Final conclusions - BEST project

The energy transition is a radical transformation of all components of the energy system, from energy sources to end uses, from the availability of primary energy to meeting the needs of individuals, businesses and governments. These needs include heat, mobility, electricity (IT, lighting, etc.) and non-energy demand (plastics, fertilisers, etc.). Thinking about these needs is not automatically associated with the energy transition, but rather with economic and social issues. And yet, it is imperative to question our needs, as reducing them can only facilitate the energy transition, particularly in Belgium, where there is a significant shortage of local renewable sources. Although not studied in detail as part of the BEST project, the question of sufficiency was raised. We found that a significant reduction in final demand would make it possible to reduce imports of renewable fuels, without any major impact on the structure of the energy system to be put in place in Belgium by 2050, unless we were to study reductions which, by their magnitude (50%), would be difficult to accept socially. The conclusions presented here have therefore been drawn from scenarios for which requirements change little from current values. They are robust to the above-mentioned reduction in requirements, except as regards imported e-fuels volumes.

By 2050, and assuming a cost-optimized system based exclusively on renewable energies, the conclusions are clear. Belgium can endogenously supply only a fraction of its needs, based on its wind, solar and biomass resources (*Thesis Xavier Rixhon, 2024*). Within the primary energy consumption of 368 TWh/year in 2050 (quite a reduction from the 554 TWh/year in 2020 thanks to the massive electrification of the energy system), local renewable resources will supply around half, the other half being imported as electricity (32 TWh) or e-fuels (150 TWh). The breakdown between the two types of import depends on the constraints imposed on the power system and on the transport of gas and liquids. Nevertheless, the majority is imported via e-fuels, as shown in Figure 1. Among local resources, solar power is the most abundant, followed by biomass and wind power. The possibility of an international offshore field in which Belgium would participate has not been considered. It comes indirectly in the form of imported energy.

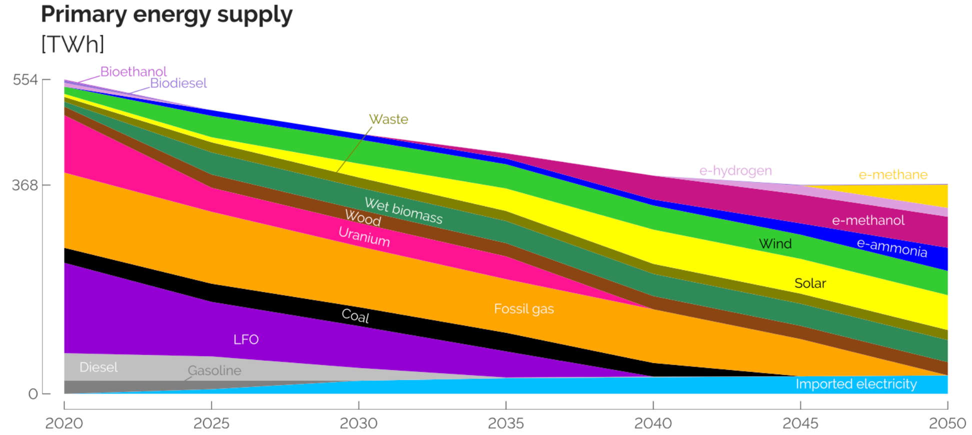

Figure 1: The evolution of the primary energy needed to supply the Belgian energy system with “business as usual” demand is almost linear over time, thanks to improved efficiency (same service with less primary energy), mainly driven by electrification – *Thesis Xavier Rixhon (2024)*

All the energy imported into Belgium could come from Europe (*Thesis Paolo Thiran, 2024*). In a Europe-wide study, prohibiting imports from the rest of the world - an extreme case, but one that is relevant to a study of the infrastructure needed in Europe - we see large energy flows between different entities, with the Benelux countries and Germany being the main importers of energy from both the south and the north (Figure 2). From the north, Norway exports a total of 395 TWh per year. From the south, Spain and to a lesser extent France and Portugal export 439 TWh per year. Italy and the rest of Europe make a smaller but significant contribution, with 110 TWh from south-eastern Europe and 89 TWh from Italy. Beyond these values, which represent an extreme case, the forms of export are important to note. Hydrogen is the dominant vector, accounting for 35% of flows, followed by electricity with 26%. Other fuels come next: methanol 9%, other synthetic liquid fuel 18%, and methane 9%. Ammonia and biomass together account for just 2% of traded energy. All in all, renewable fuels in their various forms account for 74% of all exchanges. This can only be achieved at the cost of reinforcing gas transmission networks, while maintaining part of the natural gas (methane) networks.

