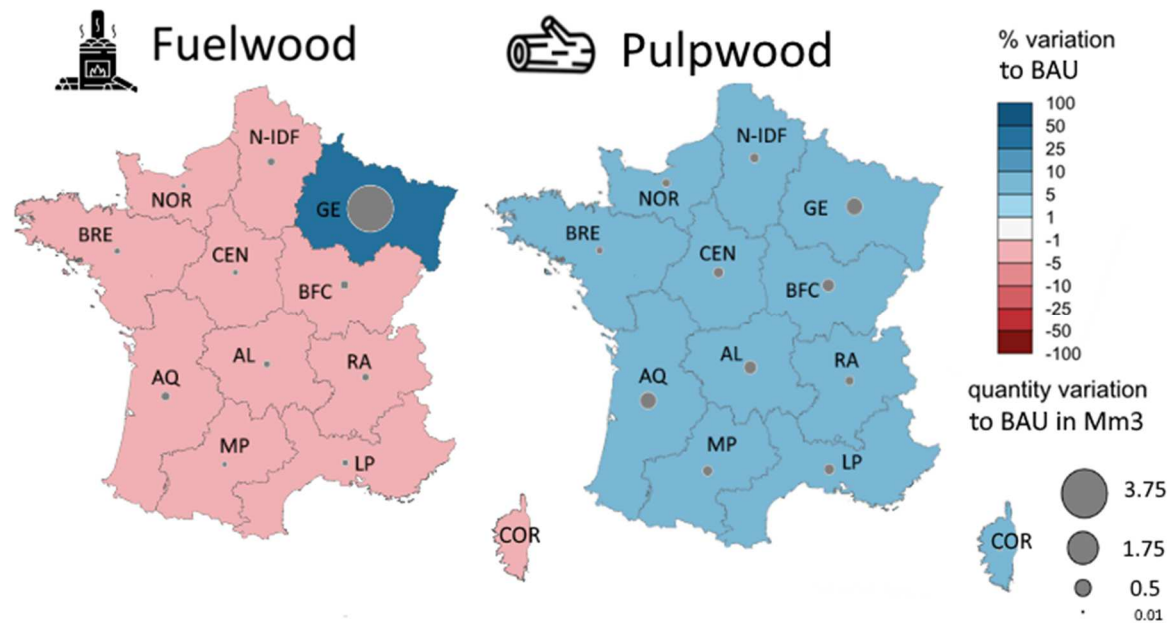
536 *Table 4 – Volume consumed in Mm<sup>3</sup> and share of total volume of all wood products for each wood*  
 537 *product in the Grand Est region in 2050*

		Fuelwood	Paper Pulp	Panels	Softwood sawnwoods	Hardwood sawnwoods	Plywood
<b>Subsidy</b>	Share of total volume	61%	15%	8%	13%	3%	1%
	Volume in Mm <sup>3</sup>	11.7	2.9	1.6	2.4	0.5	0.1
<b>BAU</b>	Share of total volume	51%	19%	10%	16%	3%	1%
	Volume in Mm <sup>3</sup>	7.9	2.9	1.6	2.4	0.5	0.1

538

539 Volumes in Table 4 also show that the quantities consumed of wood products other than fuelwood are  
 540 not impacted by the subsidy. This indicates that no substantial impact is transmitted through the market  
 541 interaction between fuelwood, panels, and paper pulp competing for the same supply of pulpwood  
 542 (corresponding to intra-sectoral interactions identified as arrow 1 in Figure 3). Indeed, paper pulp and  
 543 panel prices increase by only 1 to 3% in this scenario. It appears that the higher demand for pulpwood  
 544 is met through an increased harvest (see Figure 5), accompanied by a 10% pulpwood price hike. This  
 545 shows that the available forest resource is sufficient to feed the increased demand, in line with Caurla *et*  
 546 *al.* (2013) who found that, at the national scale for France, competition between processed products only  
 547 appears when resource availability is restricted.

548 In addition, the increased fuelwood demand in Grand Est is partially met through higher imports from  
 549 other regions. Fuelwood imported in the region Grand Est raises of 3,2 Mm<sup>3</sup> from 0,8 to 4,0 Mm<sup>3</sup> (Table  
 550 3), filling in 85% of the 3,8 Mm<sup>3</sup> consumption increase in the region. This implies a 2,4 Mm<sup>3</sup> higher  
 551 production and a 0,8 Mm<sup>3</sup> lower consumption in other regions (see Figure 5). The total quantity of  
 552 fuelwood traded between regions increases from 8,5 to 10,5 Mm<sup>3</sup>, underlying a reorganization of the  
 553 trade flows. Moreover, international trade flows are not affected, showing that national resources are  
 554 sufficient in economic terms to meet the additional demand. These outcomes reflect a spatial crowding-  
 555 out effect caused by the subsidy in Grand Est, and only interregional interactions are impacted (arrow 2  
 556 in Figure 3).



