A framework to build decarbonisation pathways for the industrial sector: application on the French pulp and paper sector

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Abstract

The challenge of deep decarbonization is putting the industrial sector under unprecedented pressure, while so far most industries have been protected from the strictest regulations. Industries would need to act quickly considering their long reinvestment cycles and their ageing assets. However, no clear path appears: a wide range of mitigation options, ranging from electrification to changes in demand, are available. In response to this issue, this paper presents a new theoretical bottom-up framework to assess different long-term pathways of the industry in terms of energy demand, CO_2 reduction and investment needs. This framework is built following a microeconomic view. Industrial assets are progressively replaced by the best available or disruptive conventional technologies according to their economic interest. The basic model is enriched with an explicit representation of demand, representing the entire value chain. An original database of existing French industrial assets, including energy and production data, was used, providing an explicit representation of industry turnover. This framework is applied to the French Pulp & Paper sector. This sector could be at the core of a new bio-energy system and thus both incremental and breakthrough changes are considered. This novel assessment reveals that, depending on the hypotheses, the CO_2 emissions could decrease by 55–90 % by 2050. This would mainly depend on if early incentives like an early development of innovative technologies or a rapid evolution of commodity prices are in place. Those would allow the sector to seize the next decade to replace a great part of its equipment's avoiding any fossil fuel lock-in.

Introduction

The industry sector accounted for about 20 % of the EU-wide greenhouse gas emission in 2018. Some of its sub sectors are considered as an 'hard-to-abate' sector (Edelenbosch, 2017) due to its process specific greenhouses gas (GHG) emissions (eg for cement and lime), high temperature heat demand (Wyns & Axelson, 2016), slow capital turnover with highly maximized efficiency (Tong, 2019), cost sensitivity and its own heterogeneity: it shows great variation in products and processes (Fischedick M., 2014).

Net-zero commitment adopted by governments in the past years have put the industry under high pressure. This sector has been partially protected from strong decarbonization regulations like the EU-ETS (European Emission Trading Scheme) until now, as such regulations could impact its competitiveness. Carbon pathways for the industry that were projecting a 50 % reduction in GHG emissions are now targeting minus 80–90 % (Bataille, 2021). Nevertheless, those new GHG targets have important implications, notably excluding many gradual improvement technologies that might have been compatible with less ambitious reduction strategies but may be seen as locked in as they are not compatible with the near net zero ones. Indeed, energy efficiency in industry only shows a limited potential of around 20 % GHG reduction (AIE, 2020).

A broad set of mitigation options are under scrutiny on the respective role they could play in different pathways: carbon capture and storage (CCS), fuel switching, feedstock switching, electrification, hydrogen, synthetic fuels, biofuels, material efficiency, product efficiency and demand reductions. Nevertheless, those options may not all be activated to achieve net-zero and hide great differences in their impact on energy consumption or lifestyles. Furthermore, a net zero system impact not only the production processes but also the industry structure. Today, industry is already experiencing evolutions on its end-use demand for vehicles, infrastructure, machinery, and buildings. Recent decarbonization pathways heavily rely on changes in the consumption models with demand reduction and material efficiency being central (AIE, 2020). We also might expect households & public spending diverted from polluting goods to green ones.

This great array of possibilities to achieve net zero creates great uncertainty around the final energy consumption, the commodities prices, and the possible business cases. This transition should be analysed with insights about the underlying socio-technical regime that links the industry to infrastructures, markets, norms & policies. Even if decarbonization is today considered technologically achievable (Rissman, 2020) there is a knowledge gap on conditions necessary to make this transition achievable.

This work is the first paper of a three-year project that will proceed with the presented framework. Further data and methodologies will be published along the three years, and at its end. With this work, we aim to develop how a conceptual framework could consider all the previously presented elements to deliver a modelling of both the industrial energy needs and their related CO_2 emissions. First, the conceptual framework itself to build energy bottom-up models is presented. This framework links each relevant dynamic to study decarbonization to its relevant study field and possible implementation strategies in a classical bottom-up model. Then, a practical implementation of this methodology is presented on the French pulp & paper sector. The sector and its modelling are presented, as well as some preliminary results as illustrating examples of what could be achieved with the proposed perspective. This work is the first of the application of this framework that will results in the next years in several models varying in the number of sectors covered and the depth of modelling for the different dynamics.

A framework to assess Industrial Decarbonization Pathways

We present a theoretical framework on Figure 1 for modelling the industry sector evolution. It integrates several dynamics using tools and methods from different study fields. This framework will be used along this three-year project with different implementations. We review how those dynamics could be implemented incrementally around a core model that is based around a bottom-up model. This would allow to represent the technological richness while improving the behaviour realism that typically lack from this category of models (Grubb 2002, Hourcade 2005) as the current trend of industrial bottom-up models already do (Fleiter, 2018; Knobloch, 2016; van Sluisveld, 2021). Inputs in the form of technological data and hypotheses, can used to feed four great dynamics, that can be considered in two categories. First the evolution of the production processes - by considering the changes of the industrial assets and technology diffusion paths. Secondly, the cross sectoral dynamics mainly consisting of the evolution of the demand and physical flows through value chain modelling and material flow analysis.