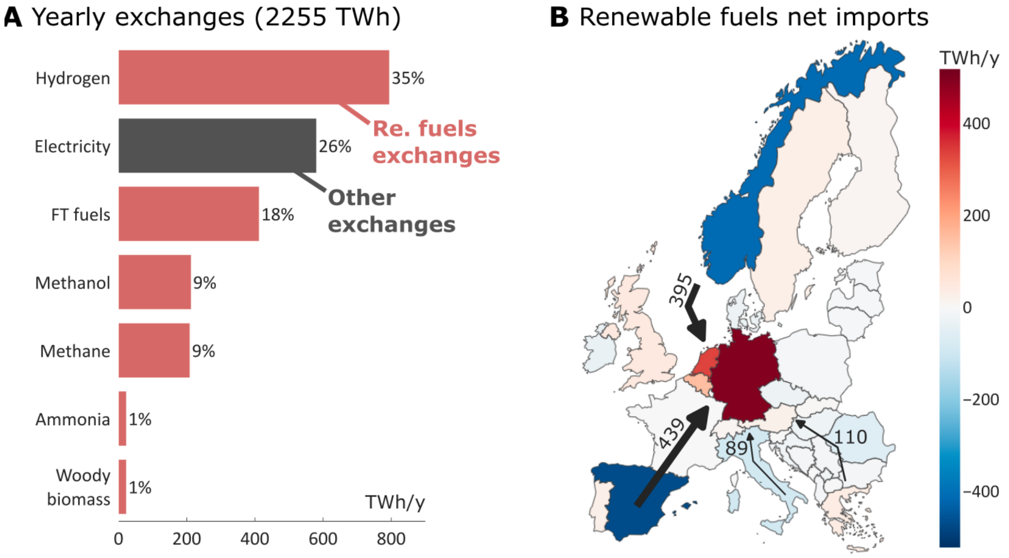

Figure 2: Europe-wide trade is mainly in the form of e-fuels (A), with flows from the periphery to the center of Europe, Benelux and Germany (B) – *Thesis Paolo Thiran (2024)*

The European case makes it possible to define realistic border conditions for the Belgian case, although this has not yet been fully exploited in the BEST project. The interest lies in characterizing the availability of energy flows at borders as a function of meteorological fluctuations and, consequently, the sizing of storage on Belgian territory. A maximum would therefore be obtained via these border conditions, since the availability of flows outside Europe would alleviate the constraints. For the purposes of this project, the results at Belgian level were obtained on the basis of constant import flows throughout the year.

Nuclear power is a facilitator without radically changing the European or Belgian situation. On a European scale, the installation of 150 GW of nuclear power represents a relatively small contribution. It is associated with a reduction in solar and wind power, with no major impact on the structure of the energy system, apart from a reduction in storage requirements. On a Belgian scale, given the local energy deficit, nuclear power reduces fuel and electricity imports without significantly affecting wind, solar and biomass production. Nuclear energy and renewables complement each other in the energy system. The results confirm that the massive deployment of renewable energies is a decision that will never be called into question, whether or not nuclear power is an option in the future.

1. How much liquid and gaseous energy carriers do we need to feed the Belgian energy system during and after the transition?

Biofuel imports begin in 2025, although significant use is observed from 2035 onwards. Based on a deterministic reference scenario (see Figure 1), all four e-fuels are imported to supply the Belgian energy system. E-methanol is the dominant vector, followed by e-methane, e-ammonia and e-hydrogen. This ranking is the result of the specific uses of these e-fuels in Belgium. E-methanol is entirely dedicated to non-energy demand. The use of methane (also from biomass) and e-methane moves from CCGT in 2020 to high-temperature heat cogeneration in 2050. Ammonia, on the other hand, becomes the fuel for the CCGTs still present in 2050. It is also used in NED. Finally, hydrogen is used for mobility, as local electricity production is insufficient. The results indicate that hydrogen will be used in trucks, but it could also be used in buses, etc.

In the context of the energy transition, biomass is an inexpensive, versatile and short-cycle source of carbon. These advantages are exploited by optimization models that maximize the use of biomass right from the start of the transition (*Thesis Martin Colla, 2024*). For this reason, the potential of biomass in Belgium has been studied to incorporate updated values into the models. Today, biomass is already widely used in energy systems. In Belgium, the potential is almost 100% exploited. Only ambitious choices could broaden the supply base and potentially double the biomass used for energy purposes, see Figure 3. Forest products remain the main source of biomass, with a potential of 12 to 17 TWh. Overall, including other residues, the potential is only 10% of Belgium's needs in 2050.