557

558 *Figure 5 – Variations in quantities of fuelwood consumed and pulpwood harvested when a subsidy is*  
 559 *implemented, compared to a business-as-usual scenario, in each region - year 2050.*  
 560 *Region names: AQ = Aquitaine + Poitou, AL = Auvergne + Limousin, BFC = Bourgogne + Franche Comté, BRE*  
 561 *= Bretagne + Pays de la Loire, CEN = Centre, GE = Grand Est, LP = Languedoc Roussillon + Provence Alpes*  
 562 *Côte d’Azur, MP = Midi Pyrénées, N-IDF = Nord + Picardie + Ile de France, NOR = Normandie, RA = Rhône*  
 563 *Alpes*

564 **Welfare impacts**

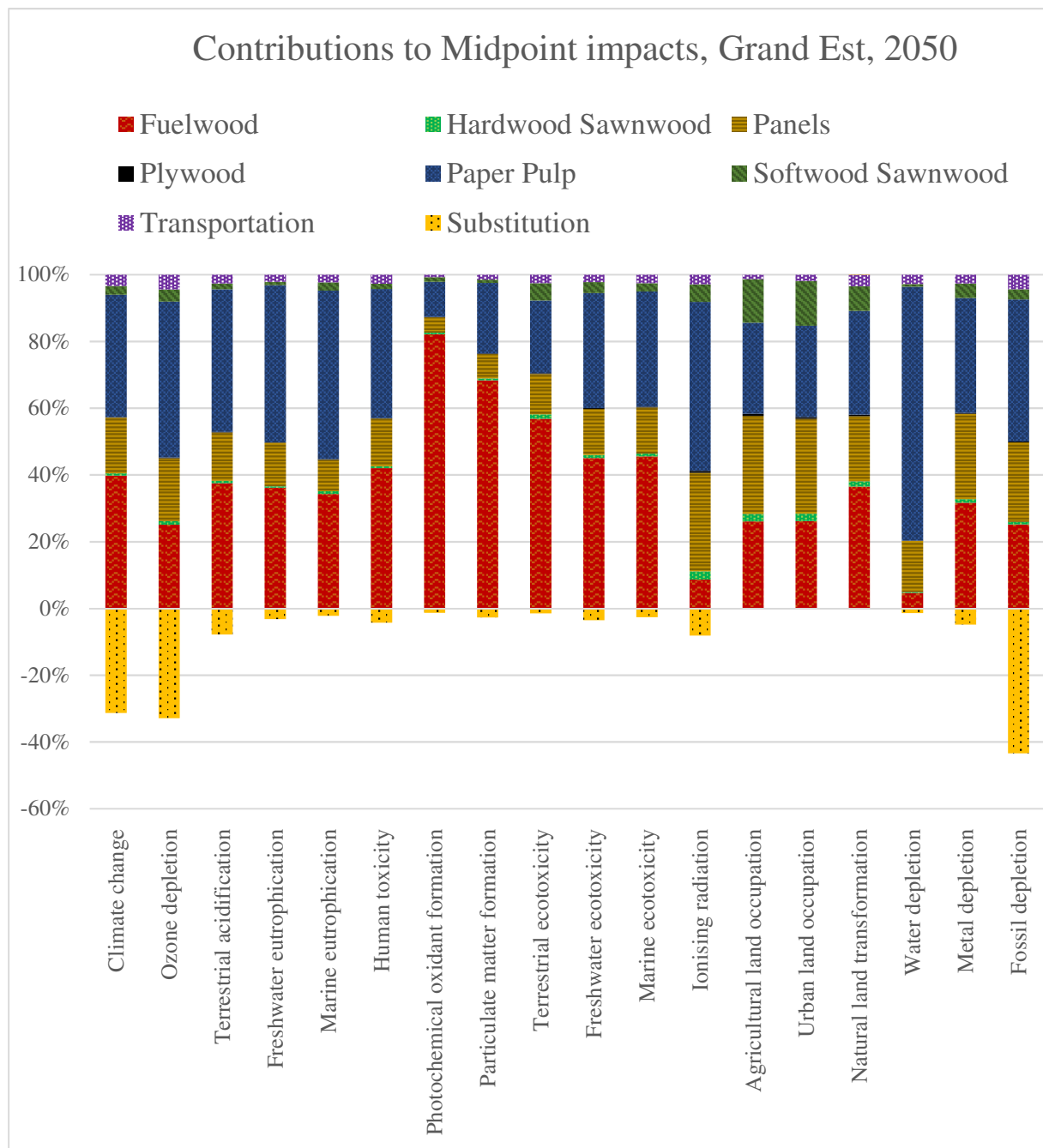
565 The simulated policy affects the welfare of economic agents in the wood sector, be they wood producers  
 566 or consumers. Given that the simulated economic incentive consists in subsidizing fuelwood  
 567 consumption in the Grand Est region, the welfare of Grand Est fuelwood consumers increases most. In  
 568 2050, consumer surplus is 31% higher in the scenario with a subsidy compared to the BAU. In addition,  
 569 the effects of the subsidy irrigate the upstream part of the sector: producer surplus increases by 3%  
 570 compared to the BAU under the combined effect of higher pulpwood prices and larger production to  
 571 feed the additional consumption. Adding consumer and producer surplus with the cost of the subsidy,  
 572 total surplus increases by 15% in Grand Est with the subsidy, compared to the BAU. In other regions,  
 573 lower consumer surplus and higher producer surplus compensate each other which results in almost no  
 574 change in total surplus.

