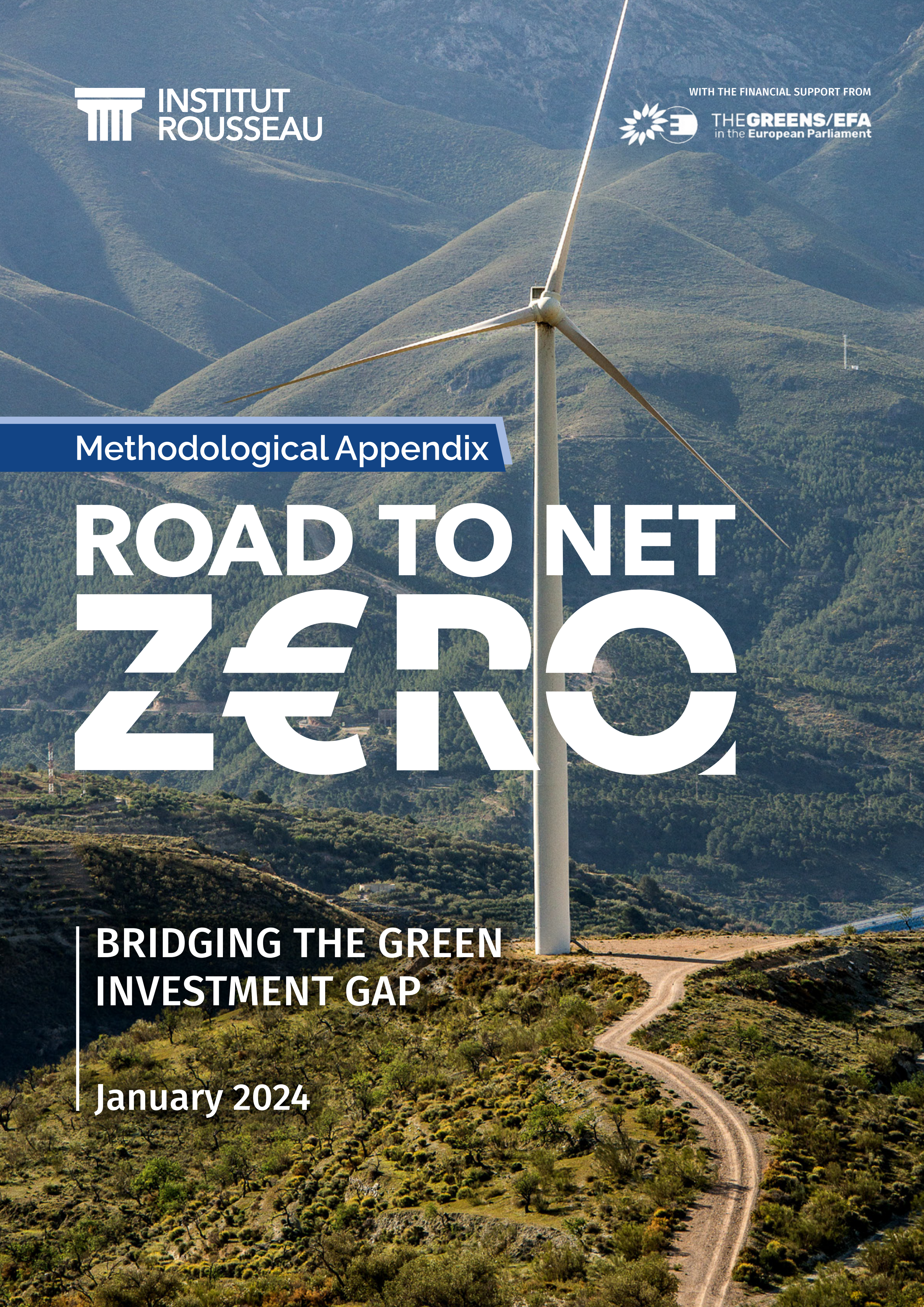

INSTITUT ROUSSEAU

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Methodological Appendix

ROAD TO NET ZERO

BRIDGING THE GREEN INVESTMENT GAP

January 2024

Summary

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Summary

Images : Storyset.com/Freepik.com, Unsplash.com, TheNounProject.com, Rawpixel.com

Study scope, key definitions and main limitations

1 Main questions addressed by this report

1. **Which public and private investments are needed** to achieve the transition to carbon neutrality in Europe by 2050?

2. **How do these investment amounts compare to the existing planned investments** in a business-as-usual scenario of similar scope?

3. **What measures can the public sector employ to guide, support and accelerate this transition? What would be their cost for public finances?**

A 3-step methodology was used to answer these questions. For further insights into the underlying approach and assumptions, please refer to the Methodological Appendix.

Fig. 1.1 3-step methodology used for the Road to Net Zero (RtoNZ) project

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1 List the decarbonisation levers required for each sector

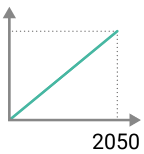
- ✔ Convert vehicles to low-carbon technologies
- ✔ Efficiently renovate housing
- ✔ Increase material efficiency in the industry
- Etc.

× 37

2 Establish a Business-as-Usual scenario and a Transition scenario, then calculate their respective costs

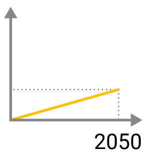
Transition scenario

Number of vehicles, % of electric
Number of buildings renovated
% of raw materials recycled
Etc.



€ TRANSITION

Business-as-usual scenario (BaU)



€ BaU

€ Transition − € BaU = € Extra Invest.

3 Define public measures for each lever in the 2 scenarios and compute their costs

Convert vehicles to low-carbon technologies	Reinforce conversion subsidies
Renovate buildings	Reinforce renovation subsidies
Etc.	Etc.

37 LEVERS → **70+ PUBLIC MEASURES**

€ Transition, Public − € BaU, Public = € Extra Public Invest.

This study is informed by a transition scenario aiming for carbon neutrality by 2050, in contrast to a baseline scenario (or business-as-usual scenario, extending current trends and policies). While the scenarios described are primarily physical ('what ought to be materially transformed for our society to be carbon-neutral?'), the present study is essentially economic, focusing on financing the described transformations.

Seven major countries are studied in detail: France, Germany, Italy, Spain, the Netherlands, Poland and Sweden. These countries represent approximately 77% of EU-27 GDP and 73% of domestic emissions. For each of the 37 decarbonisation levers and 70+ public policies, all modelling outputs (emissions reductions, public and private investments and extra-investments) are computed both at the country scale (for each of the 7 countries) and at the EU-27 scale.

Two additional questions will be addressed by future Institut Rousseau reports:

4. **How can the private and public sectors finance these investments?**

5. **What are the advantages of undertaking this ecological transition, and how do the benefits, including economic gains, offset the associated investments?**

2 Key definitions to understand the methodology

- **Investments**: The definition of 'investments' used here is broad, based on the notion of 'investment costs' in a project or asset. It refers to initial costs to implement a change (capital expenditure or CAPEX) and excludes so-called 'operational' or 'operating' costs that arise during the project (operational expenditure or OPEX). This definition is not constrained to a purely accounting perspective and will designate, for simplicity's sake, subjects and types of economic flows that are considerably broader and more heterogeneous, especially in the public sphere: direct public expenditures (e.g., investments in public transportation, renovation of public buildings) or indirect public assistance for private investments (e.g., subsidies, automotive conversion incentives), transfer mechanisms between private actors passing through public accounts (e.g., guaranteed selling prices for renewable energy producers), decreases in tax revenues, etc. For ease of language, the terms 'cost' or 'extra cost' compared to the trend are sometimes used to designate these same investments. Values are given in euros for 2022.

- **Net zero or net carbon neutrality**: The current objective set by most political institutions, including the European Union, is a 'net' objective, meaning it does not aim to completely stop emitting greenhouse gases by 2050 but rather to minimise emissions and absorb what cannot be reduced through carbon sinks (especially forests, which absorb atmospheric CO_2 during their growth). This study adopts the same logic, but aims to leverage carbon sinks (which have their own limitations) only as a last resort, after effectively decarbonising everything possible.

Additionally, the net zero objective must align with the 'carbon budget', indicating the allowable cumulative GHG emissions to stay within the Paris Agreement's temperature goals. Achieving net zero thus requires consistent efforts starting now, with particular emphasis on substantial emissions reduction before 2030.

3 Geographical scope and extrapolation methodology

The study covers 7 representative countries in detail: France, Germany, Italy, Spain, the Netherlands, Poland, Sweden.

These EU-7 countries represent around almost 80% of EU-27 GDP and domestic emissions.

For each of the 37 decarbonisation levers and 70+ public policies, all modelling outputs (emissions reductions, public and private investments and extra-investments) are computed both at the country scale (for each of the 7 countries) and at the EU-27 scale.

To get the EU-27 results, two different approaches are used, depending on the sector:

- When UE-wide scenarios (i.e. sets of transition-related physical data) were accessible and/or relevant, calculations were made directly at the EU-27 scale, as if Europe was an additional country. This was typically the case for the Energy sector and part of the Carbon sinks sector.

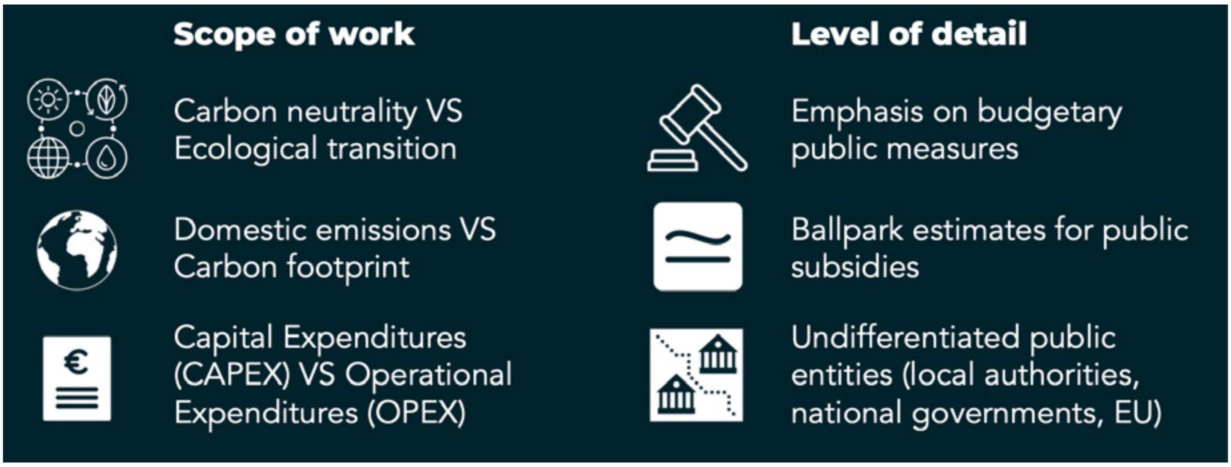
- When this was not possible and/or relevant, a bottom-up approach was used to extrapolate the rest of the EU based on average results obtained for the 7 countries.

  - Global investments were usually extrapolated proportionally to sector or sub-sector current emissions or other relevant physical metrics.

  - Public investments were usually extrapolated proportionally to this same metrics or using the current level of public expenditure on environmental protection from Eurostat.

4 Main limitations of this exercise

Fig. 1.2 **Main limits of the present study**



- **The cost of the entire ecological transition is not quantified here**; only the cost of achieving carbon neutrality by 2050 is considered. Other environmental issues, such as biodiversity preservation (addressing the ongoing sixth mass extinction), water management, chemical soil and process decontamination, etc., require equally important attention (cf. Appendix A.1. regarding biodiversity). Investments in these areas are justified and necessary but for methodological reasons, they are not directly included in this study, although several proposed investments also contribute to addressing these issues. **The amounts provided in our study thus represent a baseline for achieving carbon neutrality but should be significantly revised upwards by incorporating other ecological challenges.** This will be the subject of future work. Additionally, as explained earlier, operational costs are not directly accounted for in the totals, such as the VAT reductions recommended for transportation, food, or a portion of production subsidies in energy. For all these reasons, the extra cost for the public authority given here constitutes a baseline based on very cautious estimates.

- **The same applies to investments needed for Europe to adapt to climate change consequences.**

- **The greenhouse gas emissions considered here are solely territorial, i.e., emitted on European soil**, to align with the Green Deal. However, Europe's carbon footprint, accounting for the carbon impact of all imported products, is much broader. While these aspects are addressed whenever possible (emissions related to international aviation, management of carbon leakage through a carbon border adjustment mechanism for Europe, etc.), the associated costs are not quantified in the study. This also applies to Member States ' contributions to the UN Green Fund, an investment known to be necessary but aimed at supporting the decarbonisation of other countries.

- **The intrinsic economic or financial profitability of investments** and their impact on economic actors (production costs, household budgets) **is not systematically studied**, except in specific cases.

- **The suggested public support measures concentrate on those with substantial budgetary or**

fiscal allocations. The approach followed in this report is fiscal rather than regulatory; we do not systematically address the legislative and regulatory measures that will inevitably accompany investment deployment. Nevertheless, the most pivotal regulatory measures or those serving as prerequisites for investments are outlined. Furthermore, this study acknowledges the operational complexity in implementing this transition, and does not systematically describe all the conditions essential to successfully execute the quantified action plan.

- **Public support is sized only by an order of magnitude.** A specific modelling of case studies, measure by measure, would be necessary to determine the subsidy required to balance incentive for private actors and windfall effects or abuse resulting from an overestimation of needs. Similarly, while general guidance is given on the distribution of public support based on social or economic criteria (e.g., higher coverage rates for low-income households, prioritisation of SMEs with limited investment leeway, etc.), the exact scales of the schemes are not detailed.

- **Public investments do not distinguish between costs that will be borne by the Member States and those that will be borne by European or local authorities.** Determining distribution between national and infra-national levels is contingent upon the governance structure of each Member State. However, this distinction is deemed inconsequential due to the overarching nature of public investment in both cases. Similarly, the allocation between the European and national levels is recognised as a matter of policy and political choices, with the responsibility for decision-making belonging to the Parliament.

- **Finally, investments are considered to start in early 2024 and end in late 2050, spanning 27 years.** The reference for current emissions, from the European Environment Agency[1], is 2021, as official 2022 and 2023 emissions were not yet available at the time this report was drafted. The emission variations of Europe between 2021 and 2023 are thus not factored into this study.

Box 1.1

Integration of biodiversity and broader nature-related considerations

This report focuses on reducing GHG emissions and does not address broader human impacts on nature. Consequently, the investments linked to the Road to Net Zero scenario should be considered as a baseline for initiating a comprehensive ecological transition.

However, since climate change significantly influences various environmental challenges, adopting the RtoNZ scenario would effectively mitigate other environmental pressures. Notably, transitioning to agroecology and investing in safeguarding and expanding natural ecosystems within the LULUCF sector substantially contribute to preventing biodiversity loss and adapting to climate change.

More details are provided in Appendix A.1.

Box 1.2

Impact of this scenario on critical material resource use

Concerns about potential bottlenecks in procuring materials critical to the transition are regularly raised.