INDUSTRIAL ASSETS EVOLUTION

The core of this proposed framework is a vintage capital representation of the industrial assets, with a description of how industrial actors gradually replace aging assets by new assets that are more energy efficient. The investment decision follows a microeconomic modelling: at several repetitive timesteps each actor choose the equipment maximising its perceived value. The net present value (NPV) is the most common indicator used for such purpose, but the payback time and the internal rate of return are commonly used indicators. This representation at the industrial actor's allows the introduction of heterogeneity indicators to accurately represent the impact of the different cost perceptions among actors on the technological. Such vintage fleet evolution has the great advantage of addressing technological and institutional lock-in issues (Davidsdottir, 2004; Schuette, 1994). Considering so-called market barriers can also enhance the pathways by explaining the energy-efficiency gap: that is firms not investing in seemingly cost-effective technologies (Gerstlberger, 2016). Relevant survey data on how firms take investment decisions using several indicators and implied discount rate can be used. Those data

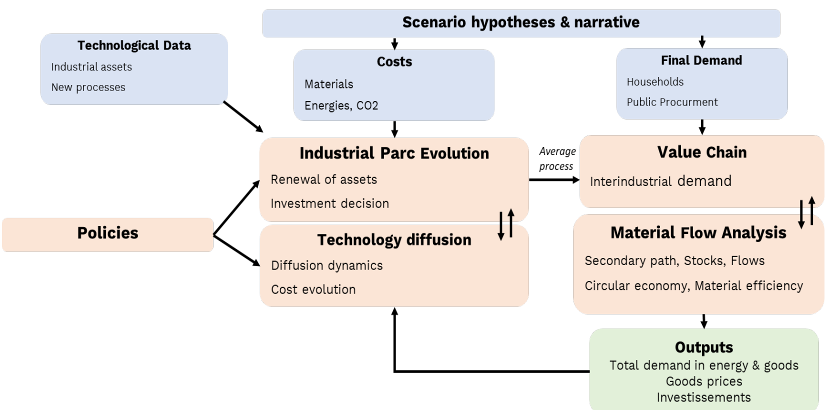

Figure 1. Schematic representation of the modular framework proposed. Each one of the different modules of the framework are analysed below.

could be implemented by varying the discount rate depending on firms' or assets' properties (Knobloch, 2016; Rivers, 2005). For homogenous sectors or when little data is available, using a logistic growth function that depends of a monetary indicator and the sector's dispersion is an interesting fallback strategy to still introduce diversity among actors.

The decision modelling could then be complexified. Indeed, most investment decisions in the industrial sector are made in uncertainty, notably about the energy markets or future regulations. Those investments are also considered as irreversible since they have high investment costs that are hardly recoverable. Those make the use of the NPV less relevant. Real option theory could enrich models by considering more complex and strategic decisions, notably about postponing an investment (Dixit, 1994) or incremental investments. It has already been widely used to analyse CCS projects (Agaton 2021) and could be expanded to manufacturing industry. Risk aversion could later be integrated with a modification of the discount rate (Hugonnier, 2005).

TECHNOLOGY DIFFUSION

Most commonly in bottom-up modelling, technology diffusion dynamics are only described thanks to exogenous hypotheses, where the user can specify macro-indicators like the availability of each technology, a maximum rate of adoption among each sector or even an exogenous diffusion curve, usually taking the shape of a logistic curve. Those macro indicators don't give insights on how they correspond to microeconomic decision making. The literature on the diffusion of green innovation from niche markets to the mainstream ones provides great insight on how to improve energy models (Geels, 2002; Wilson, 2020) and whether this description can be endogenized. Technology diffusion dynamics could be addressed with several focuses. Learning-by-doing and gradual cost reduction could be considered with learning curves based on empirical data of previous deployments. But this implementation is still a macro-description of many non-described parameters with little description power (Popp, 2010). A microeconomic perspective could describe different preferences among actors for the same technology, with an evolution of their perception with time (Rogers, 2003), that could be implemented in an industrial assets evolution. System Dynamics tools could also be used, the most famous example being the Bass model (Bordigoni, 2012) and its refinement that focus on how actors learn about a new technology and implement it. Agent based modelling and game theory are two other common tools mobilized to describe those dynamics and could be implemented in technological explicit models and offer a true microeconomic explanation of the diffusion of green technologies (Ma, 2005). The genuine implementation of the diffusion dynamics could be a mix of those options.

CROSS SECTORAL DYNAMICS

A whole system representation under net-zero targets might seem unnecessary as most sectors will need to move to net-zero emissions that could be achieved with sectoral modelling. Nevertheless, many industrial sectors are considered as hard-to abate and important differences between sectors exist. Thus, representing how all the industrial sectors and their linkage could evolve under an even decarbonization pressure might give different results than sectoral modelling. Furthermore, many industries will be in competition for the same resources (biomass, green electricity, hydrogen) or markets (paper & plastics) and require homogenous assumptions.