575 Finally, a consumer subsidy is costly for the public authority as it usually leads to a windfall effect  
 576 (Lecocq et al., 2011) : consumers that would have purchased fuelwood anyway (i.e., under the BAU  
 577 scenario) also benefit from the subsidy. To improve the cost-effectiveness of a fuelwood subsidy,  
 578 existing solutions encompass targeting the additional consumption only or subsidizing investment in  
 579 new boilers (such as tax exemptions).

580 **3.2 Environmental impacts: potential and avoided impacts**

581 In this section, we describe the environmental impacts of the wood sector in year 2050. Figure 6 shows  
 582 the impacts quantified at the midpoint level, including the avoided impacts (named “substitution”, in  
 583 brown, negative figures), for the scenario with the 50% subsidy in the Grand Est region. Considering all  
 584 impact categories, fuelwood and paper pulp have the most impacts due, respectively, to the absolute  
 585 quantities produced (see volume percentages in Table 4) and their high impact per unit compared to  
 586 other products. On a smaller level, the next most impacting products are panels, then softwood  
 587 sawnwoods, whose most notable impacts are a 10 to 20% share in impact categories related to land use.  
 588 Indeed, a more significant proportion of forestry’s high impact on land use is allocated to sawnwoods

589 due to the higher share of roundwood in total harvested volume compared to pulpwood – see Table 5 in  
 590 4.2. This allocation does not take into account the higher density in terms of volume of wood per hectare  
 591 in forest stands more specialized towards the production of roundwood. Transportation impacts related  
 592 to quantities traded between regions and with the rest of the world are low compared to other  
 593 contributors. Avoided impacts are most important in climate change, fossil depletion, and ozone  
 594 depletion as alternative fuels are a mix of fossil fuels.

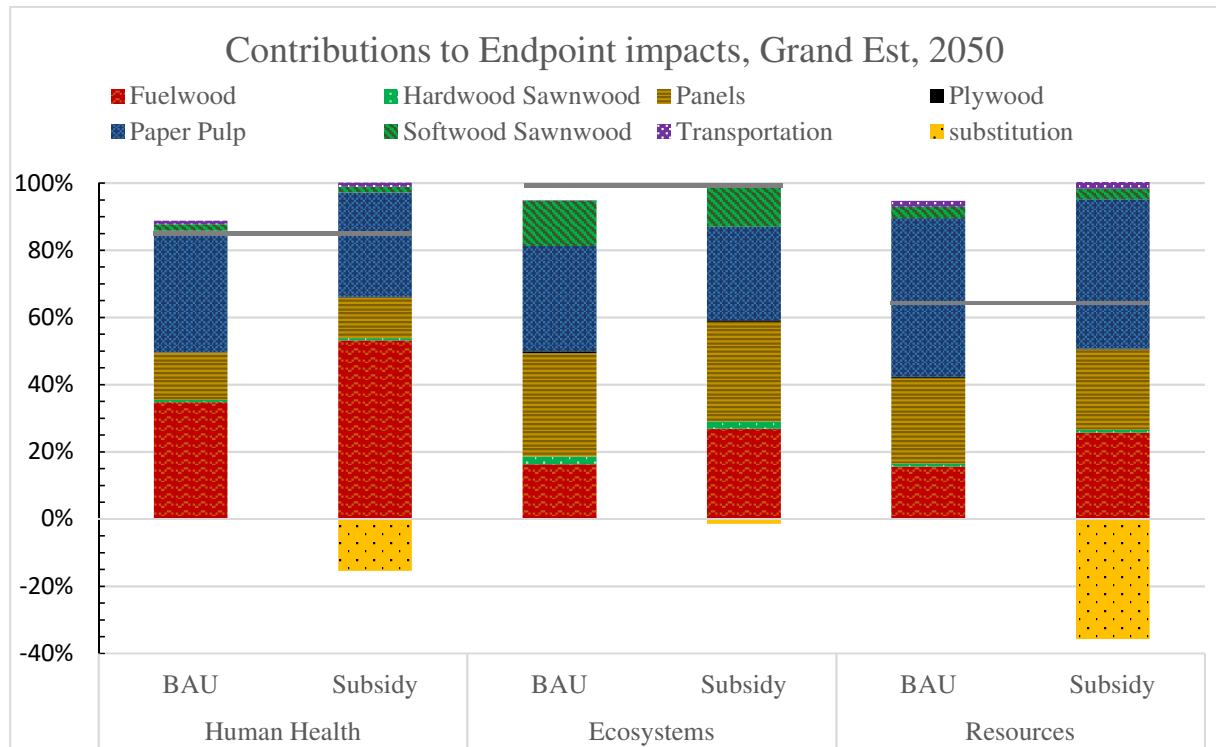


595  
 596 *Figure 6 - Midpoint impact: contributions of the products and processes for the subsidy scenario in*  
 597 *2050 in the Grand Est region modelled with the ReCiPe 1.13 method.*

