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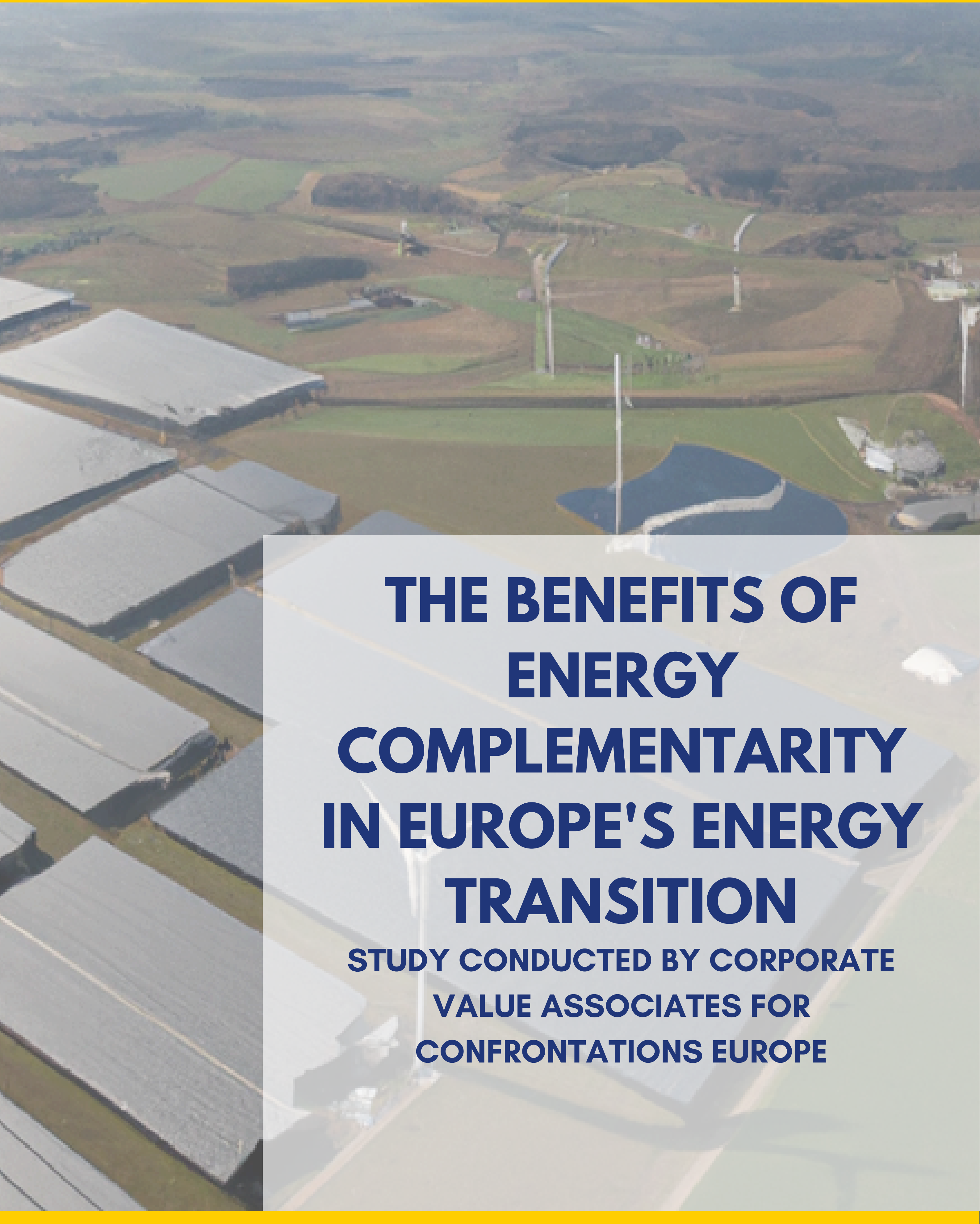

THE BENEFITS OF ENERGY COMPLEMENTARITY IN EUROPE'S ENERGY TRANSITION

STUDY CONDUCTED BY CORPORATE VALUE ASSOCIATES FOR CONFRONTATIONS EUROPE

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ABSTRACT

A European carbon-neutral energy system that better leverages the balances and complementarities between energies in 2050 (electricity, decarbonized gases and fuels), provides significant benefits in comparison to a "power intensive" energy architecture

The challenges of decarbonizing the EU energy system raise the **question of optimal allocation choices** between the mix of energy uses and sources. This study aims to compare the benefits of different "energy mixes" to reach carbon neutrality for EU 27 by 2050 and is built on differentiated scenarios from the TYNDP 2022 report (ENTSOE / ENTSOG).

The comparison of different "energy mixes" shows that aiming for a greater "**balance between energy sources**", rather than a strong "power intensive" electricity dominance, creates **significant comparative benefits** for society, both technical, economic, social and environmental:

a) The energy system **optimizes assets' sizing** and needs for new capacities construction: avoiding **>40%** extra capacities in grid-connected electrical production, flexibilities and power transport & distribution networks (700 GW avoided).

b) It **reduces deployment risks and pressure** put on vast industrial development, related trained labor temporary needs, and significant financing stakes.

c) It **reduces exposure to daily intermittent sourcing** and risk of supply, and reinforces the resilience of the system with short/long-term storage: **-15%** exposure in the supply mix.

d) Energy supply system **costs less to develop and operate** overall: saving **-700bn€** in CAPEX investments (-15%), and **1500bn€** in discounted TOTEX over 30y.