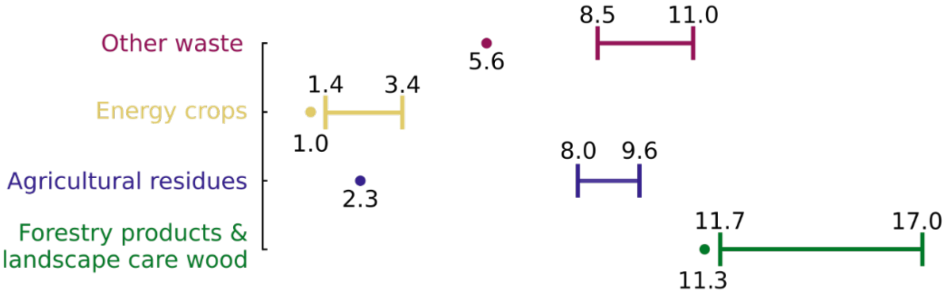

Figure 3: For Belgium, current biomass mobilization (points) could be doubled (intervals), for a total of 35 TWh, with different growth rates depending on the category considered – *Thesis Martin Colla (2024)*

Biomass is mainly used in sectors where electrical energy is of little or no relevance, i.e. high-temperature industrial heat and non-energy demand (e.g. high-value chemicals in biorefineries). Biomass remains a local energy source. On a European scale, biomass is not transported across borders. On the other hand, it is traded in transformed form, as methanol and methane.

In Belgium, the lack of local renewable energies means that e-fuels production is zero when system costs are optimized (*Thesis Paolo Thiran, 2024*). It seems logical that locally available energy should be used in the most efficient way: electricity and non-energy demand (for biomass) and that Belgium should turn to the European or world market for the remainder. Nuclear energy can reduce the need for imports, without eliminating them, unless we consider capacities far in excess of those installed to date, or a very progressive demand reduction scenario that would be difficult to accept economically and socially, as mentioned in the introduction.

On a European scale, the use of e-fuels is more diversified, as the model integrates more types of consumption (notably international aviation), as shown in Figure 4. Nevertheless, they remain predominantly present in sectors that are difficult to decarbonize, such as air and maritime mobility, as well as buses and trucks. They also contribute to NED, which requires a carbon source supplied directly by biomass or by a by-product such as methanol or methane, or by carbon capture.