Value Chain

Linking the industrial production to the final demand of goods from households and government expenditures is the first step to achieve a flow coherence in energy models. Several options exist to model the future material demand of goods. One would be to extrapolate past trends, typically using compound growth rates. Correlating the gross domestic product (GDP) and per capital material demand is often used in models. Describing the whole value chain allows to create coherence by considering the interindustry demand and possible substitutions. This is key to describe the dynamics of material production, consumption, and their resulting waste (Pauliuk, 2017). The use of the input-output formalism, or a hybrid formalism using a coefficient approach are well developed tools whether in monetary or physical units. Such models can consider for example the energy impact of steel substitution by aluminium or the impact of the agro-food industry activity level on the packaging paper production level (Teixeira & Lefèvre, 2020). The consistency offered by this approach could allow for the integration of a feedback loop between the demand of a resource and its price through supply cost curves.

Material Flow Analysis

The effects of material efficiency potentials have been assessed because they could potentially ease the transition towards low-carbon goods. However, evaluating the true potential of those material dynamics requires to make the material flows explicit. Indeed, the recycling potential is limited by many factors including capital turnover, stocks availability, recovering rates, lifetime of the aval objects and potential impurities issues due to compound material issues. Several tools have been developed in the field of industrial ecology to address this. The input-output formalism has been extended to material modelling (Donati, 2020; Duchin, 2009) and has already been implemented in France for basic materials (Sourisseau, 2020). Such formalism would allow to fully integrate the material flow analysis in the value chain description. Steel flows & stocks have also already been described with great deepness (Pauliuk 2011). This allowed to underline the quality requirements that limit the share of recycled steel. Identifying the true potential of material efficiency and the levers associated, such as regulation, elasticity of the recovery rate or the importance of the sector organisation are other crucial elements (Hernandez 2018). More work is needed to expand those work to all materials and use empirical data to feed models. As describing the evolution of the material flows need many hypotheses, those should be linked to either lifestyle evolutions or price signals. Those exogenous hypotheses could then potentially be modified through diffusion mechanisms, before being completely endogenized once the lack of empirical data would have been resolved. Those integrations could greatly improve the array of decarbonization solutions.

MODELLING OF POLICIES'S EFFECTS

Moving from the technical possibility of decarbonization to its implementation, policy makers face huge challenges to make the transition start and keep its pace. Climate policies impacting the industry can have effects at different levels that can be increasingly difficult to model. Firstly, they can reduce the perceived costs by attenuating the investment and operation expenditures or the perceived risk. The CO_2 price, taxes, feed-in tariffs or OPEX supports can have a direct financial impact in the microeconomic decision. Secondly, policies can support innovation and improve the technological maturity. Empirical data begin to be available on such impacts (Calel, 2016). Finally, policies can impact the demand side markets through regulations that could be imposed in all goods or through public procurement; impacts that the proposed supply chain formalism allows to consider. Nevertheless, policies effects are complex to assess and model, especially for long term scenarios. Thus, some argue that policies should be implemented in a dynamic way to allow for evolution if the path taken is not compliant with long term targets (Mathy, 2016).

Case Study: the French pulp & paper sector

A simplified model of the proposed framework has been developed to present its ability to be practically used. The French pulp & paper sector is presented, followed by the implementation of the framework. Finally, preliminary results are presented.

THE FRENCH PULP & PAPER SECTOR

The Pulp and paper industry is intensive in energy and raw materials. The French sector is heterogenous in company sizes, including small and medium sized to large companies integrated in international groups. This sector shares most of the basic materials industries' properties: energy represents a high share of the production costs (19 % of its added value), high CAPEX, long asset lifetime, low R&D and a highly competitive market. Nevertheless, it is often excluded from industry models focused on climate change as its carbon footprint is rather low (2 % of the CO_2 emissions of the French industry) even though it is consuming approximately 34 TWh (8% of the total industrial energy consumption). Indeed, this sector seems quite protected from the future CO_2 price pressure by relying heavily on biomass. Nevertheless, parts of it are still fossil-fuel dependent and one could expect several dynamics to impact the material and energy flows of this sector: changes in support for biomass cogeneration, increase in biomass products value as they can substitute fossil fuels, circular economy dynamics, reduction of plastic usage.

This sector has several advantages in the energy transition besides its biomass use. Plants typically have a low number of heat sources with centralised boilers which lower the burden of increasing energy efficiency and most processes don't need high temperature. Since the biomass used in the paper sector is mainly biomass of low quality (bark and non-transformed wood), it could be upgraded and possibly converted to biofuels to be exported [Material Economics, 2018]. Electrification, energy efficiency, heat recovery or innovative processes could thus play an important role in the next decades to make this sector compliant with the national trajectories.