598 Figure 7 compares the environmental impacts for the two scenarios at the endpoint level. On the overall  
 599 balance of potential impacts and avoided impact, the subsidy scenario performs better than the BAU in  
 600 the human health and the resources categories, as shown by the grey bars. Avoided impacts are  
 601 significant for both these categories, illustrating the importance of taking into account the effects of  
 602 fossil fuel substitution (arrow 4 in figure 3). Without the avoided impacts, the scenario with a subsidy

603 would have higher impacts on all categories due to higher production of fuelwood. Despite the important  
 604 increase in fuelwood quantities consumed (+48%), differences are small in terms of environmental  
 605 impacts and within uncertainty margins. The variation is highest in human health, as fuelwood releases  
 606 high quantities of particulate matters that contribute to damage to this endpoint category. For other  
 607 damages, wood products such as paper pulp and panels are still important contributors, due partly to  
 608 high energy and input consumption and land occupation.

609

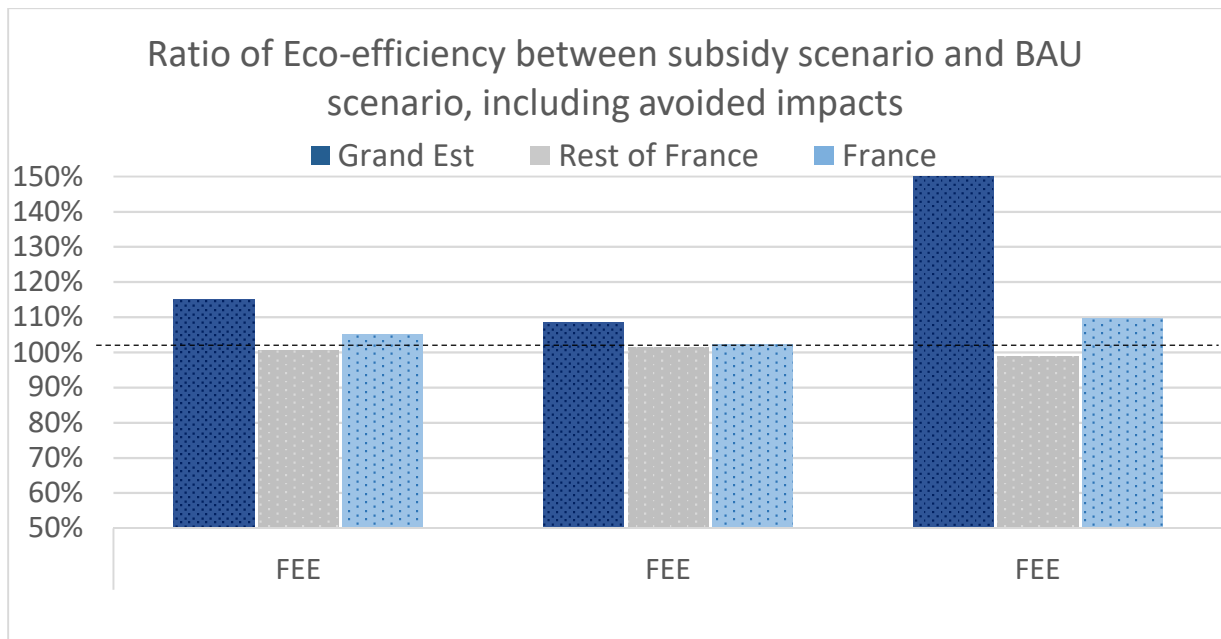


610

611 *Figure 7- Comparison between the impacts in the Grand Est region on the endpoint damage indicators*  
 612 *between the BAU and the subsidy scenario for the year 2050, modelled with the ReCiPe 1.13 method.*  
 613 *Grey bars indicate the overall balance of potential impacts + avoided impacts balance.*

### 614 3.3 Eco-efficiency

615 Partial and full eco-efficiency ratios are computed using total surplus as the economic indicator on the  
 616 numerator, and each of the three endpoint impact categories on the denominator. In Figure 8, we present  
 617 the impact of the subsidy scenario as a ratio of its eco-efficiency to the eco-efficiency of the BAU  
 618 scenario. The more the results exceed 100%, the most eco-efficient the subsidy scenario. FEE and PEE  
 619 are compared for each impact category and different areas, i.e. the region Grand Est where the subsidy  
 620 is implemented, all other French regions and the whole of France.