- Note: savings on "behind-the-meter" equipment and infrastructure from maintaining a larger share of gas usages, rather than electrifying usages, are not included.

e) Energy supply system **costs are improved for all main client types**: between **-5% to -10%** (residential and tertiary sectors respectively), reducing social acceptability risks.

f) A complementary energies system **creates more stable domestic employment and local economy dynamism: +12%** stable jobs (almost +100K FTEs), indirectlyintensified by enhanced companies' competitiveness and clients' local purchasing power.

- It **lightens the complexity of temporary jobs'** creations and reconversions.

g) It **puts less potential pressure on EV drivers' charging behavior**, by increasing energy storage through gas, rather than from Vehicle-to-Grid (V2G) non-mature solutions.

h) Such energies complementarity system **reduces land consumption: 50%** avoided, or **1.2M hectares** (i.e. Montenegro's surface), mostly for diffuse energy sources such as solar plants. It **reduces risks of land price inflation and usages conflicts**, incl. carbon sinks.

- On the contrary, maximizing biogas production (e.g. from intermediate crops) can positively impact the EU agricultural system (soil stability, biodiversity, biofertilizers)

These benefits **call for policy actions**, to avoid putting too much pressure on the power system with negative impacts, but rather:

- reconsider **improved energies mixes** and optimal equilibrium, in the energy transition **strategic planification**,
- maintain an optimal share of **decarbonized gases and decarbonized fuels usages** that can be greenified (heavy transport, industrial and domestic heat, etc.),
- and support in securing **strategic renewable gas** energy sources, especially for biogas production voluntary scale-up, which appears as a critical lever in the energy transition.

FULL REPORT

Introduction – Objectives and methodology: assess the optimality and benefits of different "energy mixes" to reach carbon neutrality for EU 27, by studying two comparable but differentiated energy transitions scenarios, showing diverse allocations between decarbonized energies

Context

The challenges of decarbonizing the European energy system raise the question of optimal allocation choices between the energy uses to be satisfied and the various decarbonized energy sources eligible to satisfy these uses – renewable electricity production technologies, decarbonized electricity, green gases or green fuels production technologies,...

There are several allocation options for achieving carbon neutrality while optimizing the cost of energy transition, considering the renewable resources available in the EU, the available decarbonized technologies to invest in, the demand constraints to be met, or other objectives such as energy independence.

Not all of these are of equal value to the "Community", and may lead to differentiated social optimums that need to be carefully explored, since these are choices that commit energy architectures and economy resilience and competitiveness for the decades to come.

Objectives and methodology

This study is built on differentiated but comparable Energy Transition scenarios, developed by the same research and modeling entity, with a common set of core assumptions. It thus enables to study and assess all the consequences of differentiated energy allocations ("mixes") and investment choices between decarbonized energy sources to achieve carbon neutrality, in terms of optimums for European society, and to draw public policy recommendations on the principles of the best configuration of decarbonized energy mixes for the EU27.

To that end, the energy transition scenarios to 2050 of TYNDP 2022 report (ENTSOE / ENTSOG) [1], served as a starting point, since they allow to study differentiated choices for allocating uses to decarbonized energy sources, using the 'Distributed Energy' (DE) scenario with a strong "power intensive" electricity dominance, and the 'Global Ambition' (GA) scenario aiming for a greater balance between energy sources ("complementarities between energies scenario"). Marginal adjustments are integrated to both scenarios to ensure a balanced comparison 'all other things being equal' (increased nuclear base in DE and reduced green gas imports in GA, to reach similar levels between the two systems, see appendix).

[1] TYNDP 2022 Scenario Report, version April 2022 (ENTSOE / ENTSOG)

Votre texte de paragraphe Both scenarios were assessed using a common set of criteria ('score card') designed to address the different dimensions of optimality in the choice of a decarbonized energy system, focusing on technical, economic, social and environmental performance.

Caveat and limits of the analysis to available and estimated data

The methodology adopted allows to measure effects and trends, but does not guarantee to be at the "optimum" in the right choice of allocations and shares between energies since an iterative quantitative study searching the best optimums on all the criteria was not possible. Absolute values for differences between scenarios could be slightly higher than the figures provided in this note, which depend on predefined scenarios of TYNDP 2022.

The scope of the analysis is strictly limited to **production, flexibility and energy transmission infrastructures** (upstream of the point of delivery) and therefore does not consider the potential impacts of these choices on downstream metering (building envelope, equipment changes, industrial performance, etc.).

Techno-economic assumptions remain **uncertain**, as they are subject to changes in the macro-economic context to 2050 (geopolitical framework, development of energy chains, etc.) and to the diversity of public data sources and may therefore be challenged. Nevertheless, the assumptions made are based on recent public sources that reflect the latest market considerations (see bibliography) and both scenarios were assessed using a common set of criteria.