To assess this risk, the critical raw material[2] requirements of the Road to Net Zero transition scenario were assessed and compared with the available reserves and resources[3] (reserves are economically viable deposits with current technologies, while resources encompass all known deposits, whether economically extractable or not). This showed that the transition scenario is associated with significant tensions over four products (nickel, lithium, copper and cobalt), despite significant sufficiency measures aimed at reducing such resource use. **Further research and policy proposals need to be considered beyond what is proposed in this report to soothe such tensions, with the ambition to achieve (and not just proclaim) global environmental justice.**

Detailed results are presented in Appendix A.2. A discussion of the geopolitical, environmental and social risks associated with mining is given in Appendix A.3.

Notes

1. European Environment Agency, 2023, 'Emissions data viewer'.

2. The definition of critical raw materials adopted here is that of the EU Raw Materials Information System (RMIS).

3. The estimates for reserves and resources are taken from the Energy Transitions Commission (ETC), 2023, Material and Resource Requirements for the Energy Transition.

Transport methodology

1 General considerations and sector specificities

Given that 95% of CO_2 emissions in the EU-27 Transport sector originate from road transport, encompassing a fleet of 325 million vehicles, of which 248 million are Passenger Cars responsible for 56% of sector emissions, our approach focuses on the following key points:

- Decrease the number of vehicles on the road by 2050 and reduce the distance travelled by these vehicles.

- Diminish the average size of vehicles to optimise material consumption in fleet renewal towards low-carbon technologies.

This can be achieved through modal shifts to non-polluting transportation modes (rail, bus, soft mobility) and by enhancing vehicle occupancy rates.

Furthermore, the unbridled growth in air traffic must be curtailed.Lastly, both air and maritime transportation must transition to the use of non-CO_2 emitting fuels.

To accomplish these objectives, we propose:

- Significant public investments in public transportation and soft mobility infrastructures. Fiscal measures are also imperative to bolster the economic competitiveness of trains compared to planes and trucks.

- A sustained policy of subsidies to expedite the conversion of road vehicle fleets.

- Implementation of taxes, particularly based on the weight of private vehicles.

- Increased public investments for the enforcement of to low-carbon fuels for air and maritime transport.

2 Reduce the number of road vehicles and convert them to low-carbon technologies

Methodology:

We define the global investment costs related to road vehicles as the sum of estimated new vehicle sales between 2023 and 2050 in each of the Business-as-usual and Transition scenarios. To achieve this, we establish a projection, per scenario, year, country, vehicle type (Passenger Cars, Light Commercial Vehicles, High Duty Vehicles, Buses and Coaches, Powered Two Wheelers), vehicle size (segments), and powertrain of:

- The number of new vehicles sold

- The average unit selling price of a new vehicle

We model annual vehicle quantities sold using a logistic function (S-curve) based on the methodology developed by the European Transport Research Review, with key parameters including:

- Initial conditions: 2022 sales volume (number of vehicles)
- Expected market dynamics over the 2023-2050 period:
    - % increase/decrease in sales volume over the period: we estimate this parameter based on assumptions made on the size and composition of vehicle fleets in 2050 (see main assumptions paragraph below).
    - Price parity date determining the inflection point of the S-curve in sales between ICE and low-carbon vehicles
    - End date for ICE vehicle sales
    - Sales growth/decline rate (slope of the S-curve)

The 2050 vehicle fleet (quantity/mix/average age of circulating vehicles) is calculated as the sum of vehicles introduced to the market between 2023 and 2050 that will still be in circulation at that date. A survival percentage until 2050 is associated with each year of introduction (close to zero for vehicles introduced in 2023 and close to 100% for those introduced in 2050), depending on vehicle types and market habits in the various countries under study (some of which are net exporters of used vehicles — i.e., they have a younger vehicle fleet — while others are net importers of used vehicles — i.e., they have an older vehicle fleet).

We estimate average sales prices by vehicle type, size and powertrain based on:

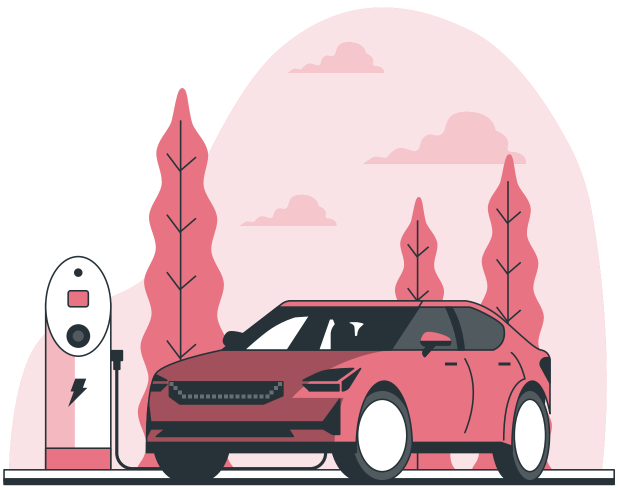
- Average price 2022 (in €)
- Price variation per year between 2023 and 2050 (in%): established in particular based on assumptions made on the evolution of battery prices

Assumptions:

The main assumptions used for the size and composition of 2050 stocks, 2023-2050 market dynamics as well as for price evolution are as follows:

Passenger cars and Light commercial vehicles (LCV):

- 2050 fleet size of Passenger cars is based on projected passenger transport demand (passenger.km) and owned vehicle per capita. Regarding the transition scenario we assume the following factors of fleet decrease:
    - Modal shift of total car transport (passenger.km): 15% to train, 15% to soft mobility, 5% to buses and coaches
    - Increase of average car occupancy rate by 20%



- 2050 fleet size of LCV is based on projected freight transport volume (ton.km)

- 2035 ICE (and hybrid) Ban is planned in both BAU and Transition scenario

- A slower decarbonization of the fleet in BAU than in transition: inflection point (which is the mid-transition point of the S-curve) in BAU 2030, in Transition 2027

- Maintaining an iso-segment sales mix (A to SUV D) in BAU vs. an evolution of the mix towards smaller segments in transition

- For a given segment, maintaining battery sizes in BAU (with increased autonomy due to increased battery performance), vs. a reduction in battery size in transition (with maintaining autonomy)

Heavy Duty Vehicles (HDV):

- 2050 fleet size of HDV is based on projected freight transport volume (ton.km). Regarding the transition scenario we assume a 25% modal shift of total truck freight to the rail freight

- Based on BCG study we assume a target sales mix of 81% BEV et 19% H2 on all countries on both BAU and transition scenarios

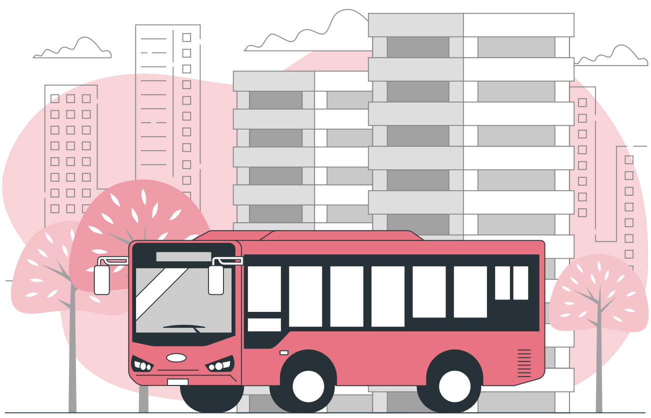
- In BAU scenarios we assume a TCO (Total Cost Ownership) parity between electric and ICE vehicles in 2030 (average of TNO & BCG scenarios) → Electric vehicles uptake starts little before the parity date, the inflection point (which is the mid transition point of the S-curve) occurs in 2033 , and the end of ICE sales is around 2047

- In transition scenarios we assume an ICE BAN effect in 2037 (no ICE vehicles sold any longer): the Inflection Point (which is the mid-transition point of the S-curve) occurs in 2028

Buses & coaches:

- As for HDV, we assume in BAU scenarios a TCO (Total Cost Ownership) parity between electric and ICE vehicles in 2030 → Electric vehicles uptake starts little before the parity date, the Inflection Point (which is the mid transition point of the S curve) occurs in 2033, and the end of ICE sales is around 2047.

- In transition scenarios we assume an ICE BAN effect (I.e. no ICE vehicles sold any longer) for buses in 2027 and 2035 for coaches: the Inflection Point (which is the mid transition point of the S curve) occurs in 2028.



Powered two wheelers:

- Moped: stock increase for transition in 2050 similar to BaU 2050

- Motorcycle: stock increase transition in 2050 around +20% compared to 2022, except for Spain +40% and Poland +60% as for those 2 countries the trend analysis of the last 10 years indicates strong growth dynamics of the park

Public policies for fleet reduction and low-carbon conversion

Measure: Strengthen public subsidy to help individuals & companies to acquire electrical & H2 passenger cars, powered two-wheelers & privately owned LCVs.

- The general formula in BaU & Transition used to compute the level of public support is as follows:

Price differentials (after malus/acquisition tax) in € per vehicle between electrical & conventional PC/LCV/PTW **×** *% coverage by public authorities* **×** *number of PC/LCV/PTW subsidised* **=** *public investment for the considered scenario*

- Assuming current conditions, these programs are anticipated to phase out upon achieving price parity

- Hybrid cars have been excluded from the public support given their ambiguous impact in terms of CO_2 emission and given that most public subsidy programs supporting hybrid cars (PC & LCV) have already been stopped in different European countries.

- LCV publicly owned fleet is excluded from this computation as owned 100 % by public sector

- The % of coverage of price differentials has been set at 80 % for transition scenario close to the % covered by the current program in France - arguably one of the most generous one in Europe and for BaU this was set based on the analysis of on-going existing programs in each respective country

Measure: Accelerate the decarbonisation of LCV Fleets owned by public administrations

- The LCV Fleets owned by public administrations comprises 10% to 25% of the overall LCV fleet, depending on countries.

- The general formula in BaU & Transition used to compute the level of public support is as follows:

Share LCV Fleets owned by public administrations (in %) **×** *Global CAPEX cost related to LCV* **=** *public investment for the considered scenario*

Measure: Strengthen public subsidy to help to acquire electrical & H2 HDV

- The general formula in BaU & Transition used to compute the level of public support is as follows:

Total Cost of Ownership (TCO) differentials in € per vehicle between electrical & conventional PC/LCV before ban or price parity **×** *% TCO coverage by public authorities* **×** *number of HDVs subsidised before economic ban* **=** *public investment for the considered scenario*

- In the transition & BaU scenario, it was assumed that public support in a form of subsidy by new HDV acquired (electrical and H2) would stop when sales of conventional HDVs are assumed to stop for economical reasons (~ economic ban) i.e. in 2037 in Transition and in 2047 in BaU.

- The TCO data for conventional & electrical/H2 HDV were built using the following methodology: A starting point of TCO differential in 2023 was based on the studies made by BCG for T&E according to which TCO are set currently at 1.6€/km for electrical HDV and 1.3€/km for conventional HDV. The average mileage of HDV per year was set at 120000 km according to data provided from TNO. This starting point was then assumed to evolve the same way as the price differentials between conv & electrical HDV

- For transition it was assumed 100% TCO differentials would be covered and for BaU this was set based on on-going existing programs in each respective country (on average 44% TCO differential coverage for elec HDV, with significant variation across countries spanning from 0 % in Poland to 119 % in Germany).

Measure: Strengthen public subsidy to help to acquire electrical & H2 bus & coaches (MHBC)

- The methodology was assuming most of this type of vehicle are related to public transportation and as a result a portion of CapEx linked to fleet renewal (be it conventional or low carbon) are covered in Transition & BaU. An additional layer was considered to capture a specific public support dedicated to low carbon MHBC.

- The general formula in BaU & Transition used to compute the level of public support is as follows:

Total CapEx until 2050 all MHBC included **×** *% covered by public authorities of all CapEx (to capture MHBC nature of being a public transportation) ~ direct support by default based on cost recovery by public funding disclosed when available for public transportation in each country* **+** *Total CapEx until 2050 related only to the acquisition of new low carbon MHBC* **×** *% coverage by public investment specifically focusing on low carbon MHBC ~ specific support coming on top of direct support by default mentioned above* **=** *public investment for the considered scenario*

- Cost recovery ratio in the formula above = the fraction of operating expenses (incl. depreciation of capex) which are not met by the fares paid by passengers nor by specific tax → by default the gap is covered by public funding.

- For transition the approach was to keep the level of direct support the same as for BaU and to increase the level of specific support to the best in class in BaU (i.e. Germany - 24 % capex coverage for this additional support).

Measure: Strengthen fiscal policies (penalty ('malus')/acquisition tax) to incentivise the switch from conventional PC to electrical PC/LCV.

- The idea is to strengthen either current tax only applicable to conventional PC (per CO_2 emission) or when non-existent to introduce it.

- BaU assumptions were derived from T&E report good tax guide (Sept 22) and with the exception of the Netherlands, which have already a very high malus/acquisition tax, for transition it was set in a way to have all countries closed to the average observed in BaU (1200€/PC on average - equivalent to an average tax of 9€/kg CO_2 emitted applied on an average CO_2 emission of 130 g/km per PC/LCV).

Measure: Strengthen fiscal policies (acquisition tax according to vehicle weight) to incentivise the purchase of lighter PC

- In order to foster the acquisition of lighter electrical PC/LCV and enable the state to find other tax revenues (as the malus/acquisition tax applicable to conventional cars will gradually decreased with the decrease of conventional fleet) a tax on the weight of PC applicable at acquisition was included in Transition scenario based on the assumptions given by Reseau action Climat (On average: 10€/kg in line with current parameters in France but lower threshold from which the tax applied - 1300 kg for conventional car & 1600 kg for Electrical/H2 cars). In most countries in BaU there is no weight tax.

Measure: Subsidy to cover scrap value of conventional PC LCV and HDV in 2050

- The remaining conventional PC & LCV fleet in 2050 is supposed to be moved out from the market through a compensation for their scrap value given by the state to the owner.

- On average assumed subsidy: 10 % car price (~ circa 2500€/conventional PC)

Electrical terminals:

- Our methodology is based on the 'European EV Charging Infrastructure Masterplan' from ACEA (March 2022). This research document presents a masterplan for electric vehicle (EV) charging infrastructure in the European Union by 2030.

- It outlines different ratios for charging points for passenger cars, commercial vehicles (trucks and buses) and light commercial vehicles. Those ratios vary according to location (across cities, homes, highways, ...) and charging technology (AC/DC). ACEA's proposal primarily focuses on widespread installation of cost-effective home charging stations.

Ratios (used for both BAU and Transition Scenario), by vehicle type and charging technology

Charger	PC	LCVs	Trucks & Buses
AC 4-22 kw	96,00%	42,70%	
DC 25 kw	1,31%	55,51%	
DC 50 - 150 kw	1,80%	0,59%	
DC 150 Kw			88,32%
DC 350 KW	0,47%	0,82%	9,58%
DC 500+ Kw	0,00%	0,38%	2,10%

H2 terminals:

- We used a ratio of 0,018 stations per vehicle from ACEA's study on truck hydrogen refuelling stations needed in Europe by 2025 and 2030.