621

622 *Figure 8 - Comparison of PEE and FEE for Grand Est, the rest of France, and all French regions, in*  
 623 *the year 2050. The percentage value is the ratio of the PEE/FEE of the subsidy scenario divided by the*  
 624 *PEE/ FEE of the BAU scenario.*

625 *Example: In the Human health category, the Full Eco-efficiency of the region Grand Est forest-based sector is*  
 626 *115% of its FEE in the BAU scenario.*

627 *The region Grand Est PEE bars are plain and FEE bars are filled with patterns for improved*  
 628 *readability.*

629 In 2050, in the Grand Est region, the PEE of forest and wood products compared to the BAU is 3%  
 630 lower in the human health category and 6 to 7% higher in resources and ecosystems respectively. The  
 631 subsidy increases the quantities of fuelwood consumed, inducing both a higher economic surplus and,  
 632 in this case where the substitution effects are not accounted for, higher environmental impacts. The  
 633 subsidy has a positive effect on surpluses, on both the consumer and the producer side, which is higher  
 634 than the economic cost of the subsidy. Moreover, this total surplus gain exceeds the environmental  
 635 impact increase. The effect of the subsidy on the producers' surplus in the other regions identified in  
 636 section 3.1 is limited to 3 to 6%.

637 In the Grand Est region, the FEE ratio for the 'Resources' category reaches 150%, showing that the  
 638 subsidy scenario outperforms the BAU by up to 50%. It also performs better in the 'Human health'  
 639 category, by up to 17%. Notably, in this case, moving from PEE to FEE induces a shift from an  
 640 inconclusive effect to a much higher eco-efficiency compared to the BAU. Conversely, for the  
 641 'Ecosystems' category, FEE is almost the same as PEE, in line with the limited avoided impacts for this  
 642 area of protection. All in all, it appears that, in this case study, the subsidy provides clear benefits and  
 643 that most of these benefits come from the avoided impacts. With FEE, clear positive eco-efficiency  
 644 effects can be shown whereas they do not appear when substitution is not accounted for. The results at  
 645 the scale of France show that overall crowding-out effects in other regions are small and do not offset  
 646 the benefits in the region where the subsidy is implemented.

## 647 4 Discussion

### 648 4.1 Indicators and policy implications

649 Eco-efficiency increases with the subsidy, due to the increase in the economic surplus and the avoided  
650 environmental impacts. Yet these variations are interrelated as economic surplus positively depends on  
651 wood product quantities just like environmental impacts. However, a significant difference occurs here  
652 between FEE and PEE. Using wood instead of fossil energy has positive substitution effects that should  
653 be taken into account, as we do in FEE.

654 In this case study, the subsidy for energy wood consumption induces a decrease in the price perceived  
655 by consumers and an increase in market price for producers in the Grand Est region. Therefore, in this  
656 region, the subsidy clearly increases the economic component of the eco-efficiency ratio. However, a  
657 crowding-out effect increases the prices of energy wood and other wood products in neighboring  
658 regions, which (1) reduces the quantities of fuelwood consumed in these neighboring regions and (2)  
659 reduces the FEE gains at national scale. One policy implication of this indirect effect is that eco-  
660 efficiency highly depends on the geographic scale, and a multi-scale analysis must be carried out to take  
661 it into account. In addition, regional policies should be coordinated in order to prevent any leakage  
662 effects. Another policy implication is that if the objective is to reach an energy wood consumption target  
663 at the country level, the measure has to be set up at a national level to prevent any crowding-out effects.

664 Using other socioeconomic metrics of the effects of the incentive have been considered, such as  
665 wages/household income and employment. However, a general equilibrium framework is required to  
666 compute such indicators endogenously. Proxies such as employment multipliers could be used to  
667 estimate employment variations from output and price variations (Fuentes-Saguar et al., 2017), but  
668 quantitative estimations are to be used with care: when evaluating an investment or project from a  
669 prospective simulation model, variations are more relevant than absolute levels. Consequently, such  
670 estimations would be strictly proportional to the surplus/revenue estimations, giving no additional  
671 information when calculating terms of eco-efficiencies.

672 As for the environmental impact, the individual contributions show that paper pulp and panels have the  
673 highest environmental impact with fuelwood. We have shown that the main driver of environmental  
674 impact variation was substitution. The fossil fuel mix has a significantly higher impact per MJ than  
675 fuelwood for several impact categories. However, this result depends on the nature of the energy mix  
676 used (Wolf et al., 2016). The impact of an increase in fuelwood use in the energy mix can be investigated  
677 in more detail by combining FFSM outputs with other energy models, accounting for the hierarchy of  
678 usage for energy sources in France and prospective studies (Albers et al., 2019; Caurla et al., 2018).

### 679 4.2 Model dynamics

680 The LCA framework is based on static inventories, while the FFSM model is temporally dynamic.  
681 Several steps could be planned to make the framework completely dynamic.

#### 682 *4.2.1 Dynamic inventory*

683 Shortcomings in the inventory are (i) the fixed ratios used to disaggregate economic outputs to match  
684 LCA process data and ii) fixed economic allocations.