Overview of the production processes

Pulp production

Paper is made from pulp, i.e., extracted wood fibres. Those fibres can be extracted through chemical and mechanical processes or recovered from used paper. The three types of pulp have very different characteristics and their core process can evolve a lot according to the paper product and grade. **Chemical pulp** is made by cooking wood chips with chemicals (Na_2S and NaOH) at medium temperature (150 170 °) and low pressure (3 bars) in a digester. Lignin and hemicellulose dissolve in the chemicals (defibration) and are recovered in the black liquor. The pulp consists of the washed cellulose with a yield of around 50 % from wood. The black liquor is then concentrated from 15 % dry content to 65–75 % dry content, allowing it to be fired in a boiler. This recovery boiler serves two purposes: producing high temperature steam (used within the processes and for electricity cogeneration) and recovering the chemicals in the form of a smelt at its bottom. A typical modern plant is energy self-sufficient. **Thermo-mechanical pulp** (TMP) is made by breaking down wood by grinding it. This pulp has a very high yield (90 %) since the lignin is not extracted, but in return the paper has as lower lifetime and strength. It is typically used in newspapers. **Recycled Composed Pulp** (RCF) is made from recovered papers. The processes, yields and energy consumption vary a lot depending on the grade of recovered paper and the final products. Finally, other non-fibres resources like kaolin clay are used in small quantities to change the characteristics of the paper.

Papermaking

In this process, the pulp is firstly put into suspension with water and then refined in order to modify its mechanical properties. This slurry is introduced in the paper machine where the paper is formed and is dried from 1 % dry content to 90 % dry content. It is dried in two parts: first through mechanical means to around 40–55 % dry content (draining on a wire mesh, vacuum, and mechanical pressing), then by passing through steam heated cylinders. This step is by far the most energy intensive step in paper making. Steps can vary quite a lot depending on the pulp and paper products and grade but also among the different facilities: the specific energy consumption to produce 1 ton of paper varies from 1MWh to 9MWh. Papermaking can be integrated in the same plant as the production of pulp, thus resulting in a lower energy consumption as the pulp doesn't have to be dried to be transported. This also allows for energy optimisation of the plant as the energy surplus of the pulp mill can be recovered. As a result, if they rely on fossil fuel boilers the non-integrated papermakers, including most of the recycled paper production, have a larger fossil CO_2 footprint to the integrated virgin ones.

Material and Energy flows

Energy flows

Energy flows were reconstructed using CEREN[1] database that produces energy consumption estimates on a yearly basis with energy, sub-sector and usages. It is completed by a database focused on industrial processes where detailed complementary information are provided such as the age of the equipment, type of energy used and technology and operation of the asset. The pulp & paper industry in France consumes annually around 34TWh as visible on Figure 2. Biomass which is the main energy source is either a co-product of its processes and

1. Centre d'Études et de Recherches Économiques sur l'Énergie.

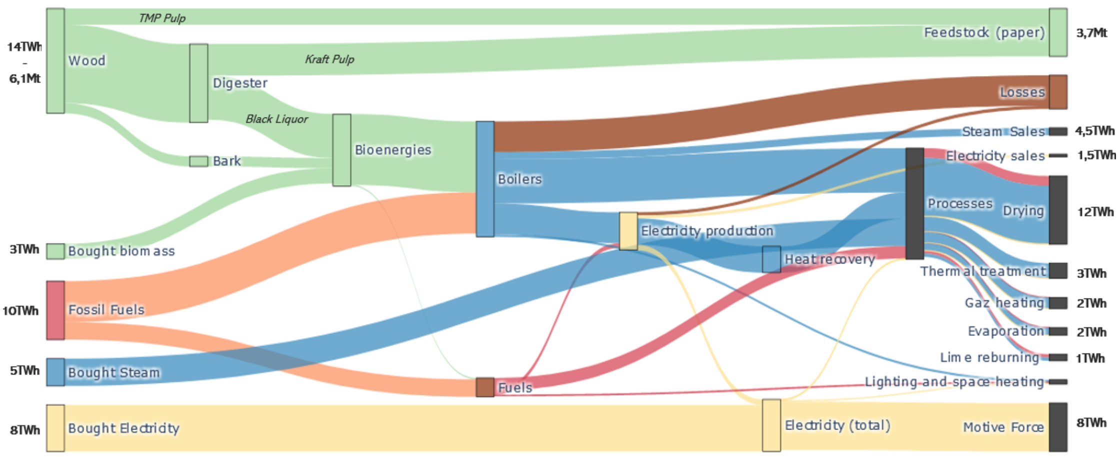

Figure 2. Energy flows of the pulp & paper sector. Author's calculations based on 2018 data.