CAPEX calculation - for both electrical and H2 terminals

- We applied the ratios above to determine the total number of installations required for each type of vehicle in both BAU and transition fleets outlined in our scenarios (see sub-levers on PCs, trucks, buses and LCVs).

- Subsequently, we applied the average prices outlined in the same report to compute the overall investment needed for both BAU and transition scenarios.

Public policies - for both electrical and H2 terminals

- Public subsidies for H2 & Electrical charging stations (CS) were considered. A difference in terms of level of public support was made between public & private charging stations.

- The capex coverage for public and private charging stations in the Business as Usual (BaU) scenario was calculated using disclosed support program data when available. On average, capex coverage stands at approximately 40%, though there is notable variation among countries. Sweden is a distinct outlier, with capex coverage ranging between 50% and 100%.

- Transition has been set at 50 % for all countries except for Sweden, which is already higher in BaU

3 Develop public transportation

3.1 Fully decarbonise the railway and increase railway traffic

Methodology:

- In order to achieve the ambitious modal shift objectives, we used high-performing countries as a reference.

- Switzerland and Austria are the rare countries that are doubly efficient in terms of modal share of travel (20% and 14% in 2019) and rail freight (34% and 31%). They are characterised by highly developed networks, a high level of investment spending, as well as high pricing of road infrastructure for road freight.

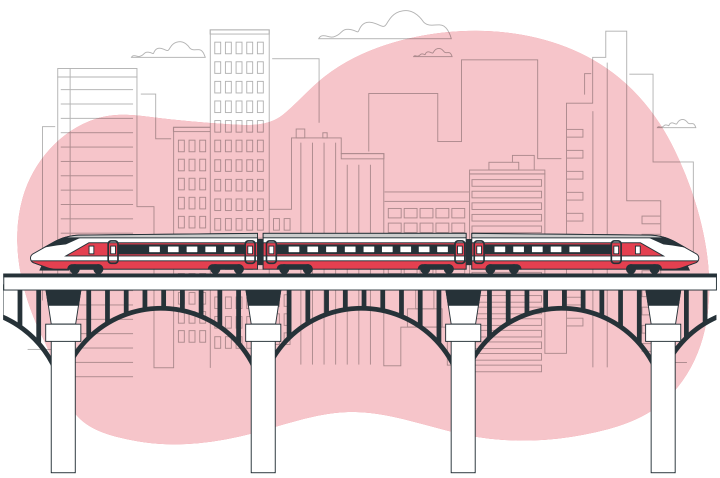
- For freight, Germany and Sweden also have high modal shares (19% and 30%) and the Baltic countries very high shares (42 to 70%). *If Switzerland is quite specific in terms of GDP level and Sweden in terms of density, Austria and Germany cover the diversity of demographic and geographical situations in the EU well.*

BaU investments:

- Gathering robust statistics on the ongoing investment expenditure on the network is challenging, several datasets highlighting important differences (IRG 2023, OCDE, Allianz).

- National documents had then been preferred to precise the BaU and build scenarios, when available and with sanity checks with the international datasets when possible. Finally the references retained to estimate the BaU investments are listed below:

  - France: ART 2023
  - Germany: IRG rail 2023 & DB, p. 262-263
  - Italy: MIT, p. 129-137
  - Spain: IRG rail 2023 & MITMA
  - Netherlands: OCDE & IRG rail 2023 & EIB
  - Poland: IRG rail 2023 & KPK
  - Sweden: IRG rail 2023, TEN-T projects & Allianz pro schiene 2023



Reference country for transition scenarios:

- Austria's very high performance in terms of rail is based on an already very developed network (620 km/M of inhabitants vs. 460 km/M of inhabitants on EU average) and massive investment expenditure (310 €/inhabitants including 43% for the current network excluding maintenance vs. +- 100 €/ inhabitants in UE), 80% supported by public funds (vs. +- 60% on EU average). Around half of the 1,7 Bn/year development investments concern several new tunnels (including the Brenner in common with Italy), but the country is also developing high-speed lines on less rugged terrain, the whole expected to add more than 400 km of by 2030 to further improve network capacity and speed.

- In addition, Germany is characterised by a very developed network in relation to its surface area (11 km/100 km²) and renewal/modernization investments greater than 200,000 €/km of line, but cannot serve reference for development investments, currently limited (less than 1 Bn/year IRG rail 2023 & DB).

- These investment levels are confirmed by detailed independent national scenarios (bottom-up type) or national strategies (e.g. DB 'strong rail'). For example, to increase by 50% the share of rail in France, the ART recommends a minimum of 5 billion/year (vs. 3) for Renew/Upgrade (i.e. 185,000 euros/km of line) and the addition of at least 3,000 to 4,000 km of new lines capacities (high speed, fine service and bypass of railway junctions) by 2040 according to the development scenario of the COI 2022 report (*i.e. a minimum of 8,000 km of new tracks to double the modal share, which would add 30% capacity to the French network*).

Transition investments:

- A single renewal/modernization investment of the current network of around 200,000 euros/ km of network, modulated according to the country's GDP, split equally between each year.

- A network development investment based on the current unit cost of the country and multiplied by the number of km necessary to achieve a network close to the references of Germany and/or Austria (620 km per M inhabitants or 11 km per 100km² - or between the two for ALL, NL and SWE having already exceeded one of the thresholds). However, most scenarios have been lowered to be more realistic, considering the already planned or studied projects of new lines. These new lines have been completed by extension projects (notably planned in Italy), which are less expensive and complex to develop though often crucial to making possible an increase in supply, notably in saturated areas.

- The whole being supported either by a minimum of 80% of public funds (including EU) as observed in Austria, or by the same percentage as in BaU if more than 80%.

Suggested Railway network

	Austria	Germany	France	Italy	Spain	NL	Poland	Sweden
M inhabitant	9	84	68	60	48	18	38	10
Superficie × 100km²	830	3600	5500	3000	5000	420	3200	5300
Current network (thousands of km)*	6	39	28	19	16	3	19	11
Network based on AUT-ALL (620/M - 11/100km²)		*46*	*42*	*33*	*29*	*7,5*	*28*	*(7-58)*
Suggested 2050 network	8	42	36	25	23	5	26	13
New lines		3	8	6	7	2	7	2
+Doubling of existing lines		4	4	6	5	2	3	1
Network to renovate (i.e., the current network)	6	39	28	19	16	3	19	11

Main sources: * IRG rail 2023 (Working document)

- The costs of new lines and of the lines' extensions have been estimated by looking at the current ongoing of forecasted infrastructure projects in each country. This research also confirmed the realism of the suggested 2050 network for each country.

CAPEX for new lines and for the lines' extension/doubling

	Germany	France	Italy	Spain	NL	Poland	Sweden
New lines (M€/km)	30	28	35	18	30	8	30
Lines' extension/doubling (M€/km)	15	18	12	8	20	4	13

Considering the Rolling stock, we introduce a single ratio between rolling stock investments and infrastructures investments based on an average of 3 ratios:

- 16/70: Europe, source CER
- 19/86: Germany, source IRJ
- 175/600: World, source: IEA (p. 116)

The percentage of public investments in the rolling stock are assumed to be equal to that of the public transport.

Moreover, as a compelling incentive for the transition, the French ART report emphasises that these investments, particularly in traffic management modernization, will slash operational costs by an impressive 38% by 2040.

4 Reduce air traffic and switch to Sustainable Aviation Fuels

For the strict needs of the study, we only need to tackle EU domestic emissions and thus target domestic and intra-EU flights. Nevertheless, decarbonising the rest of international aviation is definitely a concern, which is why we designed a model that can run with both assumptions: intra-EU flights and total EU flights. In the latter case, the model only considers extra-UE international flights departing from EU airports.

Basically, our model:

- Starts from current (traffic and) fossil kerosene consumption
- Projects it until 2050 based on business-as-usual traffic projections (basically a doubling by 2050)
- Assesses the potential of different aviation GHG emission reduction levers:
    - Technological, Infrastructure and Operations efficiency improvement (incremental aircraft innovation, airport efficiency, Air Traffic Management improvement, etc.)
    - Modal report to train
    - Biofuel / Bio-SAF (Sustainable Aviation Fuel) blending
- Computes the remaining jetfuel volume needed once these levers are applied
- Fills the gap with an adjustable mix between 2 remaining levers:
    - Sobriety
    - e-fuel / e-SAF production and blending
- Models the cost / amounts that could be collected through different fiscal measures as well as their potential impact on traffic (based on price-demand elasticity assumptions):
    - End of tax reduction on kerosene
    - End of TVA reduction on flight tickets
    - Rise of CO_2 price paid by companies

On top of this model output, the report proposes various regulatory measures to allow our various levers to be effective (see below).

Main assumptions used for each lever

Projection of business-as-usual traffic (in pkm) and fuel consumption (in Mt/yr): +2,3% CAGR corresponding to Waypoint 2050 medium scenario, leading to a raw doubling by 2050 (N.B: this is conservative, as Aviation emissions in Europe increased an average of 5% year-on-year between 2013 and 2019, according to the EU).

Technological improvement (incl. infrastructure and operations)

- T&E Roadmap to climate neutral aviation in Europe: -1,1%/yr potential (-26% by 2050)
- Waypoint 2050: -0,55%/yr including -0,45%/yr in tech efficiency and -0,1% (mid-improvement hypothesis) in infra & ops (-(13+3) = -16% cumulated 2023-2050)
- We consider an average of both hypothesis = -0,827%/yr = -20% by 2050

Modal shift to train

- Day train technical potential :
    - 'T&E - Maximizing air to rail journeys' high hypothesis = 'best practice scenario' = -7,4 $MtCO_2$ = 12% of current intra-EU aviation and 4% of all EU aviation. This switch potential is purely 'technical' (based on train speed and services improvement) and does not include the modal shift potential from changing price signals through application of a kerosene tax, for example.
    - Comparable to Institut Rousseau's in-house assessment leading to a 11% (intra)/4,5% (total) substitution potential
- Night train (for intra-UE travels > 1000km only): between 1,7% and 3% GHG gains achievable according to this Back-on-track study (2019 emissions) → we use 2% as a conservative measure.

Bio-SAF potential

- Our model rely almost exclusively on second generation biofuels
    - Hydrotreated vegetable oils (HVO) or Hydroprocessed Esters and Fatty Acids (HEFA) produced from oils and fats, typically Used Cooking Oils (UCO)
    - Bio-SAF from biomass gasification + Fischer-Tropsch
    - Part of the current G1 bioethanol production may be converted to jet fuel through the Alcohol to Jet (AtJ) process. So far the model considers that 10% of the G1 production is used for aviation. The G1 production starts from 19 Mt/yr (i.e. 190 TWh based on Eurobserv'ER's 17 Mtep in 2022) and goes down to 15 Mt/yr in 2050, according to CLEVER and taking into consideration that part of the current G1 production will be banned for insufficient GHG/Indirect Land Use Change (ILUC) performance.

- HEFA production: assessment of a 0,7 Mt/yr potential based on a UCO feedstock of 1,7 Mt/yr (Imperial College, 'Sustainable biomass availability in the EU to 2050', 2021) with 90% availability, a 90% volumic yield and a 50% SAF-selectivity for the HEFA process (French Technology Academy, 'La décarbonation du secteur aérien par la production de carburants durables', 2023).

- Bio-SAF production from gasification + Fischer-Tropsch: around 5 Mt/yr, which is equal to the volume of second generation biofuels considered by negaWatt in the CLEVER project 2023.

    - Wood available for bioenergy: between 72 Mt/yr in 2050 (expert-based + 10% compared of 2017-2021 average production of woodfuel from Eurostat) and 122 Mt/yr ('roundwood + primary residues' volumes from Imperial College's low availability scenario, to remain conservative).

    - 10% of biomass available for bioenergy to be directed to aviation needs (European Commission's hypothesis from ReFuelEU Directive impact study)

    - A 46% mass yield and 60% max SAF selectivity for the gasification + Fischer-Tropsch process (according to French Technology Academy).

e-SAF needs function of planned sobriety level

- The model allows to set a 'e-SAF VS sobriety' ratio, to fill the kerosene consumption gap left after having applied the first set of decarbonization levers (technological improvement, modal report and bio-SAF incorporation). Depending on this ratio, it:

- Determines the volume of e-SAF needed and compares it to the volume of synthetic fuels already included in energy scenarios used by the energy production sector team (to avoid double counting); These energy scenarios don't provide specific % of the alternative fuels volumes that are to be used by the aviation sector. We thus estimate this aviation share based on processes selectivity to SAF.

- Assesses total and additional (compared to energy scenarios) renewable production capacity needed in GWe by 2050 (based on TYNDP 2022 Distributed Energy future energy mix used, among others, in the energy production section of the report)

- Computes e-SAF production CAPEX needed by 2050, including the whole production chain (i.e. electrolysers and renewable power capacity, .

Fiscal and regulatory measures

- To ensure modal report:

    - We propose and assess 3 fiscal measures to make train more competitive compared to planes, based on T&E Tax gap report 2023:

        - Airlines currently pay zero tax or duty on their fuel in the EU, unlike other forms of transport → end of tax exemptions and application of a 0,38 €/L tax on fossil kerosene

        - Plane tickets are currently exempt from VAT in some countries (current average of 1,1%) → VAT back to 20% for all EU

- Rise in CO_2 price paid by airline companies, from 45 €/tCO_2 to 85 €/tCO_2

  - We propose a progressive flight ban for all trips having a train alternative inferior to 4h30, as proposed by the French Citizens' Convention for the Climate

- To allow some part of sobriety (by reducing business-as-usual quick traffic growth): we propose a ban on all airport extensions and on the construction of any new airport in the EU.

- To allow SAF incorporation :

  - Definition of regulatory SAF blending mandates (based on fit-for-55 mandates but upscaled to reach 100% by 2050 instead of 70%)

  - Fiscal measures to penalise (stop incentivising) fossil kerosene (cf. above)

  - Redistribution of part of the fiscal income to incentivize SAF production sector

5 Transition to zero carbon navigation

In this study, we focus on registered boat fleets within the countries under consideration. We categorise them into three types: merchant, fishing, and pleasure fleets.

Fluvial infrastructure is not addressed here due to the limited number of potential projects, with only a few listed in the RTE-T, notably the Seine-Nord and northwest Italy initiatives.

Current fleet and scenarios:

- Current fleet size by country:

  - Merchant fleet: UNCTAD (Merchant fleet by flag of registration)

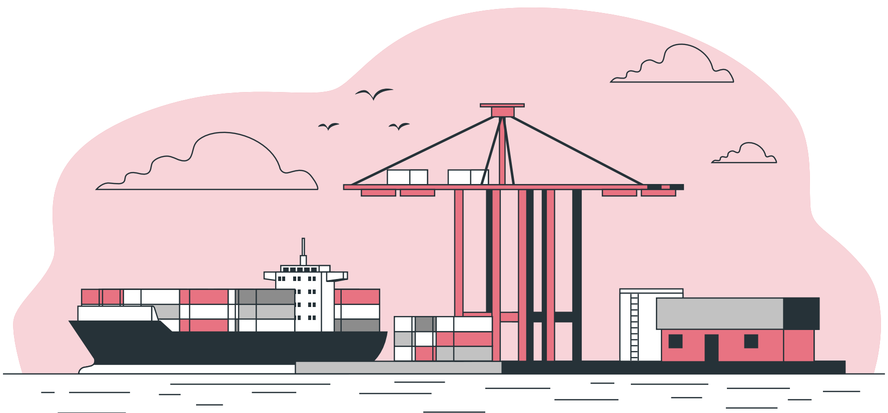
  - Fishing fleet: European Commission, Fleet capacity reports 2022

  - Pleasure fleet: gathering statistics on those fleets is challenging. We used a mix of government and article - based sources.