685 Disaggregation ratios are based on the MFA results for the initial year. However, these ratios change  
686 over time according to forest and economic dynamics. Ideally, FFSM products should be more  
687 disaggregated, especially for products related to low-diameter wood and residues such as cleft timber,  
688 pulpwood, chips, or residues. Doing so would require data that are lacking for some products, especially  
689 residues or cleft timber. Indeed, these products are often directly consumed by producers on site or



690 exchanged through informal markets, causing a lack of consistent data on prices. Some minor alterations  
 691 could be implemented, e.g. estimating residues dynamically according to sawnwood products. A fully  
 692 disaggregated description of residues would make it possible to take into account recycling loops and  
 693 thus add up, in the environmental assessment, non-linear relationships that are difficult to assess outside  
 694 such a framework.

695 Allocations are another cause of consistency issues. A mass allocation is performed for the impacts of  
 696 products from harvest – roundwoods, industry wood. However, the proportions of products will not  
 697 necessarily be the same between the LCI database and FFSM beyond the initial years. Table 5 shows  
 698 that the outputs from harvest may vary according to resource availability and market price dynamics.

699 *Table 5 - Proportions of roundwoods and Industry wood + energy wood in the total harvest.*  
 700 *HW stands for Hardwood and SW for Softwood*

	<b>Ecoinvent documentation<sup>4</sup> (based on German data)</b>	<b>FFSM initial year 2011</b>	<b>FFSM final year 2050</b>
Roundwood	55% (HW 7%, SW 49%)	55% (HW 26%, SW 29%)	49% (HW 26%, SW 23%)
Pulpwood and Fuelwood	45%	45%	51%

701  
 702 More generally, the allocation made for primary products from harvest does not consider the higher  
 703 density in terms of volume of wood per hectare in forest stands that are more specialized towards the  
 704 production of roundwoods. FFSM calculates detailed information on the types of forest stands – high  
 705 forests, coppices, intermediate stands - and the diameter classes of trees at the scale of 8x8km pixels.  
 706 This information could be used to determine a typology of intensive/extensive forest operations, thus  
 707 allocating the impacts of forest operations according to yield.

708 Except for these products from harvest for which a mass allocation is performed, economic allocations  
 709 are used for LCA coproducts, i.e., sawnwood products and residues. Prices used for the allocation  
 710 performed in the ecoinvent database are different from those used as initial conditions of the model. We  
 711 kept ecoinvent prices for simplicity reasons in the allocation process, as allocation prices are embedded  
 712 in ecoinvent data and recalculating allocation based on different prices would have required significant  
 713 work. Table 6 shows that for sawnwood products, FFSM prices and ecoinvent prices are in the same  
 714 range. Moreover, these allocations lead most of the impact toward products with a low share of the total  
 715 potential impacts in the Grand Est Forest sector (up to 2% for Hardwood Sawnwoods and up to 14% for  
 716 Softwood Sawnwoods). However, the variation within FFSM in the long run may be high (+75% for  
 717 softwood roundwoods between 2011 and 2050). Using these higher 2050 prices would marginally  
 718 increase the impact of sawnwoods and decrease the impact of fuelwood, panels, and paper pulp.

<sup>4</sup> Wernet, G. et al., 2016. Roundwood, industry wood dataset informations

719 *Table 6 - Ecoinvent prices used for allocations and FFSM prices in the initial year*

<i>Process</i>	<i>Co products</i>	<i>Ecoinvent<sup>5</sup> (EUR2005)</i>	<i>FFSM initial year 2011 Grand Est (EUR2011)</i>	<i>FFSM final year 2050 Grand Est (EUR2011)</i>	<i>Comment</i>
<i>Debarking</i>	Debarked log	80€/m <sup>3</sup>	99€/m <sup>3</sup> HW 62€/m <sup>3</sup> SW	112€/m <sup>3</sup> HW 109€/m <sup>3</sup> SW	Hardwood (HW) / Softwood (SW)
	Bark chips	12€/m <sup>3</sup> (0.034 €/kg)	NA	NA	Converted in €/m <sup>3</sup> using a density of 350kg/m <sup>3</sup> <sup>6</sup>
<i>Sawing</i>	Sawnwood	265 €/m <sup>3</sup>	516€/m <sup>3</sup> HW / 172€/m <sup>3</sup> SW	478€/m <sup>3</sup> HW 159€/m <sup>3</sup> SW	Hardwood (HW) / Softwood (SW)
	Sawdust	12€/m <sup>3</sup> (0.034 €/kg)	NA	NA	Converted in €/m <sup>3</sup> using a density of 350kg/m <sup>3</sup> <sup>6</sup>
	Slabs and sidings	49€/m <sup>3</sup> HW/ 34€/m <sup>3</sup> SW (0.077€/kg)	NA	NA	Converted in €/m <sup>3</sup> using a density of 640kg/m <sup>3</sup> (HW) / 440kg/m <sup>3</sup> (SW) <sup>7</sup>

720 Implementing dynamic price allocations (prices calculated by the model for each year) could be relevant  
721 to explore the effects on residue valuation in scenarios favoring cascading uses of wood. However, such  
722 variability in the price-based allocation raises issues regarding the robustness of the indicators and the  
723 validity of proceeding with economic allocations (Ardente and Cellura, 2012). Thus, dynamic  
724 allocations should not be implemented and used systematically. Performing sensitivity studies to  
725 parameters such as initial product prices would allow this variability to be isolated. In a long-term  
726 research perspective, using a stochastic economic model instead of a deterministic one should lead to  
727 more stable calculated prices.