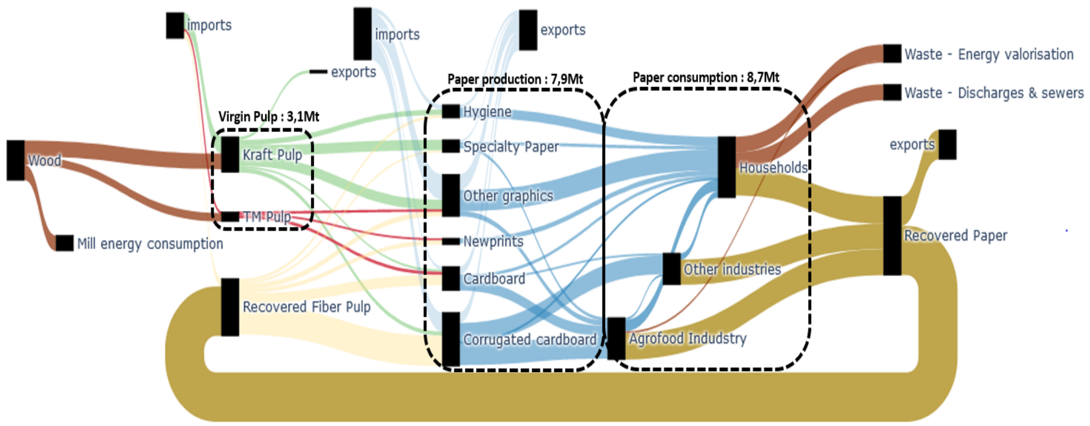

Figure 3. Material flows of the pulp & paper sector. Author's calculations based on 2018 data.

originates from the wood necessary to make the pulp (9TWh from barks and black liquor) or bought to complete the energy needs of the plant. Boilers are the most energy intensive units since most of the processes use low pressure steam. Nevertheless, this hides several discrepancies: fossil fuels are still commonly used for the lime kiln, non-integrated papermakers that have mainly gas boilers or for processes with high requirement issues like tissue drying. Electricity represents a third of the energy consumption (10TWh), with a low CO_2 impact (10 %) thanks to the low carbon footprint of the French electricity.

Material flows

The reconstruction of the physical flows is shown on Figure 3. Paper production in France is almost a closed loop since the appearing recycling rate is quite high. It only needs a low share of virgin pulp to meet the quality requirements of the paper proprieties (35 %). Indeed, most of the paper consumed is packing carton board for inter-industry exchanges, with a very high recycling rate. Other products, such as hygiene products or graphic papers, have high requirements for virgin pulp, and lower true recycling rate. Studies on the French paper sector lack details on the recycling paths, and have difficulties reconciling the material paths from aggregated sources. Physical determinants to the limits of recycling are thus not well defined (ADEME, 2017; Bémol, 2019).

MODEL OF THE PULP & PAPER SECTOR

The model implementation is summed up on Table 1, with how each relevant dynamic was implemented in this practical example. This implementation focused on modelling the gradual replacement of the industrial assets in a bottom-up simulation model.

Techno-Economic Data

A technology database was built thanks to the compilation of already existing databases aimed for bottom-up energy models following the aspects of Table 2. It was enriched with sector specific literature and reports (Lerede, 2021; Griffin, 2018; Kong, 2017). The compiled data will be published at the end of the project. Furthermore, little information about true technological parameters and costs is available for technologies that are still in R&D phases or with only a few plants have. For complex integrated plants with several processes linked with energy cascading and optimisation, the data was collected as different facilities configurations. Technologies and plant modifications considered in the model were classified in three types:

Table 1. Implementation of the framework.

Aspect	Representation
Heterogeneity of the industrial assets	Sector dispersion of processes, equipment's age Size sensibility *(production level **PL**, scaling factor **SF** , energy prices **EP**)*
Heterogeneity of the decision making	Dispersion of the discount rates (**DR**) related to the plants financial results
Policies	Energy taxation & biomass cogeneration subsidies CO_2 price (**CP**) Scenarios (commodity prices & technology availability)
Value chain	Coefficient description
Material flow	Exogenous growth hypothesis per product & material flows
Technological diffusion	Exogenous hypothesis of maturity date (tech availability **TechA**)

Table 2. Aspects and indicators used to characterise technologies.

Technology	Economics	Risk
New energy consumption, lifetime, compatibility with products and other technologies in place	CAPEX, lifetime, maintenance costs Current and potential deployment Co-benefits, co products, other pollution evolutions	Risk and potential disruption indicators Technology Readiness

More efficient processes

Papermaking and pulp making processes still show great potential for energy efficiency without major refurbishment of the installations. Pulping, screening, dispersers, de-inking are steps for which energy consumption could decrease with incremental improvement and optimisation. Analysis and audit on specific plants show that between 7 % and 32 % energy savings could be achieved with payback times of less than 4 years (Blok, 2004). Mature technologies that can increase mechanical pressing like the shoe press still have room for diffusion. They are particularly interesting as they reduce the need for the thermically energy intensive drying. Heat electrification could also play a role, as it is usually more efficient and has a low CO_2 footprint in France.