- The model assumes a 0% variation from 2023 to 2050, both for BaU and transition scenarios.

Technology mix by 2050:

- Merchant fleet: from DNV's study on Maritime Forecast, we selected the scenarios 17, 18 and 19, which are the one that rely the most on e-ammoniac, like it is recommended in other reports like BCG's or T&E's



- Fishing fleet: we decided to align the technology mix to the one of the merchant fleet, as 'Fishing will not determine fuel infrastructure development. It will follow in the footsteps of the larger marine players.' (according to the United Nations Conference On Trade And Development)

- Pleasure fleet: 100% electric

CAPEX:

- Merchant fleet: we derived the global accumulated investment required for port infrastructure and retrofitting boats to cleaner energies from DNV's Maritime Forecast study. Utilising UNCTAD data, we estimated each country's fleet share relative to the global fleet and calculated the corresponding investment requirements. Our focus is solely on investment needs, working exclusively with overcost considerations.

- Fishing fleet: we used the same average retrofit cost as for the merchant fleet.

- Pleasure fleet: to calculate the retrofit cost of switching to electrical motorisation, we used motor and battery prices directly from online retailers

Public measure equivalent to a conversion subsidy is considered for transition scenario only, as we did not find any measure of such kind as of today to help us define a BaU scenario.

- Share of fleets covered by the subsidy:

    - commercial & fishing fleets: 100%. This percentage is arbitrary and contingent on the government's willingness to support businesses, specifically targeting fleets of SMEs or companies meeting specified criteria.

    - pleasure boats: 0% as we do not consider that this should be tackled by the private sector

- For merchant & fishing fleets, we set the % price differential covered by public investment at 50%, inspired by:

    - DNV Decarbonization of Icelandic Maritime Sector, with Iceland full decarbonisation scenario that pushes for 50% of subsidies

    - Financing levels for European refuelling facilities, as indicated in International Transport Forum study on Maritime Subsidies, currently reaching up to 60%.

6 Develop soft mobility and encourage modal shift

Physical quantities

- Bike lanes
    - Transition:
        - France, Spain, Poland, Italy in 2030: goal = 2 ml/hab of bike lanes and green paths: ADEME study (scenario 3) + geovelo database
        - Germany 2030: goal = km of bike lanes and green paths x1.3 compared to 2019: ADEME study (scenario 2) = german scenario → it then needs to transition from scenario 2 to scenario 3.
        - France, Spain, Poland, Italy, Germany in 2050: goal = 4.6 ml/hab of bike lanes and green paths: based on Danemark: geovelo database
        - Netherlands and Sweden= BAU until 2050: their construction rate is already sufficient: ADEME study (scenario 3 = Dutsch scenario) + geovelo database
    - BaU: Every country continues to build bike lanes and green paths at the historical rhythm until reaching the Transition goal according to geovelo database.
- Bike:
    - Transition: goal = 1.1 bike/hab in 2030 and then approximately constant until 2050 ADEME study (scenario 3) (we consider commercial bikes like cargo bikes). The percentage of EV bikes evolves at its historical trend until reaching 70%. Source historical trend: Statista Bicycle market
    - BaU: Statista Bicycle market until 2028 and then we consider the sales/inhabitant constant until 2050.
- Parking stations: Increase of bike parking correlated to the increase of the bike fleet.

CAPEX calculation

- Infrastructure:
    - Price: €350 000 euros per kilometre for France, according to an ADEME study. The price is then modulated according to the countrys' GDP.
- Bike:
    - Timespan: 7 years in BaU and 8 years for Transition (notably because 70% of the fleet is electric) according to an ADEME study.

- Price: The price is a function of the number of bike/inhabitant, which enables one to consider the penetration of cargo bikes (ADEME study): ~700 euros for a mechanical bike and ~2400 euros for an E-bike (again the price considers cargo bikes as well).

- Parking station for bikes:

  - The number of new parking stations is a cross multiplication between the increased number of bikes and the investments in parking for bikes in France: source: ADEME study → ~530 euros/increase of one unit of the total bike fleet.

Public measures:

- Infrastructures: 100% Public

- Parking for bikes: based on ADEME study, 30% is public in France. Because of the lack of European data on this matter, we consider the same value for every country.

- Bike:

  - BaU:

    - National programs: ECF, 0 for every country except France and Italy

    - France: National Bicycle plan plans (2023-2027): 500 million euros → ~40 euros/new bike until 2030

    - Italy: PNRR (2022-2026): 120 million euros → ~14 euros/new bike until 2030

  - Transition:

    - 0 for Sweden, Germany and Netherland: penetration of bike is already high

    - For the others: we took the best in class in BAU (40 euros/new bike for France), and we multiplied it by the increasing rate of the bike fleet between now and 2030 (for instance: we double the bike fleet between 2022 and 2030 in Poland → subsidy = 40 × 2 = 80 euros/new bikes)

Industry methodology

1 General considerations and sector specificities

The industry sector gathers a large number of sub-sectors, from heavy to light industry, cement to cloth production. An exhaustive bottom-up assessment of decarbonisation investment needs for this wide diversity of sub-sectors was beyond the capacity of the Institut Rousseau and its partners. We therefore focused on assessing decarbonisation investments needs for the nine most energy-intensive industrial sub-sectors: steel and aluminium (metallurgy), cement and glass (construction materials), olefins & aromatics, ammonia and chlorine (chemistry), sugar (food processing), paper-cardboard production. We also assessed investment needed to decarbonise methanol production in Germany, representing the bulk of European production. In the seven countries of focus of this study, these sectors represented close to 60% of industrial emissions in aggregate.

2 Sufficiency

- GHG emissions reductions achievable through sufficiency have been estimated using the CLEVER scenario, which projects production levels until 2050, for steel, cement, olefins & aromatics, and glass production.

- Ammonia's production has been anticipated to halve until 2050 thanks to a complete phasing out of nitrogen fertilisers.

- We estimated that aluminium production in all countries considered would increase in line with what has been scenarised by negaWatt in the negaMat scenario for France (to which we added a 20% increase due to diverging hypotheses on aluminium requirements in 2050).

- We estimated conservatively that chlorine, sugar and paper/cardboard production would be the same in 2050 than today.

3 Other levers

Specific levers applied to decarbonise each sector and the GHG emissions associated have been identified relying on scientific and grey documentation. Notably, we made use of the *Plans de Transitions Sectoriels of ADEME* (the French ecological transition agency), scenarios and analyses from national and European professional associations (such as Federbeton or the Confederation of European Papers Industrie, assessments by Material Economics, DECHEMA, etc.).

Investment requirements have been estimated via two methods. Most of the time, we multiplied the unit investment cost of a technology by the production capacity to which it should

be applied. In some cases, such as for the paper/cardboard production sector and to estimate the investments needed for several national cement industries, we used overall investment figures already provided by professional associations (which we usually reprocessed to adapt to our production scenario).

4 BaU investments

BAU investments have been estimated via first estimating public BAU investments, and adding to them the private investments they are meant to unleash. For this, we assessed public policy programmes, identified all public investment programmes in industrial decarbonisation and their associated amounts. Most programmes propose to subsidise private investments, and their documentation usually provides the share of the overall investment which the programme proposes to cover with a subsidy. This enabled us to derive from public investments the private investments which they will unleash. For carbon contracts for difference (CCfD) programmes implemented in Germany and the Netherlands, we estimated the share of the subsidised amounts which are likely to go to investments VS opex spending. To do so, we used estimates by Material Economics of the share of capex and opex in total costs of various green technologies in sectors targeted by these programmes.

This methodology is conservative as it only takes into account investments which are public or which are tied to a public subsidy. It therefore leaves aside investments implemented without any public support. Nonetheless, such investments are likely to be low, considering the lack of business case for many low-carbon industrial investments.

5 Extrapolation methodology

We estimated investments needed for the 40% of GHG emissions non-covered in the seven countries of focus by extrapolating the average investment needed per tonne of GHG emissions reduced and extrapolating it to the GHG emissions of non-covered sub-sectors.

Once required investments were estimated for the seven countries in scope, we estimated investments required for each of these sectors overall in the EU by extrapolating using the following formula for each sub-sector (and for all sub-sectors non covered which were aggregated in one fictitious sub-sector):

$$\text{Investment needed at EU level (€)} = \frac{\text{Investment needed in 7 countries covered (€)} \times \text{GHG emissions at EU level (MT)}}{\text{GHG emissions in 7 countries (MT)}}$$

Agriculture methodology

1 General considerations and sector specificities

- **A scenario going beyond GHG considerations**: in the agricultural domain, our proposals and scenarios aim to incorporate not only GHGs but various concerns such as biodiversity, water and food quality. We also face the challenge of integrating the entire energy system, impacting discussions on topics like biomethane.

- **Our approach is anchored in the** TYFA GES scenario **from IDDRI and AScA**.

- **Agriculture global investments are mostly approximated by public expenditures**: in most other sectors, we calculate public costs as a proportion of overall costs. But for certain agricultural levers, like the shift to agroecology, estimating private actor costs is challenging (here, due to the very heterogeneous nature of farms). In such cases, we approximate total costs with public costs, assuming that subsidies are appropriately sized to cover transition costs. Therefore, exceptionally for these action levers, total cost equals public cost.

- **EU and Member States public expenditures are approximated**: another unique aspect of agriculture is that a significant portion of aid comes through the EU level (Common Agriculture Policy). We equate CAP expenditures with national expenditures, assuming that each country theoretically contributes to the CAP at the level it receives (though not entirely accurate).

- **Interfaces with other sectors**:

    - Investment related to biogas production is included in the energy sector.

    - Investment related to farmers training is addressed in the cross-sector section.

2 Convert crop systems to agroecology

- The objective is, in line with recent INRAE/CNRS works, to gradually move towards 100% ambitious systems combining organic farming, diversification (of crops and livestock), and agro-ecological infrastructure.

- In the absence of other benchmarks, **we approximate the costs of transitioning all farms to agroecology by the amount of subsidies currently deployed for organic farming** (cumulative conversion and maintenance).

- **Baseline scenario (BaU): we rely on maintaining current subsidy levels (2023)** until 2050, as detailed in reports from IFOAM such as 'Evaluation of support for organic farming in draft CAP Strategic Plans (2023-2027)', 2022, and National CAP Strategic Plans via the EU Commission website.

- **Transition scenario: we align all countries with aid levels historically deployed by the 'best-in-class' countries and regions** in Europe, where organic farming has made significant progress. For arable crops, this is an average of the best regions in Italy, notably Tuscany, and for grasslands, it's Denmark.

3 Reduce herd size and adapt breeding practices

The qualitative description of the evolution of the livestock system aligns with the TYFA GES scenario recommendations, including reduced reliance on grains, extensive cattle farming, and waste management. In quantitative terms:

- Emission reductions follow the TYFA GES scenario, encompassing feed supplements.
- Livestock numbers:
  - In transition, the EU-scale livestock population evolves according to the TYFA GES scenario (+14% for cattle due to increased emphasis on cattle farming, -30% for sheep, -48% for pigs, -62% for poultry).
  - At the national level, the breakdown follows the current distribution of cattle among countries (source: Agridata 2019).

Intensive Meat Tax: implemented from 2024, this tax exclusively targets intensive meats to avoid hindering the challenging conversion of various livestock types to agroecology. The tax aims not to stigmatise current extensive farmers, often at the forefront of ecological transition and poorly compensated.

- **Share of meat production to be taxed**: starting from current 'extensive/intensive' ratios (i.e., extensive or agroecological vs. conventional intensive) of 10% for pork, 10% for chicken, and 20% for beef. A linear progression of this ratio is assumed to reach 100% extensive for all animals by 2050, with a 2040 milestone of 50% for pork and chicken and 60% for beef.
- **Tax Amount**: a gradual and linear increase from nearly zero in 2024 to the following by 2050: +4.5 €/kg for chicken, +4.7 €/kg for pork, +1.4 €/kg for beef. The 2050 amounts are based on the proposals of the True Animal Protein Price Coalition (TAPCC) but adjusted proportionally to the livestock changes projected by TYFA GES (in contrast to TAPCC, which primarily targets beef).
- **Tax Redistribution**: based on TAPCC's suggestions, we propose redistributing the tax amounts (approx. €700 billion by 2050) as follows:
  - 40% to farmers, either as support for conversion or compensation for herd size reductions.
  - 50% to consumers, in the form of checks or 'agro-ecological food' social protection, with the amount indexed to household income for universal access to quality food.
  - 10% for aid to developing countries (mitigation and adaptation). This redistribution aims to make agro-ecological products more accessible, promoting changes in production systems through demand, in addition to conversion and employment aid.

To prevent a rebound effect on imports of environmentally inferior meat, we also propose a border tax and/or safeguard clauses (going beyond GHG considerations).

Feed supplements:

- Feed supplement cost: €30/kg based on provider quotes; 0.37 kg/LU/year; €11/cow/year.
- Applied to 60% of the cattle population, based on TYFA's animal types and coverage rates.

4 Decarbonise the energy used in agriculture: tractor fleet and heated greenhouses

4.1 Tractors fleet

We specifically address tractors here, not the entire agricultural machinery. According to a 2022 report from the French General Council of Food, Agriculture, and Rural Areas (CAAER), this accounted for 53% of the energy consumption on farms in 2021.

Current fleet and transition:

- Gathering statistics on the current tractor fleet size by country is challenging, with Eurostat 2013 being the only available data.
- In the Business-as-Usual (BAU) scenario, no transition in the fleet number (currently 0%, with a few pilot projects and showcase models).
- Difficulty in projecting fleet evolution by 2050 due to limited historical information. By default, the model assumes a 0% variation from 2023 to 2050.

Renewal and technology mix by 2050:

- Regardless of the scenario, the average lifespan of a tractor being 27-28 years (CGAAER 2022), a complete fleet renewal is inevitable by 2050.
- In BaU, a predominant use of diesel is anticipated, with a slight potential for B100 biodiesel (currently 3% in Sweden, for instance). A 2050 mix of 80% diesel - 20% biodiesel is considered across all countries.
- In transition, a mix of B100 biodiesel (55%), bio-CNG (25%), and electricity (20%) is envisioned based on the CGAAER 2022 report and expert interviews.
- Hydrogen is deemed ineligible due to its complicated distribution logistics, safety issues in uncontrolled environments, higher losses due to the need for a cryogenic reservoir, and higher costs compared to other alternatives.

Unitary CAPEX and public measures:

- Current average conventional tractor cost: Thermal €150,000.
- Low-carbon alternatives average premium: +25%, based on a benchmark of first models such as New Holland's, with cost parity achieved by 2050.