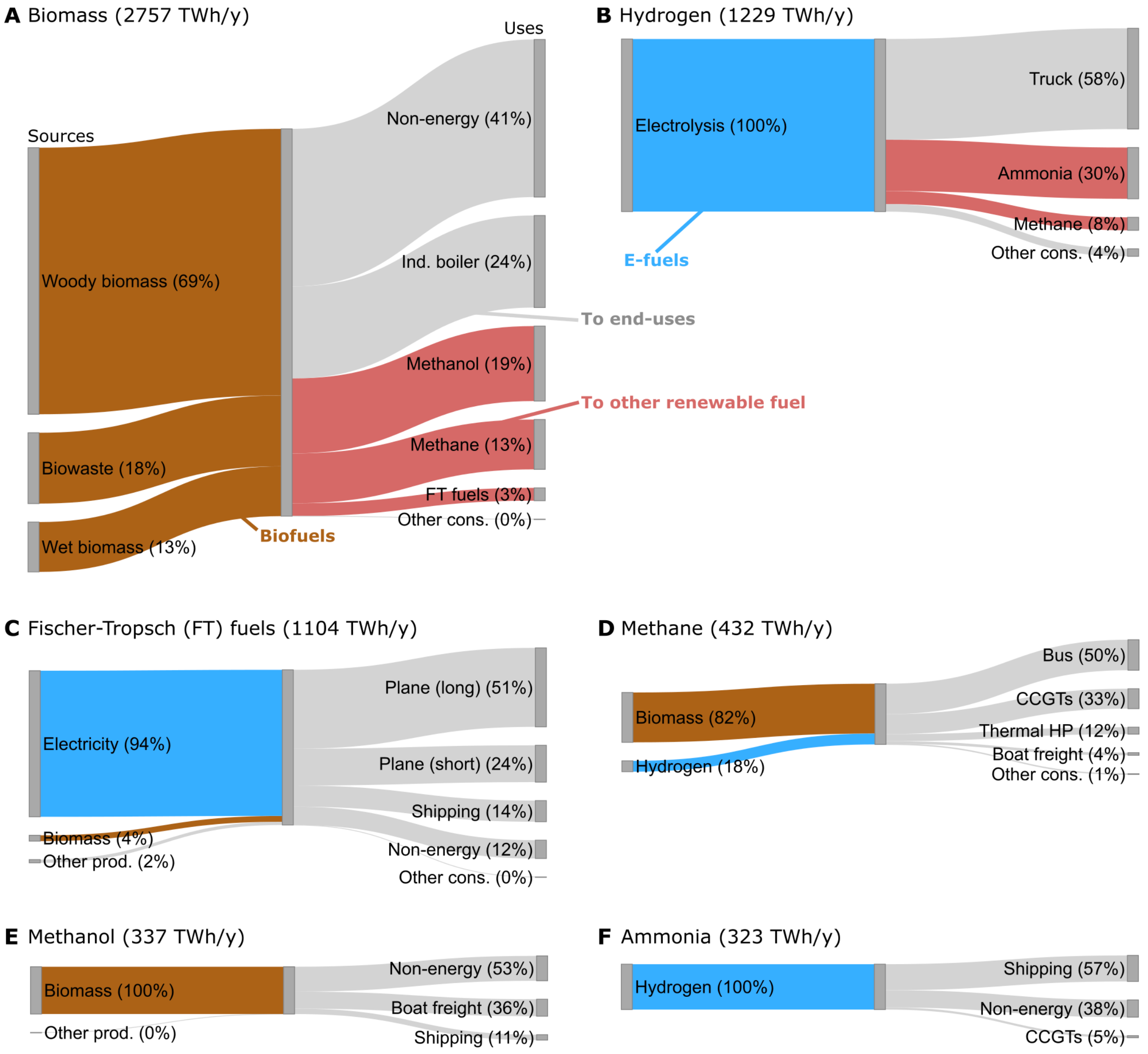

Figure 4: On a European scale, the use of e-fuels is focused on sectors that are complex to electrify, such as air mobility and boat transport – *Thesis Paolo Thiran (2024)*

Part of the e-fuels requires a carbon source that can only be obtained through capture, in addition to carbon from biomass. In total, in the reference scenario, Europe captures 305 Mt of CO2 with a post-combustion capture solution placed on industrial installations such as biomass boilers. Europe uses 15 Mt of CO2 for methane production, and 290 Mt to produce synthetic liquid fuels.

2. How compatible are these carriers with our current energy system, including the grid? What is their impact?

As illustrated above for the case of Europe, e-fuels are used in many different applications for which appropriate technologies already exist or are under development. There are no obstacles to the use of e-fuels in energy systems.

The first stage in e-fuels production is water electrolysis. Even if the optimal system in terms of cost does not include local production of e-fuels, some electrolysers could be installed in Belgium. For example, 500 MW of electrolysers would produce 5% of the total demand for hydrogen and its derivatives, but with a fairly low load factor of 25 to 35%. These figures illustrate the gap between demand and local availability of renewable energy. These electrolysers could be integrated into the Belgian energy grid on a centralized or decentralized basis, without affecting the transient stability of the transmission network (*Thesis Aurélia Hernandez, 2024*). Optimal placement of the electrolysers, close to coastal areas or wind farms with a high share of renewable electricity, could improve the dynamic behavior of synchronous generators.

3. What are the most economic scenarios and storage needs (daily, monthly, seasonal) to implement these renewable fuels?

For imported e-fuels (methane, methanol, ammonia and hydrogen), the model imposes constant flows throughout the year. Without this constraint, the quantity required would simply be imported instantaneously. Imports are therefore smoothed over time, but not used, which follows seasonal variations (mainly heating). Part of the methane is therefore stored in summer to be available in winter. As the use of (e-)methane decreases over the transition period, from 150 TWh to 50 TWh, the storage capacity installed at the start of the transition, 16 TWh (for comparison, the Loenhout storage facility has a capacity of 7.6 TWh), remains more than sufficient throughout the transition period. Hydrogen does not need to be stored, as its consumption is also regular over time (mobility does not present a seasonal profile). This storage is complemented by 3 TWh of low-temperature heat storage, electric vehicle batteries and pumped storage facilities (i.e. Coo Trois-Ponts).

4. What are the main uncertainties concerning the energy system, now and in the future, to be considered while optimising the system?