Heat recovery

Heat is currently not recovered in most paper plants as it requires the exhaust gas to be cooled down below the water dew point resulting in low temperature heat. Heat pumps and mechanical vapor recompression could thus be used to raise the recovered heat temperature. Great improvements are expected on the temperature level achievable with heat pumps, which would increase their potential integration. Paper drying, evaporation of black liquor and TMP pulping are steps that show great potential for reducing the steam demand while consuming little electricity. (G Rogers, 2018).

Innovative technologies

Several innovative technologies allowing to produce paper have been studied, such as: black liquor gasification, deep eutectic solvent, dry forming, enzymatic pre-treatment, ligno-boost, impulse drying of paper. Some of them are already implemented in a few mills around the globe or are being studied as potential long-term decarbonization options. Several plant configurations that implement the biorefinery idea have been integrated in the model. Black liquor gasification is one of the technologies that opened the perspectives of this concept: the chemicals are recovered while producing syngas. This syngas can then be fired in a combined cycle with a high power efficiency or to produce biofuels such as hydrocarbons, methanol or dimethyl ether (Rafione, 2014).

Asset evolution

Plant site data

Several databases of industrial sites have already been built aiming at providing information about heat recovery potential, energy efficiency or energy consumption in a plant level (Manz, 2021). For this study, firm data was built, aimed at giving an empirical estimation of the heterogeneity between industrial plants rather than being accurate on a plant level. We have combined several databases including EU-ETS (European Union Emission Trading System), the Diane-Astree database [Van Dijk, 2019], the ERPTR (European Pollutant Release and Transfer Register), local data about fossil gas and electricity consumption [SDES, 2019], and the CEREN databases. Further methodology on this database will be published at the end of the project. For non-integrated paper mills, the industrial assets were represented with an aggregated form, while the low number of mills producing virgin pulp in France made it possible to use specific information about specificities of their pro-

Table 3. Some commodities prices assumptions.

Scenario	2030 CO_2 price (€/t)	2050 CO_2 price (€/t)	2030 Natural Gas Price (€/MWh)	2050 Natural Gas Price (€/MWh)
Standard	110	200	22	35
Aggressive	170		27	

Table 4. Some technology readiness assumptions.

Scenario	Introduction year for tech with TRL 7	Introduction year for tech with TRL 8	CAPEX reduction after 5 years	CAPEX reduction after 10 years
Tech -	2040	2030	-	-
Tech +	2030	2025	-10%	-20%

Equation 1. If the industrial asset is eligible to a renovation, the investment decision was made to maximise its NPV supposing perfect information.

$$\text{NPV}= \left[-CAPEX_{tech} * SF_{firm} + \sum_{t=T}^{T+Lifetime} \frac{OPEX_{t,tech,firm}}{(1+DR_{firm})^{t-T}}\right]$$

Where $OPEX_{t,tech,firm} =$

$$-O\&M_{tech} - \sum_{e\ (energies)} (EP_{t,firm,e} + EF_e * CP_{T,firm}) * SEC_{tech,e} + \sum_{exports} EP_{t,firm,E} * SEP_{tech,e}$$

SEC/SEP: Specific Energy Consumption/Production; EF: emission factor. Other acronyms in Table 1.

cesses and already implemented energy efficiency technologies thanks to the databases built or public data from local environmental impact studies concerning specific facilities.

Decision implementation

Every year, renovation conditions are checked for each asset. Those consist for each technology of two discrete possibilities. First, at midlife a new investment can be done, or the old equipment can be kept by spending 20 % of its CAPEX as a renovation investment. Those regular renovations could represent the opportunities offered by plant wide renovations that require it to stop as regular revamping (Davidsdottir & Ruth, 2004). The second investment possibility is at the end of the technical lifetime, when the equipment must be changed, as it is considered obsolete. If the industrial asset is eligible to a renovation, the investment decision was made to maximise its NPV supposing perfect information, Equation 1.

Every year, the production capacities for each product were adapted to the actual demand by closing and opening facilities thanks to the material flow modelling. The choice of a new production facility was made by the same NPV maximisation and associated to the plant that had the greatest NPV with a maximum increase of 20 % from its initial production capacity, as it was considered as the most profitable and thus most likely to invest. Closures of plants were made by non-replacing the assets with the lowest NPV among those which needed renovation. No transition from different kind of paper mills were considered as data was difficult to acquire about transition costs and requirements.

Finally, several aspects that cause choice heterogeneity are considered through a modulation of the discount rate for each company. This can be seen from different perspectives, like introducing perceived barriers in an NPV framework. Those could consist of the risk perception of the technology transition due to the lack of information, the different preferences for the future, short term or long-term strategies, the high perceived risk of energy efficiency investment or the cost of capital depending of the risk profile into an NPV framework (Dixit and Pindyck, 1994). The rentability rate was used as a proxy of the depth of their long-term perspective. Literature discount rate issued from surveys were used, varying a lot for energy investments (ranging 5–34 %) (Rivers, 2005; Boie, 2016). The discount rate was then modulated linearly with the rentability rate.