Public measures equivalent to a conversion premium are considered for both BaU and transition scenarios, with public support covering the entire additional cost between conventional and low-carbon tractors. For instance, France public support already covers 30-40% of investment cost (i.e. more than the average extra-cost considered here).

4.2 Gas consumption for heated greenhouses

Greenhouses' boilers, currently primarily heated with fossil gas, can run on biomethane and require no extra investment for the switch to biomethane. Biomethane production investments are included in the energy sector.

Buildings methodology

1 General considerations and sector specificities

- **A scenario going beyond direct GHG emissions**: our scenario incorporates not only direct GHGs (13%) but also indirect GHGs (>36%) counted in Energy (power and heat for buildings) and Industry (construction). Beyond GHG, these investments will lower energy bills, improve adaptation to climate change, foster local employment growth, will have positive impacts on health residents and therefore health system, and limit the impacts on material extraction and biomass exploitation.

- **The central strategy revolves around robust support for the efficient renovation of the EU's energy-intensive building stock**, excluding recently or deeply renovated structures (as stated in most studied countries' Long Term Rénovation Strategies - LTRS).

- **Priority should be given to stock** (>130 kwh/m²/year in most cases) **built before recent thermal regulations** (varying greatly from country to country).

- **The proposed approach prioritises building insulation, as a reliance on decarbonising heating systems has significant drawbacks** (increase in peak of electricity and limited impact on energy consumption, material extraction and energy production importations).

- **This involves comprehensive energy works to ensure the insulation of building envelopes** (walls, roofs, floors, windows, and doors) and to upgrade heating and ventilation systems. These measures can surpass 'low consumption' standards and cut energy consumption by 40 to 80%[1].

- **The building stock up for renovation should also include vacant housing**, in order to limit new construction projects, while increasing the total supply of housing and curb land price hikes.

- **Interfaces with other sectors**:
    - Power and heat production (see 'Energy' section)
    - Construction (see 'Industry' section)
    - Biomass for energy (see 'Agriculture' and 'Carbon sinks' sections).

2 Efficient renovation of housing

- Renovation targets are generally close to each country's Long Term Renovation Strategy (LTRS) objectives (2 to 3% of the stock to be renovated annually).

- **These were adjusted to account for both future demolitions** (±2% of the stock between 2023 and 2050) **and already 'deeply renovated[2]'** housing stock (±0.2% per year, according to the EU comprehensive study or ±3% since 2010).

- Efficient renovation costs are based on average expenses for energy-related works to achieve low consumption standards in housing (**excluding non-energy works**, e.g. electrical repair)

- Reference costs are derived from extensive efficient renovation samples[3] or calculated from databases of average costs per work item[4], with Spain and Sweden estimates based on similar countries (Italy and Germany, respectively, considering recent inflation and VAT levels[5]).

- **These 2016-2018 costs were adjusted for sector inflation** until Q2 2022[6].

- *Energy renovation costs are categorised under the 'Energy' sector when heating network development is involved (cf. 'Energy production' section).*

- **BaU investments are estimated from the** Comprehensive study (notably pp.30-34, with 2014-2016 prices updated by inflation until 2022).

- To estimate all transition investments, **we added to** efficient renovation of the energy-intensive building stock, **the maintenance of BaU investments on the recent buildings** (e.g. heat and windows replacement every 20-25 year).

- On the other hand, public costs do not take into account the non-renovated stock overall because **'maintenance' energy work is not/no longer supported**.

- Public support represents 20% to 80% of capped costs, notably depending on owner income, with an average of 50%. The increased public support complements a mandatory reorientation of current subsidies, which primarily target inefficient 'heating replacement'.

3 Preferential-rate loans to cover the remaining costs

- We recommend to support the remaining costs borne by households through **subsidised loans, featuring a 2-point interest bonus on the nominal market rate** for a 20-year loan.

- The gain for lenders which is an extra public investment is the difference between the market loan annuity and the bonus loan annuity using the constant annuity formula.

- The total amount takes into account the 20 years maturity of such loans and 27 years production.

4 Technical support for individual housing renovation

- Some public subsidies must also be directed towards project management assistance, focusing on individual and semi-individual private dwellings.
- A proposed 100% subsidy, approximately €1500 per dwelling, addresses the pressing support requirements and current recourse limitations.
- Conversely, tertiary property owners and social landlords already have access to in-house experts or technical support. The unique needs of collective private housing can be seamlessly integrated into broader subsidies for efficient renovation.

5 Support for efficient renovations in the public tertiary sector

- We systematically searched the surface areas of 4 main categories (offices, education, health, commerce & hotels and restaurants) and took into account the variable perimeters of the national statistical systems on 'tertiary' vs. 'non-residential' surfaces (which can include artisanal and industrial buildings , even agricultural).
- The share of tertiary stock requiring efficient renovation varies from 60% in Germany to over 80% in Poland, due to differing energy consumption states.
- **Costs of efficient renovation per square metre also exclude 'non-energy' work** and are typically based on reference costs for schools and offices due to a lack of such references for shops and hospitals.
- Sources on tertiary buildings reference costs notably include LTRS, providing data for France (€320 to €400/m² for schools and offices), Italy (~ €400/m² for schools and offices), and Poland (around €150/m² excluding heating), also updated.
- BaU investments are also estimated from the 'UE comprehensive study of building renovation', in 2020 having in mind that these data seem less robust than for residential.
- **Public support of 100%** (public owners).
- **Public BaU include subsidies and tax expenditures, but not the amounts loaned** (particularly significant in Germany), regardless of the types of energy renovations supported (including aid for energy efficiency of new buildings).

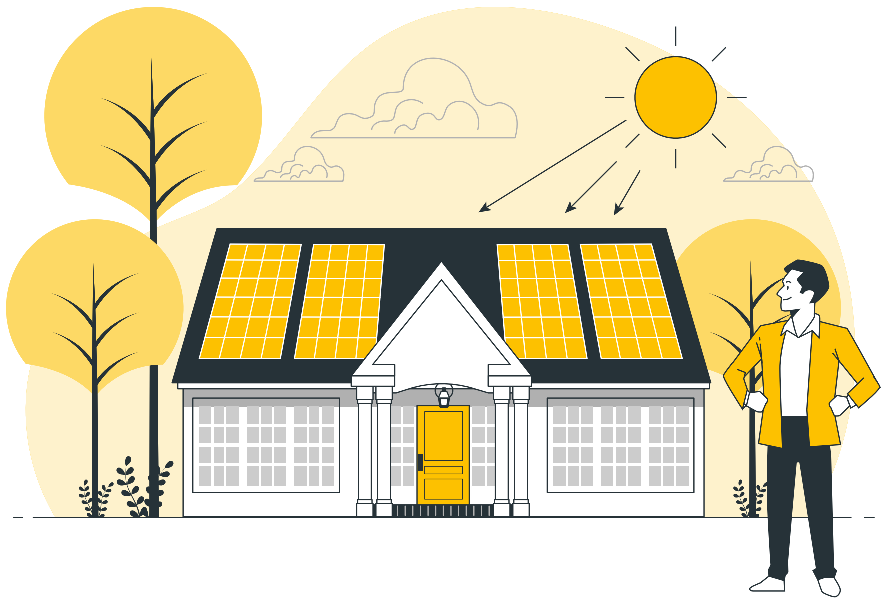
6 Support for efficient renovations in the private tertiary sector

- *See Public tertiary method above for surfaces area and reference costs.*

- The distinction between public and private areas is usually available for offices in the statistical data, but **for education and health we consider them to be public** even if +- 20% of these areas may be private in certain countries.

- **Public support of 20% to 50% for efficient renovations**, with an average of 30%.

- As the most robust BaU data don't differentiate public and private surface areas, we use proportional estimates for the current costs of these two sub-sectors.



Notes

1. 'Efficient' energy renovations are those making it possible to achieve low consumption standards (between 50 and 100 kwh/m²/year for heat, hot water and cooling, depending on climatic zones) and/or 'deep renovation' within the meaning of the EU comprehensive study of building renovation (energy gains of at least 50-60%) close to low consumption standards (e.g. with partial insulation of the street facade due to technical/urbanistic constraints involving high surface losses).

2. Deep renovation is defined by the UE comprehensive study as a renovation > 60% savings.

3. Ademe 'Perf In Mind', 2021 for France (+-520€/m² in houses and 300€/m² in collective housing) and Prognos 'Evaluation EBS WG im Förderzeitraum', 2018 for Germany (+-680€/m² in houses and 500€/m² in collective housing for EH 100). Note that the VAT on energy works is 5.5% in France compared to 20% in Germany.

4. See in particular LTRS Poland 2022 (+- 350€/m² for individual houses including heating and 200€/m² for collective housing excluding heating networks), LTRS Italy (+- 450€and 320€/m² in average zone E) and BPIE for the Netherlands (+- 600€and 450€/m² which corresponds to the price difference of -10% with Germany).

5. European Commission, 'VAT rates applied in the Member States of the European Union', 2021.

6. Maintenance-improvement inflation between 2018 and mid-2022 varied from 15% for Italy to almost 40% for Poland, to which we added the maintenance of BaU energy works on the non-efficiently renovated park (estimated thanks to the Comprehensive EU renovation study 2019, pp.30-34, updated prices 2022).

Energy production and infrastructure methodology

1 General considerations and sector specificities

- Given the energy system's intricate nature, particularly the electricity system, we **mainly draw on existing prospective studies** targeting carbon neutrality by 2050 from reputable organisations. Our focus was comparing and translating these studies into cost assessments:

    - On a **European scale**, nine scenarios: three EMBER's scenarios, two European Commission's scenarios, negaWatt CLEVER, CAN PAC, ENTSOS' TYNDP 2022 Global Ambitions (GA) and Distributed Energy (DE) scenarios.

    - On a national scale, existing carbon neutrality scenarios for 7 EU countries representing more than 80% of the EU's GDP: France, Germany, Italy, Netherland, Poland, Spain and Sweden. The national scenarios are a mix of national results given by some of the EU-scale scenarios (EMBER, TYNDP, nW, etc.) and local country-specific scenarios (RTE in France, DENA in Germany, etc.).

- Although we highlight the advantages of certain transition scenarios, we have chosen not to be prescriptive in favour of a specific scenario but to **estimate min/max/average costs of transition for the energy system**. There are several reasons for this:

    - The main goal of the study is to draw attention to the necessary investment amounts that are needed and not necessarily to focus attention on debates that are sometimes more political than technical-economic in nature (such as the question of the mix of nuclear vs. renewable energy production, which is very divisive in France).

    - Based on the scenarios studied, it appears that whatever the energy mix or the technological choices made, the amounts in terms of investment remain within a 10% variance overall (except for CAN PAC).

- An overall cross-reference is made to ensure that the **assumptions made in the energy sector are consistent with the other sectors** covered in the study.

- Transition **public costs were calculated as a proportion of overall costs**, by listing public policies for each decarbonization lever.

    - For the years 2019 to 2022, we aggregated public support for CAPEX from each policy across the seven countries, verifying the alignment with existing aggregated data.

    - Finally, we projected the historical percentage of public support by decarbonization lever and by country, accounting for changes in LCOE per technology. While not predicting support levels, this result aligns with evolving energy mixes, technological development, and historical support levels.

2 Decarbonise and adapt the power system

The following steps were taken to calculate the **investment** in low-carbon power generation capacity:

1. Identification of existing energy transition scenarios at EU level and by country, produced by recognised organisations.

2. Comparison of scenarios in terms of carbon neutrality, installed generation capacities, energy mix and imports, assumptions of demand, transition pace and technology, etc.

3. Development of a CAPEX calculation tool, based on a multiplication of the CAPEX cost per technology (€/MW) and the capacity per technology to add or renew (MW):

    - The assumed capacity to be installed (MW) are taken from the scenarios studied.

    - The unit CAPEX cost per technology (€/MW) is retrieved from diverse sources (TYNDP, EMBER). These costs evolve over the years, with a reduction assumed for most technologies.

    - Renewal costs are assessed based on:

        - Lifetime assumptions given by diverse sources (TYNDP, EMBER, RTE). They vary over years, with an increase for most technologies.

        - The amount of expiring capacities on a given year, which is calculated based on historical and scenarios data, and the lifetime of each technology assumed at the time of their installation.

4. Calculation of CAPEX at EU level and by country – projection of CAPEX for each neutrality scenario studied using the tool developed – and calculation of an average cost of transition, as the average of all scenarios that have been studied and costed, at the EU and country levels.

Investment in new **flexibility capacities**:

- The 'flexible' generation assets are included in the assessment of power generation capacities costs, and the 'flexible' cross sectoral assets (electrolyzers) are included in the assessment of gas production costs.

- Therefore, we focused here on Hydro Pumped Storage, Battery storage (stationary), and Demand Side Response. Costs associated with the flexibility provided by Electric Vehicles Batteries (Vehicle-to-Grid) is included in the assessment of the transition of the Transport sector. We assumed no CAPEX for Demand Side Response, which is considered a pure OPEX resource.

- The unit CAPEX cost per technology (€/MW) is an estimation based on various sources, including EMBER and RTE ('Futur Energétiques 2050').

- The costs of flexibility and storage resources were assessed as the cost of new assets plus the costs of renewal, based on unit costs.

- When no data was available in a scenario regarding future storage capacities (negaWatt, CAN PAC), an average was computed to adjust those scenarios based on the others.

Investment in **electricity networks**:

- As most scenarios do not include data on the transmission & distribution (T&D) networks until 2050, we developed our own estimates of the investments needed in the electricity networks - for each scenario - according to the following methodology:

    1. Investments in the transmission and distribution national networks:

        - From a pool of data from different European countries (European TSOs and DSOs), we estimated the investment needs as a function of:

            - The penetration of variable renewable resources (in %) in year n

            - The total electricity demand in year n

        - From each scenario's hypothesis on renewables penetration and electricity demand, we computed the network investment needs.

    2. Investments in interconnexions: the EMBER scenarios provide data on the development of interconnections' capacities (MW).

- Calculation of the electricity grid costs according to each transition scenario studied. It should be noted that this is a pure addition to the stated studies, which do not include national electricity networks in their perimeter (apart from exceptions, such as RTE in France).

Business-as-Usual (BaU) scenarios:

- We considered two BaU power scenarios:

    1. **TYNDP 'National Trends' Scenario**: TYNDP's estimate of the 'most likely' scenario, based on official climate and energy policies of EU member states and ongoing national initiatives. We extended the projection from 2040 to 2050 to cover this period.

    2. **Own-built 'Historical Trend' Scenario**: This involves a regression on historical data, projecting future values such as installed generation capacity and final consumption. Historical data on the installed capacities was retrieved from various sources (Eurostat, Entso-e's transparency platform, and IAEA for nuclear plants).

- The 'Historical Trend' scenario is a more conservative estimate, assuming a constant decarbonization pace. In contrast, the National Trends BaU already incorporates announced energy and climate policies.

- For cost assessment in transition scenarios, our CAPEX calculation tool, including power network costs, was applied to both BaU scenarios. The final BaU cost is derived as the average of the costs from the two scenarios.