Most of the project's results are based on a deterministic approach to the energy system, with all parameters at their most-expected values. Yet, the past five years have shown the impacting role of disruptive events. Several approaches have therefore been explored to propagate uncertainities within our models (*Rixhon et al., 2021)*. The most advanced approach is based on reinforcement learning. Of all the uncertain parameters, some have a greater impact on the energy system and its evolution than others. These include the cost of natural gas and, more generally, of fossil fuels, the presence or absence of nuclear generation, the cost of importing e-fuels, the discount rate used and industrial demand. As the uncertainties are not centered on the mean value (e.g. -40% + 80% for fossil fuels), the mean of the stochastic solutions is different from the deterministic solution, Figure 5.

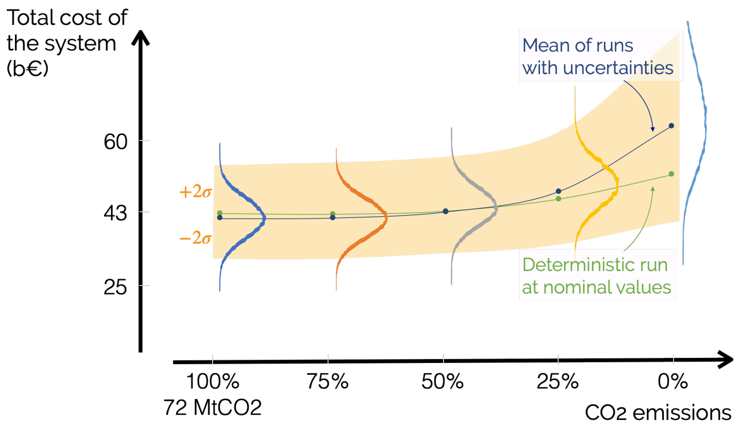

Figure 5: Since uncertainties are not centered around mean values, they have a non-linear impact on transition costs – *Rixhon et al. (2021)*

5. How to convert these fuels back into final energy in the most efficient ways?

This question has many dimensions, since it potentially applies to all fuels for all applications. Only a few specific studies were carried out as part of the BEST project.

CCGT power plants are part of the optimized Belgian energy system (*Thesis Antoine Verhaeghe, 2024*). During the transition, they are fueled with natural gas. At the end of the transition, they are fueled with ammonia. However, carbon capture on natural gas/methane plants has been studied. For large units (560 MW), without adaptation, the capture penalty is high, with efficiency dropping from 61% to 47%. By adapting the cycle (exhaust gas recirculation, improved solvent and thermal integration), the penalty is reduced and cycle efficiency remains high at 54%. At partial loads, performance deteriorates rapidly, with capture leading to a net efficiency of 40%. At the other end of the power spectrum, for small installations (microturbines), the penalty is higher, making capture impractical without even considering subsequent CO2 management. This is due in particular to the greater dilution of CO2 in combustion fumes.

One potential application for methanol is mobility, since it is in a liquid state under ambient conditions and is therefore easy to transport (*Thesis Ward Suijs, 2024*). For applications such as buses, locomotives, barges, etc., it may be relevant. However, compatible engines are needed, since these applications are equipped with diesel engines, and methanol is a fuel suitable for spark-ignition engines. In the context of this project, it has been shown that, theoretically, the power per cylinder of a methanol engine can be increased up to 314 kW, with efficiencies (indicated) close to those of diesel engines (around 47%). These values are obtained for mixtures that do not lend themselves well to flue gas treatment. If we wish to continue using three-way catalysts, a unit power of 220 kW is possible. By imagining combinations of 6 to 16 cylinders, the possible power ratings well cover the range of applications envisaged. For applications requiring even higher outputs (large container vessels), other combustion modes need to be considered, such as pre-chamber systems, which have not been studied.

With regard to stationary applications, such as cogeneration, the combustion of methane/hydrogen/oxygen mixtures has been studied, demonstrating the beneficial effect of oxygen addition on power density in the HCCI combustion mode (*Thesis Sara Spano, 2025*). This oxygen would be available as a by-product of the electrolyzers. However, the absence of electrolyzers in Belgium ultimately ruled out this approach.

The BEST project has also focused on e-fuel pollutant emissions and their reduction, through the development of a predictive model to determine pollutants emitted on the basis of fuel and combustion conditions, in particular NOx associated with ammonia combustion (*Thesis Roeland De Meulenaere, 2024 and Thesis Matteo Savarese, 2024)*. The power of artificial intelligence tools now makes it possible to take account of uncertainties in such tools, and offers a great opportunity to make progress in these areas, which are closely linked to e-fuels.

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