Scenarios

Four 2050 scenarios were built with variations on the technological readiness hypotheses and energy & CO_2 prices since those were the inputs with the less empirical data to build on. The commodity prices have the same 2050 target taken from the EU reference scenarios but follow either a linear evolution in the *Standard* scenarios, or a more aggressive evolution with intermediary 2030 targets as visible on Table 3. Those scenarios

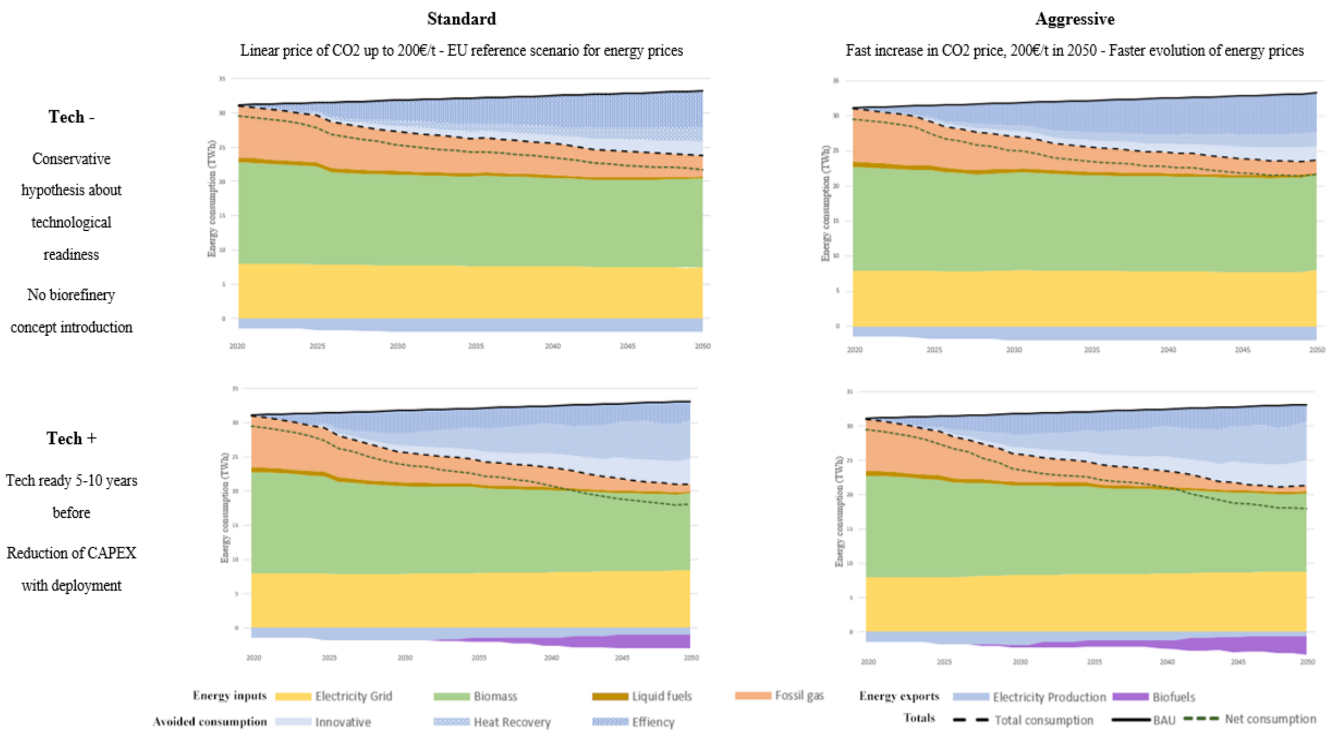

Figure 4. Total energy consumption of the Pulp & Paper sector in 4 scenarios.

could well represent different policies related to energy and CO_2 prices or technology development funding.