Public share of investment needed for the transition of the power system:

- Choice of method: To achieve a level of detail by decarbonisation levers, we opted as a first step for a bottom-up approach. We identified the existing public policies on renewable energy in each of the Member States covered, and then translated them into annual budget envelopes added together. This total then constitutes a historical trend scenario (2019-2022) reflecting a level of public support per Member State for the transition of the power system.

- Sources used to carry out this assessment of existing public spending:

    1. Official National Documents: Utilising information from national ministries, financial statements of relevant agencies (e.g., GSE in Italy, CNMC in Spain, RVO in the Netherlands), and data from independent national energy regulatory authorities.

    2. Consultancy Reports: Referring to reports by reputable consultancies in the energy sector. When specific figures were elusive, estimates were derived from historical data related to the mechanisms, providing an average expenditure on these public policies.

- Quality check: We qualitatively evaluated the bottom-up approach using aggregated sources on renewable energy subsidies. To validate results, a top-down approach was employed, comparing our spending estimates with figures in Enerdata/Trinomics reports commissioned by the European Commission's DG ENER.

- Structural limits of this work:

    - The bottom-up approach was chosen for its alignment with our study's detailed requirements and data availability. The absence of consolidated national data for all covered expenditure categories may result in omissions. Our aim is the most accurate order of magnitude possible, acknowledging the impossibility of quantifying renewable energy subsidies to the nearest euro.

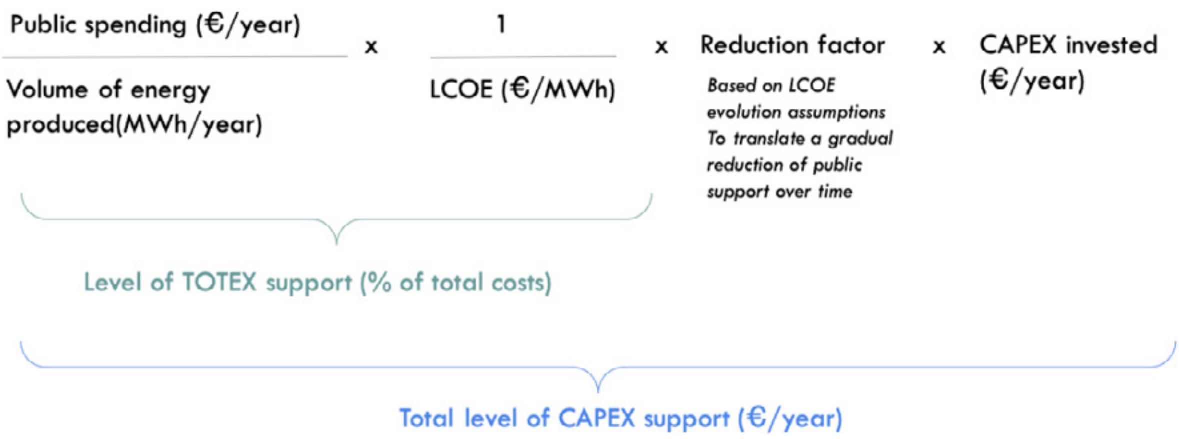
    - Certain Member States' lack of transparency in public spending management necessitated seeking information from independent institutions. Occasional difficulty arises in disaggregating data when a public policy funds multiple levers simultaneously, prompting exhaustive efforts to discern precise expenditure breakdowns.

- Projection of public spending:

    - To estimate public spendings in year zero (2023) for a given technology: the historical amount of annual public spending was divided by the related energy production (giving an amount of public support per MWh), and then by the technology's average national LCOE. This defines the public support in % of the technology's TOTEX. The share of public support for TOTEX (%) was then assumed equal to the public support for CAPEX.

    - To project this public support share over time, we assumed a reduction proportional to the technology and country specific LCOE.

- The LCOE for renewables was calculated based on ENTSO-E's TYNDP CAPEX, OPEX, lifetime, and national availability factors assumptions, with an actualisation factor of 7%.



3 Replace fossil gas with biogas and other 'green' gases

The following steps were taken to calculate the investment in **low-carbon gas generation capacities**:

1. Based on the **same existing energy transition scenarios as the ones used in the power section**, we made a comparison of scope and data available for gas production between the different available scenarios. The 4 vectors studied are **hydrogen, conventional methane, biomethane and synthetic methane**.

   - The scenarios considered did not all cover those four categories.

   - As an example, at the EU level: TYNDP and negaWatt provide an assessment of the evolution of both Methane and Hydrogen demand and supply, within important differences in the use of hydrogen and e-methane to generate electricity. EMBER focuses on the transition of the hybrid electricity-hydrogen system and provides results for hydrogen only. Future synthetic methane production was assessed only in TYNDP.

   - When no data was available in one scenario for one of those categories, the mean of the costs incurred in the other scenarios was assumed for comparability purposes

2. Development of the CAPEX calculation tool considering:

   - Unit cost retrieved from EMBER for electrolysis, ENGIE for biomethane, and ENEA/ATEE for synthetic methane.

   - Lifetime assumptions retrieved from various sources

   - Historical data on biomethane for the 'Historical Trend' scenario was retrieved from EurObserv'er

3. Calculation of CAPEX costs for the scenarios' gas generation capacities with our CAPEX calculation tool.

4. Cross-check of assumptions made in the considered external scenarios, and considering the sectoral demands of the RtoNZ general scenario, concerning:

    - Gas supply and demand

    - Biomass supply and demand (including agriculture, waste and carbon sinks biomass potential, to ensure that there is no overuse).

Investment in **gas networks**:

- None of the studied scenarios provided quantification of the evolution of gas networks, neither in capacity nor in costs, which is why **an in-house methodology was developed**. The associated costs are thus a pure addition to the initial scope of the selected scenarios.

- These costs can be divided in two categories:

    - Costs related to the **methane network** (which can include a portion of hydrogen).

    - Costs related to the development of a **pure hydrogen network**.

1. Calculation of the methane network costs:

    - At the EU level: while methane demand will inevitably be reduced to satisfy the decarbonization goals, the methane grid will have to adapt in order to integrate the new decentralised biomethane production assets. The different scenarios consider various levels of biomethane production, which could incur different costs. Plus, these costs will be strongly dependent on the size of the biomethane production assets (which can strongly vary depending on national policies), with smaller units leading to higher connection costs than larger units.

    - Due to the lack of detailed data, a strong assumption was made that the cost incurred will be approximately the same for all transition scenarios (cf. below).

    - For the BaU scenarios, a correction based on the lower methane demand reduction was implemented.

    - At the national scale (example of Spain): to assess the costs linked to the methane network, we developed a method based on:

        - The costs anticipated for the development of the French gas grid, based on the 2023 report from the French energy regulation agency (Commission de Régulation de l'Energie - Rapport 'Avenir des infrastructures gazières aux horizons 2030 et 2050, dans un contexte d'atteinte de la neutralité carbone')

        - The size (in km) of the Spanish national gas network

2. Calculation of the Hydrogen network costs, based on data from the Hydrogen Backbone scenario:

- at the EU level, directly assuming the costs assessed in the Hydrogen backbone scenario
- at the national level, the costs incurred were estimated based on the share of the national H2 demand over the total demand
- the demand assumed in the Hydrogen backbone scenario was found in the range of demands found in our scenarios

Business-as-Usual (BaU) scenarios:

- The estimation of additional investment needs requires a comparison between global investment needs and BaU scenarios. As for the electricity system, this analysis of the gas system relies on two BaU scenarios:
    - TYNDP 'National Trends' scenario: an estimation by TYNDP of the 'most likely' scenario, based on official climate and energy policies of EU member states and on ongoing national initiatives. We projected the National Trends scenario from 2040 to 2050, as this period was not covered.
    - An own-built 'Historical Trend' scenario: a regression we made on historical data used in a projection of the future (installed generation capacity, final consumption). The 'Historical Trend' scenario is a more conservative estimate of the future transition as it assumes that the pace of decarbonisation will remain the same, while the National Trends BaU already includes announced energy and climate policies.
- Calculation of the two BaU scenarios' cost with our CAPEX calculation tool, including the gas network costs associated.
- As per the transition scenarios, the final BaU cost is obtained as the average of the two BaU scenarios' costs.

Public share of investment for the transition of the gas system:

- Same methodology as 'decarbonize electricity system' (see section 6.2), with a different reduction factor of the public support share:
    - For biomethane, it is based on the evolution of the difference between a reference price (price of natural gas plus CO_2 allowances incurred, retrieved from ENTSOS' TYNDP) and the LCOG (trajectory retrieved based on ENEA, ENGIE, from 88€/TWh in 2022 to 66€/TWh in 2050).
    - For Hydrogen, it is based on the evolution of the difference between a reference price (2€/t) and the LCOH.

4 Move away from fossil oil and cease refining activities

Investment in **liquid fuels production capacities**:

- TYNDP scenarios incorporate e-fuels and biofuels production to meet incompressible liquid fuel demand, supplemented by imports of decarbonized liquid fuels. Other scenarios lacked data on liquids production and imports, prompting consideration of an average from TYNDP transition scenarios.

- The CAPEX for developing **domestic synthetic e-fuel capacities** was determined using the following methodology:

    - Only the **Fischer-Tropsch process** costs were considered, as hydrogen production costs are already included in the gas section.

    - Unit CAPEX costs for the Fischer-Tropsch process were extracted from 'E-Fuels: A Techno-Economic Assessment of European Domestic Production and Imports towards 2050' (Concawe, 2022).

    - Only the cost of new assets was factored, excluding renewals. The assumption is that assets will be predominantly constructed from 2030 onward, leading to minimal renewal by 2050.

- The CAPEX incurred by the development of domestic biofuel production capacities was assumed based on the following methodology

    - The biofuel production hypotheses was retrieved from Negawatt CLEVER

    - The unit costs of biofuel production units were calculated based on IEA Bioenergy (2022) 'Technical, Economic and Environmental (TEE) Assessment of Integrated Biorefineries'.

- **BaU scenarios**: The estimation of additional investment needs requires a comparison between global investment needs and 'Business-as-Usual' (BaU) scenarios. As for the other energy systems, this analysis of the gas system relies on two BaU scenarios: TYNDP 'National Trends' scenario, and an own-built 'Historical Trend' scenario.

    - The business as usual scenarios are assumed to have no e-fuel production, as e-fuel production data was not available for TYNDP National Trends, and the absence of production today leads to zero production in our scenario Historical Trends.

    - The business as usual scenarios are assumed to have zero additional biofuel production capacities built. This strong assumption was taken due to a lack of projection data.

- To calculate the **public share** of investment for the transition of liquid fuels production:

    - 50% of public support was assumed for e-fuels (downstream process).

    - 0% of public support was assumed for biofuels, as the technology is more mature (mandates should be enough), and relatively little public support for biofuel production capacities was found in the countries studied.

5 Decarbonise heat production for district heating and other residual emissions

- This decarbonisation lever is focused on district heating systems. It does not take into account public spendings on individual and building-scale heating. For example, subsidies for the purchase of individual heat pumps, biomass boilers, or budget envelopes that confuse renewable heating with energy efficiency (including insulation measures of all types) are taken into account by the "Buildings" sector of this study.

- The analysis of the decarbonisation of heat production is based on the negaWatt CLEVER scenario (only one to provide multi-country data on this topic). The transition of heat production relies on the evolution of the heating demand, new generation infrastructures, and specific changes to the heating networks.

- To calculate the investment needed in district heating networks, we relied on:

    - The evolution of the demand for district heating in the negaWatt scenario.

    - The evolution of the cost of the pipeline network, on the basis of the data from the EU-scale JRC report 'Long term projection of techno-economic performance of large-scale heating and cooling in the EU'.

    - Data on the French district heating system to establish an average ratio of distributed kWh per route metres of heating pipeline.

- Capacity factors and unit costs retrieved from various sources, including EU Reference Scenarios 2020 and Heat Roadmap Europe HRE4 hypothesis.

- With the absence of any available BaU scenario, and the relative current slow evolution of this sector, the costs of the BaU scenario was assumed zero.

- To calculate the public share of CAPEX for the transition of the heat production, the same methodology as for decarbonizing the electricity system has been used (see section 6.2).

6 Additional analysis: energy imports

The deployment of renewables may alleviate substantial OPEX associated with energy imports. The costs of imports of solids, liquids, and gaseous energy carriers are calculated only at the EU level based on:

- Scenarios which have sufficient data to calculate a balance per fuel: TYNDP (all energy carriers), EMBER (only Hydrogen), negaWatt (all energy carriers).

- The price of those imported energy carriers, retrieved from various sources: TYNDP (for Coal, Oil, Natural Gas, decarbonised H2, renewable H2, synthetic methane, and assuming the most conservative price), CONCAWE (for decarbonized liquids).

The difference in import dependence of the scenarios studied is quite heterogeneous:

- As an example, TYNDP relies on significant imports of fossil, and later decarbonised, energy carriers, in particular in its Global Ambition Scenario. Newagatt assumes no significant import of decarbonised energy carriers. EMBER scenarios look only at hydrogen electrolysis, which domestic production is assumed to fulfil entirely the EU demand.

- To fit with the available data, we compute an average of the total OPEX costs on imports for each category of energy carrier (Coal, Oil, Natural Gas, Hydrogen, Synthetic Methane, Biofuels, E-fuels) of both the transition and BaU scenarios.

- We then compare these averages between transition and business as usual scenarios. This provides an order of magnitude of the OPEX import savings of the transition.

Waste management methodology

1 General considerations and sector specificities

Three emission reduction levers have been considered in this report: 1/ the separate collection and recovery of bio-waste (e.g. food waste and garden waste); 2/ the reduction of incinerated plastics, whether with or without energy recovery; 3/ the recovery of biogas produced by methanization in wastewater treatment plants and the decarbonization of the energy consumed in these same plants.

The emission reduction potential associated with the levers dedicated to wastewater and plastic waste leverages the work carried out by V. Parravicini (and H. Nielsen; D. Thornberg; A. Pistocchi) for wastewater and by SystemIQ ("Reshaping Plastics", 2022) for plastics. The emission reduction potential of biowaste has been calculated directly in this report.

Regarding European wastewater treatment plants, it should be noted that there is little data available on precise operating procedures at plant-level (e.g. whether or not they include a methanizer; details of the treatment processes used; etc.). As a result, there are few decarbonization scenarios at European level that take into account all the decarbonization levers that could be leveraged in this sector, despite the fact that there are reportedly plentiful (e.g. A/B processes; deammonification; etc.). This report is therefore based on the latest, most advanced scenarios for European wastewater treatment plants, but does not quantify all the levers that could be activated by the sector in an exhaustive approach.

2 Recovery of municipal biowaste

2.1 Investments

Investments for the biowaste have been thought as the factorization of:

- Volume of biowaste not collected separately, calculated as the multiplication of the 2050 EU population by the difference between the maximum capturable quantity of biowaste per individual and the quantity of biowaste currently captured separately (Zero Waste Europe).

- The split between recovery by anaerobic digestion or industrial composting, calculated as the continuation of the current split in European biowaste treatment capacity (EEA) between composting and anaerobic digestion.

- The investment required for anaerobic digestion and industrial composting, based on various sources (e.g. GRDF; ADEME; Actu Environnement; Expert calls) and taking into account multiple recovery steps: collection; massification; hygienization (when necessary); composting or anaerobic digestion.