#### 728 *4.2.2 Dynamic modelling of environmental impacts*

729 FFSM provides dynamic outputs that may be used in a dynamic assessment of environmental impacts.  
730 First, it provides information on forest stands. While the total forest area remains constant in the model  
731 simulations, the type of forest stands – species, diameter class, management - can change yearly  
732 according to economic and environmental pressures (Lobianco et al., 2015). Using FFSM results to  
733 provide more detail on land occupation in LCIs would not be valued at this time. This is because LCIA  
734 methods do not differentiate between the effects of forest stands or forest management practices on  
735 biodiversity. However, developments are underway to better account for impacts on ecosystem services  
736 in LCA, and links could be investigated in this sense (VanderWilde and Newell, 2021). In particular,

<sup>5</sup> Wernet, G. et al., 2016. Sawing process Dataset Informations.

<sup>6</sup> GuidEnR BOIS-ENERGIE > Les caractéristiques du combustible pour le bois-énergie - Masse volumique

<sup>7</sup> Wernet, G. et al., 2016

737 broadleaved forests and/or high forests are usually associated with higher performance on biodiversity  
738 indicators than coniferous forests or coppices (Gao et al., 2014; Storch et al., 2018).

739 In the framework used in this paper, carbon accounting is not detailed. We used the assumption of carbon  
740 neutrality for biogenic carbon, though this presents shortcomings (Wiloso et al., 2016). Thus, global  
741 warming impacts are based on emissions related to process data on forest operations, transport, and  
742 industry operations (inventories from ecoinvent), as well as emissions related to fossil fuel production  
743 and use in the event of substitution. A simple accounting of biogenic carbon using FFSSM capabilities is  
744 possible (Lobianco et al., 2016), but precise estimations of the carbon footprint would require  
745 significantly deeper work, including detailed modelling of secondary processing industries as well as  
746 further uses in other sectors. This matters most for material substitution and wood product end-of-life,  
747 as shown by recent works pointing out the specifications for a complete biogenic carbon framework to  
748 assess the impacts of biomass use for energy policies (Albers et al., 2019). This remark that stands  
749 particularly true for biogenic carbon modelling in the case of a forest sector model is also true for other  
750 impact categories. Focusing on energy issues, our static energy mix is a strong assumption on a time  
751 horizon of 30 years. In this period, the share of renewables, gas power or biomass itself is likely to  
752 increase, and such scenarios on the evolution of the French electricity mix would substantially modify  
753 the assessment. Thus, a prospective LCA based on evolutive emission factors would be worth  
754 considering. More generally, this remark stands also for all technological processes considered in the  
755 economic and LCI modelling where improvements in terms of yields or different use can occur.

## 756 5 Conclusion

757 We coupled a partial equilibrium sectoral model with a territorial LCA framework to compute eco-  
758 efficiency indicators at the regional scale while taking account of multiple interactions with economic  
759 sectors and other regions. Several adaptations to connect the outputs of the economic model and the  
760 process LCA data based on process yields and material balance were needed, based on forest sector  
761 MFA data.

762 Computing economic and environmental metrics in a consistent framework enabled us to build two eco-  
763 efficiency indicators: the first, PEE, is computed as the ratio between the total economic surplus of the  
764 forest sector in a given region and the endpoint impacts. The second, FEE, integrates the impacts  
765 avoided thanks to the substitution of energy in addition to the endpoints environmental impacts.

766 We tested this framework with a simple case study based on a subsidy for energy fuelwood consumption  
767 implemented in a single French region, the Grand Est. We showed that although fuelwood is, along with  
768 paper pulp, the largest contributor to forest sector impacts, its additional consumption stimulated by a  
769 subsidy was eco-efficient due to the economic effect on consumer welfare and the impacts avoided by  
770 substitution to fossil fuels. This result underscores the importance of developing integrated indicators  
771 that encompass a wide range of interactions. The need for further developments has been identified,  
772 such as dynamic yields or more disaggregated economic outputs for wood residues. This will pave the  
773 way for a stronger coupling between the two approaches. Improving the modelling of the substitution  
774 with fossil fuels would also be required.

775 CRediT authorship contribution statement

776 **Thomas Beaussier:** Data curation, Methodology, Software, Visualization, Result analysis,  
777 Writing - original draft, review & editing. **Sylvain Caurla:** Conceptualization, Validation,  
778 Writing. **Eleonore Loiseau:** Conceptualization, Validation, Writing **Philippe Delacote:**  
779 Supervision, Writing - review & editing **Véronique Bellon-Maurel:** Supervision, Writing -  
780 review & editing

781 Declaration of Competing Interest

782 The authors declare that they have no known competing financial interests or personal relationships  
783 that could have appeared to influence the work reported in this paper.