PRELIMINARY RESULTS

If only the demand evolution was considered, the final energy consumption would increase by 7 % by 2050. Thanks to a high implementation of energy efficient technologies that are cost effective in all scenarios, it actually decreases by 10–31 % (see Figure 4[2]). Most assets are only replaced at the end of their technical lifetime, with the highest share of replacement at midlife is only 5 %, reached in *Tech+ Aggressive*. This explains that the three *Tech+* and/or *Aggressive* scenarios can take advantage of the needed replacement of a great part of the industrial assets in the next decade to implement highly efficient technologies such as innovative heat recovery or dry-forming technologies. In those scenarios, key technologies like heat pumps or impulse drying become cost-effective for most plants before 2030. Thus, those scenarios show the most important decrease in total energy use and where CO_2 emissions decrease the most (-70 to -80 %, following a similar trend to the fossil gas use). On the other hand, a scenario with late decarbonization incentives (as in the *Tech – Standard* scenario) some lock in occurs even if gas assets are slowly replaced by low-carbon technologies and energy-efficient technologies (principally shoe press and hot pressing). Indeed, some gas assets are still widely in use in 2050 resulting in only a -55 % CO_2 reduction. The *Tech* – scenarios mainly result on energy efficiency equipment's (~60 % of energy savings) and show the lowest energy related investments (5bn€ for the *Standard* and 5.4bn€ for the *Aggressive*). The *Tech+* scenarios have the lowest carbon footprint mainly thanks to innovative heat recovery (~45 % of energy savings) that in return need greater investments (+10 % and +15 % relative to *Tech- Standard*). Those scenarios thus show the greatest capital/energy substitution. The electric consumption increases at most by +13 % in the *Tech+ Aggressive* scenario but doesn't decrease in any scenario as energy efficiency development is compensated by new electrified usages (shift from gas in tissues manufacturing or heat recovery). The biorefinery concept is selected under the Tech + assumptions that make the exportation of Fischer-Tropsch fuels highly interesting for firms that can afford the investment thanks to scale economies and a low risk profile, making electricity the major energy net consumed in the *Tech+ Aggressive* scenario. The energy saving frees up energy resources to be transformed into biofuels that results in little evolution of the global biomass consumption.

DISCUSSION

The model is coherent with the literature analysing the European pulp & paper sectors and the impact of technological change on the energy consumption (-14 % to -9 %) or the GHG emissions (-67 to -75 %) (Moya, 2018; Mobarakeh, 2021). Those studies used different decision rationales and hypotheses to avoid any winner-takes-it-all problem like a limitation the development rate of the technologies or by using scenarios narratives as the main driver. We show that our model of the current assets in place at the level of the equipment is another solution to avoid such a problem. The evolutions shown are still speculative and depends on many parameters among which the market formation for biofuels, capital access, technology development and policies support for such transformation. Several critical

2. The net consumption is excluding the energy exports and thus represents the true energy consumption used for the paper production processes

inputs to this model could be identified. Technology stock turnover highly depends on the revamping considerations, for which data and literature lack to accurately calibrate the model. The lack of data and heterogeneity of the processes considered increase the uncertainty of the results but would most likely not impact the general conclusions

Indeed, the aging industrial assets of the French industry open a window of opportunity for the next 10-15 years. Those assets can effectively be replaced with low carbon technologies, as shown by the impact of early incentives to reduce gas consumption in the *Tech* + and *Aggressive* scenarios. Public support could be the main driver of those needed early incentives. Contract for Difference or OPEX support schemes that make up for the difference with fossil fuels prices are examples of such policies that change the perceived prices. Other public support could help the *Tech*+ scenario to realize by increasing the development of key technologies like innovative heat recovery on which those scenarios heavily rely. Indeed, even though decarbonization of papermaking can rely on several solution including biomass and electrification with innovative heat recovery, due to upcoming tensions on the biomass markets the latest is of great interest. Nevertheless, as this technology shows little implementation today, it is difficult to assess the likely high perceived risk by investors and derisk needs.

Improvement to this model could be made in the future regarding the description of the material flows to precisely identify the physical and economic limitations of recycling and thus reducing the number of exogenous hypothesis. Taking this dimension into account would help to give precious insights about the interactions between the circular economy and techno-economic scenarios. Also, the technology description mainly relied on selected plant configurations which could be more numerous. For integrated plants such as pulp mills with complex energy flows, optimisation of the whole facility could also increase the technology resolution. Other aspects described in the framework as important are still to be well implemented with various challenges. Linking the evolution of the production costs and the expected demand, considering uncertainty and strategic behaviours using real options as well as integrating the diffusion process could improve the model.

Conclusion

The work presented has several limitations but provides a starting point for future research on modelling decarbonization in the industrial sector. The proposed bottom-up microeconomic framework provides strategies on how to implement several endogenous dynamics that go beyond pure technological profitability, in particular technology diffusion by considering existing assets in place. We applied some of that framework by modelling the pulp and paper sector, with various price signals and technological development assumptions. The results show that in any case, energy consumption could significantly reduce (-10 to -31 %) while achieving a profitable decarbonization. Nevertheless, the constructed scenarios show that early incentives in the next decade are necessary to mainly have climate neutral technologies in 2050. Indeed, to go beyond a 55 % reduction of GHG emissions and reach -80 %, a high implementation of innovative technologies and heat recovery are necessary, that would make up to 60 % of energy savings. Such incentives could be in the form of financial support or rapid technological development for non-traditional technologies that are crucial. This study thus gives an overview of the decarbonization potential of technological innovation and how to implement long-term goals with short-term incentives. Being data intensive, it may make worthy to replicate this study once more data is available, especially regarding processes that are still in early stages of development. This work could also be adapted to all industrial sectors, given that modelling the pulp and paper sector required to consider both a concentrated sector with high energy intensity and a diffuse sector. This would then allow significant cross-sectoral dynamics related to interties and limited resources such as biomass to be modelled, leading to consistent industry-wide trajectories.

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