Investments per country are proportional to the volume of biowaste not yet collected separately in each country.

2.2 BaU

The BaU share of investments equals to the ratio between:

- The growth rate of biowaste volumes collected separately over recent years
- The growth rate of biowaste volumes collected separately required to separately collect the entire maximum collectable volume of EU biowaste, over the 2023-2050 period

2.3 Emissions

Reduced emissions correspond to all landfill-related emissions, minus the increase in emissions related to composting and methanization, as newly separately collected biowaste is channelled towards these valorization pathways (factoring in the additional volume of bio-waste collected separately and the emission factors for industrial composting and methanization).

3 Reduce emissions induced by plastics incineration

2.1 Investments

Levers mobilised to reduce incinerated plastics are the reduction of plastic consumed, the substitution of certain plastics by other materials, and plastic waste recycling (e.g. mechanical and chemical recycling). Investments required for all these levers leverage the ‘Circularity Scenario’ of SystemIQ's ‘ReShaping Plastics’ study (2022), from which all costs associated with upstream decarbonization levers (calculated and included in the industry section of this study) have been subtracted. Investments are then allocated to countries according to these countries’ share of WtE emissions in Europe.

It should be noted that investments dedicated to plastics incineration reduction are calculated in the waste section but included in the industry section of this study as these levers also impact industry emissions.

2.2 BaU

All the investment costs have been by design calculated as additional costs compared to a business as usual scenario.

2.3 Emissions

The emissions base impacted by these levers corresponds to emissions generated by waste incineration, whether carried out with or without energy recovery (EEA). The share of emissions reduced is considered proportional to the share of plastic waste diverted from incineration (-86%, SystemIQ). This is made possible by the fact that virtually all fossil waste entering incinerators today is plastic (ADEME).

4 Develop WWTP sludge methanisation

2.1 Investments

Levers quantified in this section are the injection of biomethane produced by wastewater treatment plants into the gas network as well as the decarbonization of the energy consumed by the plants. Investments required to decarbonize the energy consumed are taken into account in the energy section of this report. The investments detailed here take into account both municipal and industrial wastewaters:

- Municipal wastewater: Investments equal the factorization of the total treatment capacity (in population equivalent) of plants with a unit capacity greater than 30k PE (Population Equivalent), by the proportion of wastewater treatment plants that do not currently upgrade their gas production in the gas network and by the average investment cost per PE (ADEME).

- Industrial wastewater: Investments correspond to the volume of industrial wastewater generated annually in Europe, multiplied by the share of direct releases (e.g. releases that are handled directly by industrial players and are not channelled towards public wastewater treatment plants) and the investment ratio required per m3 of treated wastewater, as calculated for municipal wastewater.

2.2 BaU

BaU equals the ratio between:

- The growth rate of the share of biomethane injected into the grid between 2018 and 2021.

- The growth rate of the share of biomethane injected into the network required to reach 100% of the biomethane produced injected into the network, over the 2023-2050 period

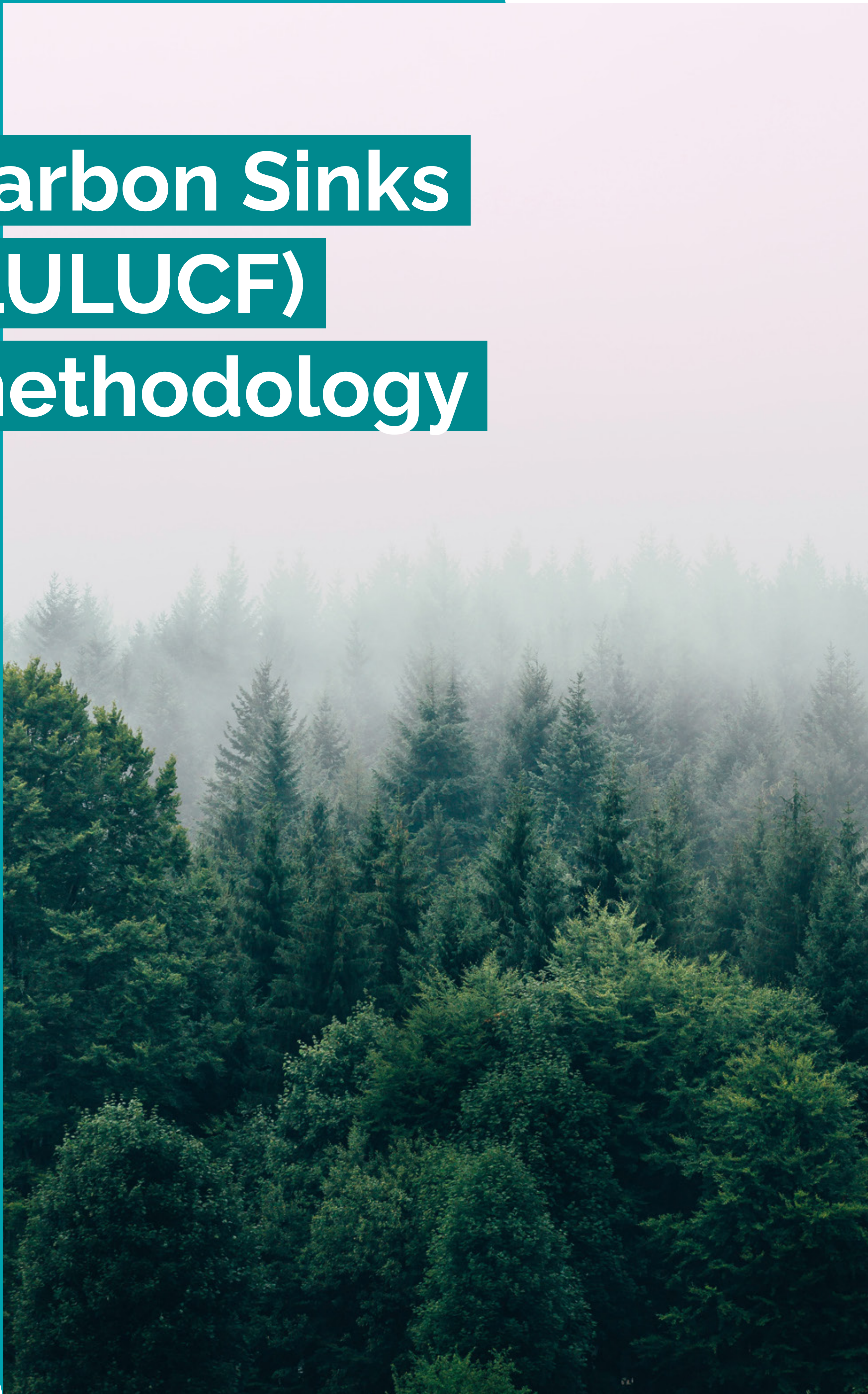
2.3 Emissions

Emissions to be reduced correspond to EEA data, while the potential for reducing emissions by injecting biomethane into the grid and decarbonizing the energy consumed by the stations (-47%) leverages the work of V. Parravicini, H. Nielsen, D. Thornberg, A. Pistocchi.

5 Extrapolation

The extrapolation is based on the ratio between the sum of GHG emissions generated by the waste sector in the 7 countries explored in this study, and the total GHG emissions linked to waste management at European level.

Carbon Sinks (LULUCF) methodology



1 General considerations and sector specificities

- **LULUCF perimeter & negative emission role**
    - Nature based solutions storing carbon and concerned by other critical challenges related to strong sustainability (biodiversity, wildlife, climatic stakes, etc.)
- **Strong sustainability approach**
    - Strong sustainability asserts that there are critical natural resources and services that cannot be substituted by other forms of capital, emphasising the preservation of natural capital, such as biological diversity, as essential for human well-being. It prioritises ecological integrity over economic gains and aims to maintain economic, environmental, and social capital through the efficient use of resources
- **Quantifying CAPEX for LULUCF - revitalisation example:**
    - OPEX can represent significant costs but are excluded from the scope as the key goal is to assess government extra cost efforts.
    - Let's take the example of revitalisation - active regeneration is recommended for degraded ecosystems. The study focuses on establishment costs (tree planting and fencing) and does not include longer-term management expenses (OPEX).
- **BaU scenario investments**
    - Country level and aggregated data wasn't transparently available and couldn't be reliably tracked. BaU (public or private) investments are likely underestimated.
    - Total extra cost can therefore be considered largely conservative at country and aggregated level.
- **Interfaces with other sectors:**
    - **Agroecology** - CAPEX enabling grasslands to turn to net sinks are considered in the TYFA scenario integrated in the Agriculture sector
    - **Biomass and Energy** - the forest sink preservation logic is closely linked to energy policies. The biomass supply must indeed be accurately balanced to accommodate energy needs, wood substitution effect in the building sector, long-lasting wood products while conserving standing timber stocks.

Extrapolation method

Computed at the national scale for 7 countries (list), GHG emissions projections and costs quantification were extrapolated to the EU-27 scale.

- In the LULUCF sector, country 2050 **emissions projections** were all estimated using the same model since physical country-level input data is available at the EU level (emissions factor, forest area, etc.)
- Necessary **financial data** to quantify costs were however not always available. An Identical quantification model was applied when the input data was available. In other cases, a linear extrapolation based on existing public spending dispatch was adopted. A 79,37% factor was operated. This proxy originates from public spending on environmental protection by countries (i.e. Total of the 7 core countries divided by the total 27: Eurostat - Data Browser

Investment profile - 2030 Milestone

Due to the nature-based character of the transformative changes proposed, several investment efforts must be carried out as early as possible. Forest resilience must be a key focus to minimise emissions during the entire period before 2050 and enable the newly adapted forests to grow and evolve ahead of multiplying disruptions.

To ensure a timely and coherent implementation, we recommend prioritising investments in restoring degraded ecosystems, harvested wood products and wood industry, training forestry workers, tree nurseries, and wetland/peatland preservation. The remaining forestry management is allocated evenly, with half until 2030 and the second half distributed from 2030 to 2050.

2 Improve forest management

Rationale: generally, investments remain insufficient to ensure forest’s sustainable management. A balance between removals / wood export and carbon sink capacity is to be found. It requires high tree species diversity and trained forestry workers.

Core shift → implementing new forestry management practices:

- Forest management must focus on resilience
    - Local climate conditions should drive tree species selection processes (based on climate scenarios and modelling) to anticipate long term climate shift.
    - Tree harvesting practices must evolve. Selective logging methods will gradually replace the systematic monoculture clear-cut legacy. This will require a more granular access to parcels as well as dedicated machinery and reliable inflow of seedlings.
    - To successfully manage those forestry practices, more numerous and trained forestry workers are required. This will enable fostering resilience like fire avoidance management where success depends mostly on parcels management rather than material investments.
- Obviously the same model is not to be blindly applied everywhere. Trained experts ponder the best way to manage forest ecosystems (parcel-specific clearcut vs continuous cover, tree species selection, logging frequency, beyond-carbon matters management, etc.)

Mechanisms:

- Tree nurseries
    - Seeds and seedlings play a pivotal role in supplying the most ecosystem-relevant species while absorbing the increasing demand. They are sourced from public entities. A European fund will be created to finance private projects: capacity increase for existing tree nurseries and support in the creation of new companies. [100% Public subsidised]
    - National entity tree nurseries development will also be allocated an envelope. [100% Public subsidised]
- Forest management
    - A tax-credit mechanism will be introduced and made available to taxpayers for their forestry operations if they manage their forest using new sustainable practices (detailed above). [35% Public subsidised].
    - Existing forest workers will be trained / educated with new sustainable forestry practices [100% Public subsidised].
    - The public sector will finance forest access improvement as selective logging methods require more granular forest roads [100% Public subsidised].
    - Subsidies in order to foster selective logging and low weight machines up to 50% will be set up [35% Public subsidised].

Main assumptions:

- Emission forecast models were considered to best estimate negative emissions generation by 2050. In the context of various uncertainties (soil carbon capture potential, climate evolution, weather events impact, etc), high modelling complexity and low scientific maturity in forecasting forestland emissions, it was decided to rely on conservative emission factors. Additionally, resources were limited and the core goal of the study was to focus on costs rather than emissions forecast modelling.

- Final ‘emissions factor’ for **existing** forests (combines deciduous and coniferous as well as forest types + a ‘security coefficient of 0.75’ to account for uncertainties): between 2.3 (Poland) and 3.3 (Italy) tco2-e/ha/yr depending on countries.

- The workforce is increased in each country to reach a headcount of 5.85 workers per 1000 hectares: average of European countries with a temperate forest (biotope with the most workers per hectare in Europe).

- Road network to facilitate forest access is enhanced for most countries except Germany and Sweden.

    - More granular access is needed to adopt irregular logging practices. It is essential to bear in mind that this aims to decrease clear cut and not increase the removals.

    - The cost considered is 400€/ha.

- Mechanisation (light and agile machinery) is a key asset to facilitate productivity of forestry workers. A target of 174 machine/Mha (all machines type combined) has been set up.

3 Revitalise degraded ecosystems

Rationale: the main lever to ensure a reliable carbon sink capacity is **to protect our forest ecosystems**. As a first step, we recommend a significant effort in **revitalising today’s degraded ecosystems**. A robust basis of healthy forest is key for the other measures to be efficient as well. Revitalization approaches will differ based on ecosystems. First, it will follow the same rationale as forest management practices below. Second, it will consist of a mix of tree planting + fencing, natural regeneration and other techniques.

Mechanisms:

- Public authorities will managed forest revitalisation [100% Public subsidised]

- Financial rewards are to be set up to incentivise private owners to restore ecosystems. Private forest landowners already have significant mid- and long-term interests to invest in restoration given the financial shortfall of leaving a forestland unmanaged. Those degraded ecosystems are key and this is why we would recommend to slightly push the owners to invest. [35% Public subsidised]

Main assumptions:

- All defoliation stage 2-4 level parcels are considered as areas to be revitalised.

- Regeneration costs: 139 €/ha/yr which is the highest estimated cost in the case of plantation + fencing.

4 Support wood industry adaptation

Rationale: the main goal is **long term carbon capture in wood products**. Some avoided emissions by using wood for other uses are accounted for by the construction and energy sectors. Budget definition derives from country-specific financial contexts and past investments.

Mechanisms:

- Governments will subsidise a 50% budget increase for the downstream wood industry [100% Public subsidised].
  - Recent years have seen drastic increases in these budgets (20% to 70% YoY depending on countries). We estimate that an additional 50% increase is necessary for the industry to match the upcoming wood transformation demand. Investments will support qualitative capacity increase and wood lifespan enhancement techniques research.
- Preferential credits (reduced rate and government-secured) are also granted to sustainable wood transformation practices (CAPEX) targeting especially renewal and increase of machines fleet. [Final cost for the government is 10% recovery of defaults' total loans].

5 Increase forest area

Rationale: we would not recommend dramatically expanding the overall forest area. Given the highly degraded health level of EU forests and their low resilience to climate change, the core goal of this measures package is to ensure forest preparedness to the changing climate. A slight increase would however make sense to ensure the need for carbon storage and wood supply.