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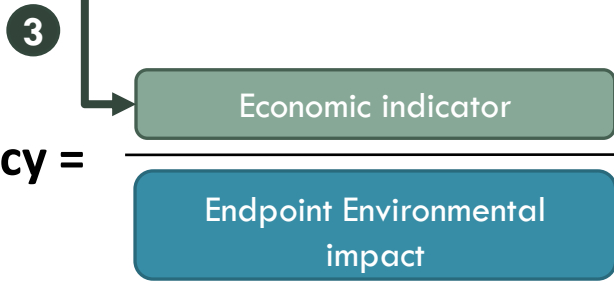
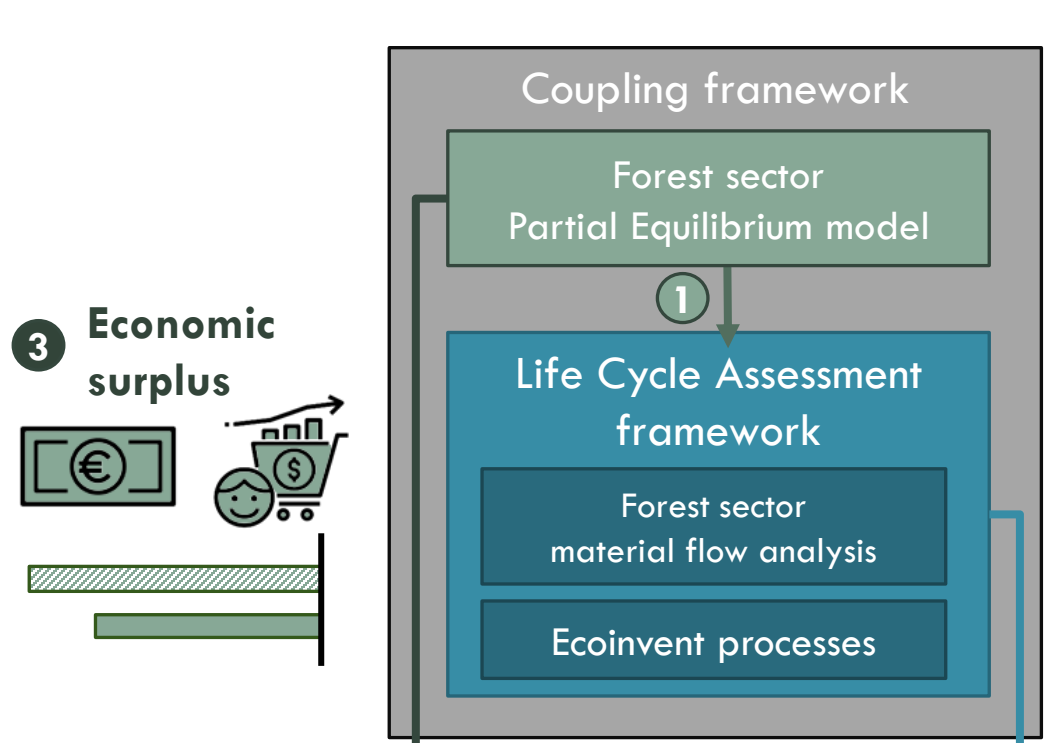
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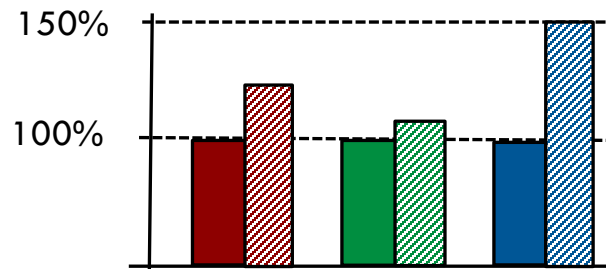
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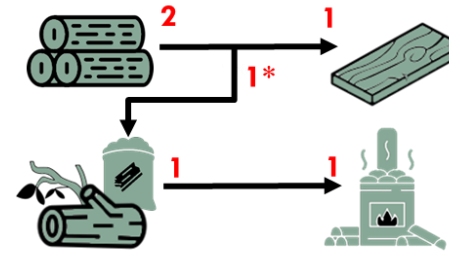


**Eco-Efficiency =**

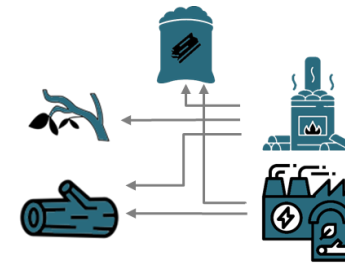


Eco-efficiency including avoided impacts

**① Product quantities**



**② a. Life Cycle Inventory**



**② b. Life Cycle Impact Assessment**

- Human Health (Red)
- Ecosystems (Green)
- Resources (Blue)

- BAU (Black)
- Fuelwood subsidy (Hatched)