Mechanisms:

- Enhance existing forest management labels to subsidise forest area increase. Targeted area are previously forested area to avoid degradation of natural grasslands or wetlands. [100% Private investments].
- A compensation / balancing mechanism is implemented to force the private sector to finance forest area expansion when it artificializes land. Governments use the collected funds to expand protected areas (namely exposed wetlands, threatened biodiversity hotspots, etc.) [100% Private investments].
- No capital intensive measure is deemed necessary here to reach the recommended ~3% forested area increase. Regulating land use via fiscal measures is however recommended.

Main assumptions:

- Recommended forest area increase to target 3% at the EU scale.
- The Netherlands and Poland have an increased forestland area target of 10% from today. In both countries ambitious expansion plans are feasible and stand at advanced discussion stages.
- Emissions factors for **newly planted forests**: (combines deciduous and coniferous as well as forest types + a 'security coefficient' of 0.66): between 5.0 (Sweden) and 7.4 (Italy) tco2-eq/ha/yr depending on countries.
- Afforestation costs sums land acquisition cost and plantation cost (1700-2900€/ha).

6 Turn grasslands back to net sinks

- **Costs included in Agriculture section perimeter**.
- Rationale: grasslands are today a net emitter and should be turned back into a net absorber before 2050.
- The Agriculture group caters and details these topics (out of scope here):
    - The adopted scenario (TYFA-GHG from IDDRI) is based on the abandonment of synthetic pesticides and fertilisers, the redeployment of natural grasslands and the extension of agroecological infrastructures (hedges, trees, ponds, stony habitats).
    - It also envisages the widespread adoption of healthier diets, less rich in animal products and more fruit and vegetables. Despite a 35% drop in production compared to 2010 (in kcal), this scenario satisfies Europeans' food requirements while maintaining export capacity for cereals, dairy products and wine.
    - It enables a reduction in greenhouse gas emissions from the agricultural sector by 40% compared to 2010, a recovery in biodiversity and the conservation of natural resources (biological life of soils, water quality, complexification of trophic chains).
- No land usage conflicts are identified between the Carbon Sinks and Agriculture sector's strategies. (i.e. the slight expansion of forestland is compatible with agriculture and net zero artificialisation objectives plan.)

7 Plant hedgerows and field trees

Rationale: While they are not democratised as of today, agroecological infrastructures (hedgerows and trees in open fields) are simple to implement, have solid co-benefits and enable to sequester GHG (especially at the beginning of the implementation).

Mechanism: To finance interparcels agroecology infrastructure, the following development scheme is proposed:

- Public: the new Common Agricultural Policy would subsidise agri workers 50% of the total implementation cost (seedlings, machinery, workforce) on half of all projects (Public - EU). The OPEX related to the maintenance of the projects have been estimated but are not included since they are out of scope of the study.
- Private:
    - Agroforestry practices will generate high quality carbon credits that companies will acquire on the Voluntary Carbon Market. The private sector contributes to 30% of the total subsidy.
    - Agri workers will be charged for the remaining 20% (as an aggregated total for the EU) to establish agro forestry infrastructures.

Main assumptions

- Total afforestation costs:
    - hedgerows: 3500€/km.
    - trees in open field: 413€/ha (Source 1, Source 2).
- The baseline scenarii consider that no agro ecological infrastructures are in place as of today (except for France for which recent data were available) - This results in conservative total cost estimations.
- Estimated negative emissions generated:
    - per km of hedgerows: 4 tCO_2-eq/km/yr.
    - per ha of interparcel trees (70/ha): 3,12 tCO2-eq/ha/yr (ADEME 2050 report, p. 291 and p. 634).
- Infrastructure deployment coverage of total total cultivated area:
    - Hedgerows: 12%.
    - Interparcel trees: 7%.
    - An approximate total of 20% matches TYFA scenario as well as the land use distribution recommend by the corresponding ADEME 2050's scenarii.

8 Protect and Restore Wetlands and Peatlands

Rationale: wetlands and peatlands are critical to manage at EU scale as 50% of peatlands are considered degraded. These ecosystems can represent massive emitters if not preserved or managed adequately. It's paramount to protect such ecosystems to maximise avoided emissions.

8.1 Protect & sanctuarise peatlands in national parks

Mechanisms: acquire 10% of peatlands for strict protection thanks to the conversion of those areas into national parks, Natura 2000, etc. [100% public subsidised]

Main assumption:

- The current goal of the EU defined in the EU Biodiversity Strategy for 2030 is to protect 30% of EU land and sea by 2030 among which, ⅓ must be under strict protection. It is suggested an increase by 10% in absolute terms of this area for peatlands through the acquisition by each state of the corresponding peatlands area and the conversion of those areas into national parks or integral reserves.

- The costs considered here cover acquisition costs only (1 Ha of arable land totals 7 500€ on average in Europe)

8.2 Foster the development of wet agriculture projects

Mechanisms: subsidise all paludiculture projects [33% public subsidised].

Main assumption: about ⅓ of the investment required to start a typical paludiculture project is subsidised materialising as a 2 500€/Ha compensation.

8.3 Restore & preserve degraded peatlands

Mechanism: subsidise peatland restoration projects at a level of €400 per hectare. This represents about 33% of the restoration cost per Ha and reserving 10% of carbon credits to fund the project and incentivize direct stakeholders (land owners, local communities...) (if applicable) [33% public subsidised].

Main assumptions

- Due to the avoided emissions stakes of peatlands preservation and restoration/rewetting, the ambition is to restore 100% of degraded areas by 2050.
- Long Term Carbon Accumulation: 0.66 tCO_2-eq/Ha/yr
- Average emissions from peatlands degradation: 26 t CO_2-eq/Ha/yr
- Restoration cost: max 1 200€/Ha

8.4 Other measures (not budgeted / no CAPEX)

- Create a dedicated governmental body in charge of research, supervision of stakeholders, identifying ecosystems at risk, building a strategy and being accountable to deliver according to a plan, etc.
- Build a legal framework to ensure wetlands & peatlands protection.
- Fight against ecosystem's disturbance and threats: invasive species & pollution.

Main assumptions: No legal framework to ensure protection and restoration of these areas exist. Adopting a strong sustainability approach (biodiversity, water quality, flood and drought prevention...) is essential for these ecosystems to strive.

Cross-sector measures methodology

1 General considerations and sector specificities

The Cross-sector measures does not aim to directly calculate GHG gains, but to identify and quantify measures that will support all other sectors.

The majority of cross-sector measures concern the financing of R&D. Other measures are considered, but the lack of available data does not allow for quantification. They are therefore presented only qualitatively in the report (Green IT, strengthening of public servant staff).

2 Enhance Research & Development in transition solutions

- As the link between R&D expenditure and the improvement of knowledge and ecological solutions is difficult to quantify (globally and at the scale of a country), there is no completely objective 'research' transition scenario.
- However, R&D efforts in these areas should **at least respect the main commitments made by the EU**, including in particular:
    - The commitment to double public spending to support 'clean energy' research made as part of the innovation mission of the International Energy Agency (IEA), knowing that this spending stagnated between 2015 and 2019-2021 compared to GDP (see below);
    - The objective of EU Organic Action Plan to devote 30% of EU agricultural R&D funds to organic issues (*vs. less than 5% currently according to our interview with TP Organics*), in order to facilitate the achievement of the 25% organic objective (by 2030) and consistent with the excuse of "lack of alternatives" to agriculture intensive in fossil fertilisers and chemicals;
    - The more general objective of reaching 3% of GDP devoted to R&D against public and private R&D spending capping around 2.3% of GDP en 2021.
- In order to quantify the investments making it possible to achieve these objectives and compare them to current public spending, **two sets of sources have been used**:
    - The International Energy Agency (IEA) collects with a uniform method public R&D expenditure for 'energy technologies' which include all energies, energy efficiencies and R&D on electricity storage: These data are also disseminated by the OECD and do not include tax credits for private R&D (*not included because marginal except France and without precision on % dedicated to these topics*) as well as international funding (in particular Euratom and ITER programs for Nuclear - *added thanks to other direct sources*);

- Eurostat and the OECD collect data on public expenditure on agricultural R&D at EU level, without specifying the share devoted to agro-ecological systems and practices (*estimated between 1 to 2% by our interview with TP organic - IFOAM*).

- The objective of doubling R&D spending in 2015 and/or alignment with countries with the highest support for 'low-carbon' R&D both corresponds to around 0.08% of the GDP = 12 billion/year (in euros 2021) for State expenses + 4 billion/year for EU expenses.

- As 'energy' R&D spending has increased significantly in 2021 or 2022 due to recovery plans (particularly in France and Spain), a 2019-2021 average was used to estimate the BaU to limit the biases linked to multi-year commitments.

- For agriculture, Eurostat, Government support to agricultural research and development 2023 and Horizon Europe Program, 2023, "Agriculture, forestry and rural areas" have been used to estimate the BaU.

- Eurostat data has been corrected for France, whose national publication indicates €900 million extra per year. OECD/Eurostat and French ministry have been interviewed, they indicate slight differences in the scopes of these data but do not explain theses significant differences between these two data, c.f. French Minister for Research and Education.

- 1.5 billion/year are add to a largely reoriented agriculture R&D (in euros 2022) as part of the general increase targeted at 3% in R&D on GDP (*i.e. +30% increase on EU average to go from 2.3% of GDP in 2021 to 3% vs. a BAU around 5 billion/year*).

3 Foster public awareness of environmental challenges and solutions

This measure employs a two-part approach methodology.

The first part involves awareness costs of €2 per person per year, based on the recommended expenditures for tobacco control, as outlined in the Tobacco Control Scale Report 2021[1].

The second part of the measure involves training sessions conducted by associations, with each session accommodating a group of 25 individuals. These sessions, termed 'Climate Fresk', aim to educate the entire population over a span of 10 years. The cost of facilitating a day's session is estimated at €500[2].

The total cost of the measure is the sum of the costs incurred in both parts.

4 Boost the Fair Transition Fund to support professional transitions

This measure employs a two-part methodology, the results of which are averaged for a more comprehensive understanding.

The first method extrapolates from the methodology of the French report '*2% for 2 degrees*'. It considers the number of jobs destroyed by the transition in France according to the Shift project[3] and extrapolates this ratio of destroyed jobs to total jobs to other European countries. Adjustments are made for the number of retirements (2.47% of employees per year). The cost of training is estimated at €16,000[4] based on a one-year Agricultural or buildings CAPa, these sectors being considered as providing the most employment in the context of the transition. The Business as Usual corresponds to the funds currently allocated to the Just Transition Fund.

The second method utilises data from the McKinsey World Report[5] to the European Union. The ratio of distressed employment to total employment worldwide is applied to the European Union.

The result obtained with the second method is twice as that obtained by the first method. The difference is explained by the fact that in the world, regions will be more distressed than Europe because they employ a lot in the hydrocarbon sector.

We have averaged the two methods for the European Union and then ventilated the distribution of aid according to the same distribution as the Just Transition Fund today.

Notes

1. Smoke Free Partnership, 2021, The Tobacco Control Scale in Europe.
2. Ministère de l'Education Nationale, 2018, Le Guide du Bénévole.
3. The Shift Project, 2021, L'emploi: Moteur de la transition bas-carbone.
4. AFPA, constructeur bois and CFPPA, Brevet Professionnel de Responsable d'Exploitation Agricole (BP REA).
5. McKinsey, 2021, The net-zero transition: What it would cost, what it could bring.

Appendix A.2

1 Compatibility of this scenario with critical material resources constraints

Concerns about the shift from a fossil-intensive to a mining-intensive economy in the decarbonisation process have been raised due to the mineral demands of green technologies. The aim of this appendix is to compute an order of magnitude of the mineral demand of the transition scenario presented in the report, and to compare this demand with the current estimates of global reserves and resources.

- Only the mineral demands of the most significant low-carbon technologies are assessed i.e. solar PV, onshore wind, offshore wind, batteries of electric vehicles (EVs), chargers of EVs, electrification of railway tracks, reinforcement, and extension of the electricity network

- The cumulated installed capacity between 2023 and 2050 is retrieved from the transition scenario for each of these technologies, and expressed in MW, MWh or km. This cumulated capacity takes into account the need for renewal of certain technologies when they reach the end of their lifetime during the period of the transition.

- The material intensity of each technology is then taken for 12 materials present in the list of critical materials of the EU[1]. These material intensities are retrieved from:

    - Pulido-Sánchez (2020)[2] for PV;

    - the supplementary material of de Castro and Capellán-Pérez (2020)[3] for wind technologies. Yet, the stainless steel intensity of wind turbines, which directly translates into their nickel intensity, was updated to take stock of more recent developments[4];

    - Pulido-Sánchez *et al.* (2022)[5] for electric vehicles and railway tracks;

    - The LOCOMOTION project[6] for the electricity network.

- The demand for each mineral is computed by summing the products of cumulated installed capacities by material intensities.

- The reserves and resources of each mineral are taken from the Energy Transitions Commission report[7] for cobalt, copper, lithium and nickel, and from the U.S. Geological Survey[8] for the other 8 minerals.

- The demand for each mineral is compared to these reserves and resources. By doing so, a potential bottleneck is identified for 4 minerals: nickel, lithium, copper and cobalt.

- The calculation for determining the allocation of reserves and resources to the EU, while considering transition fairness, is computed by multiplying these values by the average ratio of the projected EU population to the projected global population in the year 2050[9].

- The demand of the 4 bottleneck minerals is compared to the shares of reserves and resources allocated to the EU in a just transition scenario. Notably, these figures surpass 100% for reserves of nickel and cobalt.

- To read the discussion which follows from these figures, see Appendix A of the main report.

Notes

1. See the Raw Materials Information System (RMIS).

2. Pulido-Sánchez, D. (2022). Requerimientos materiales y EROI de las tecnologías fotovoltaicas en la transición energética.

3. de Castro, C., Capellán-Pérez, I., 2020. Standard, Point of Use, and Extended Energy Return on Energy Invested (EROI) from Comprehensive Material Requirements of Present Global Wind, Solar, and Hydro Power Technologies. Energies 13, 3036.

4. Stainless steel is assumed to be composed of 8% nickel. In de Castro and Capellán-Pérez (2020), the steel, and thus the nickel intensity, are the following:
   - onshore wind: 126 100 kg/MW steel - 10 088 kg/MW nickel
   - offshore wind: 400 000 kg/MW steel - 32 000 kg/MW nickel

   Based on Figure 6 an NREL 2023 Report, we modified it with:
   - onshore wind: 108 000 kg/MW steel - 8 640 kg/MW nickel
   - offshore wind: 252 300 kg/MW steel - 20 184 kg/MW nickel

5. Pulido-Sánchez, D., Capellán-Pérez, I., Castro, C. de, Frechoso, F. (2022). Material and energy requirements of transport electrification. Energy Environ. Sci. 15, 4872–4910.

6. Locomotion project (2023).

7. Energy Transitions Commission (ETC), 2023, Material and Resource Requirements for the Energy Transition.

8. U.S. Geological Survey, 2023, Mineral commodity summaries 2023: U.S. Geological Survey, 210.

9. See World population projected in 2050 | United Nations and Population projections in the EU | Eurostat.