Technical analysis of the scenarios studied – 2 energy transition scenarios using diverse allocations between decarbonized energies: DE with a strong "power intensive" electricity dominance and GA* aiming for a greater balance between energy sources*

Technical analysis of scenario with a strong "power intensive" electricity dominance by 2050 – scenario DE*

The aim of this section is to present the main technical dimensioning results for the adjusted Distributed Energy (DE*) scenario, as a more power centric scenario.

1.1 Final energy demand: 1/3 reduction in final demand by 2050 in the DE* scenario vs. the counterfactual situation (2015), linked to the electrification of uses and the activation of energy efficiency levers

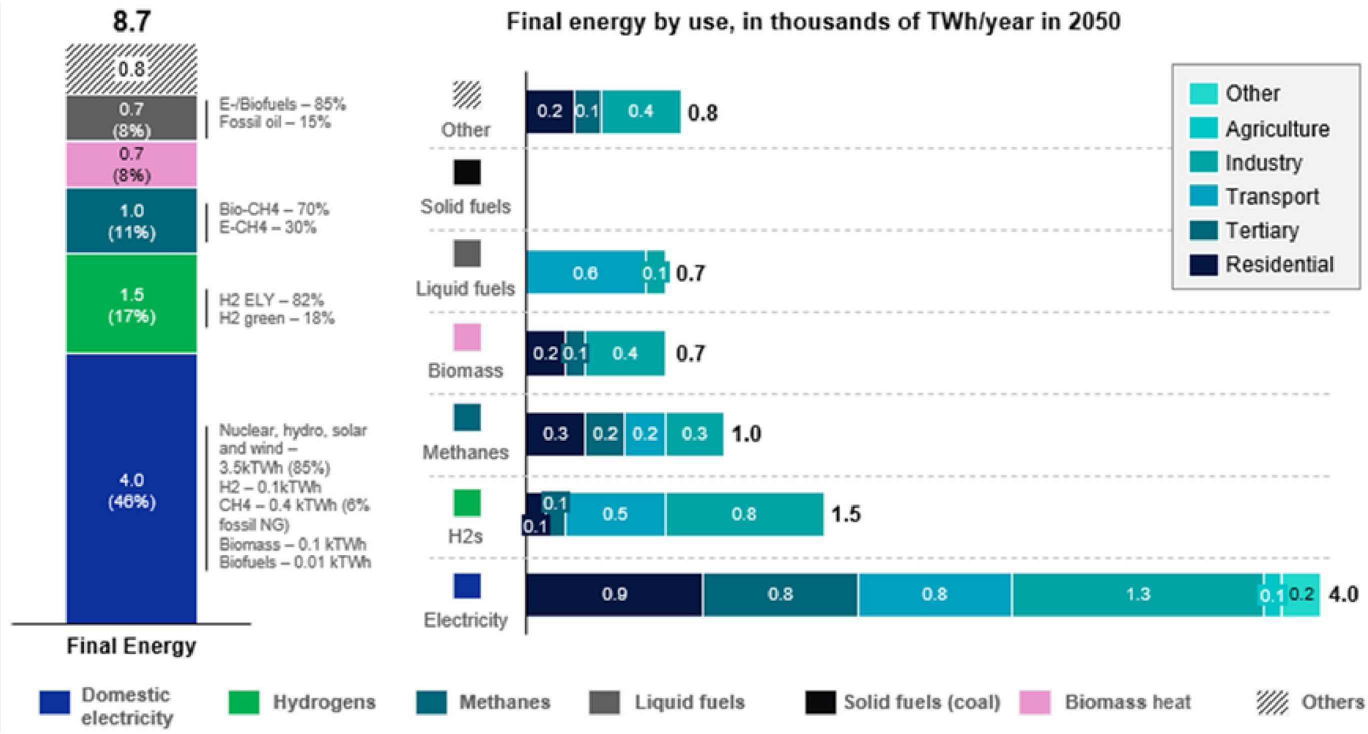

Figure 1 – Final energy supply by energy carrier and by sector in the DE* scenario, in thousands of TWh/year in 2050[2]

In 2050, **8.7 kTWh of final energy** is consumed to meet EU27 demand – down 33% on 2015 (counterfactual).

- An energy transition scenario in which almost half of end-uses in 2050 (**46%**) are electrified, i.e., a +58% increase in electricity use in end-use consumption vs. the counterfactual (2015).

- A proportion of green gas uses (direct H2, bioCH4, e-CH4) will be maintained, mainly for heavy mobility uses (ships, aircraft and trucks) and heat uses (residential, commercial and industrial), accounting for **28%** of the total mix.

[2] Initial electricity production + electricity production from H2, CH4, Biomass and biofuels. yc. system losses / compatibilized process efficiency, P2G to P2M & P2L processes, others

- The remainder in biomass heat in the Residential/Industrial segment, accounting for **8%** of the mix; and in liquid fuels (85/15% bio and e-fuels vs. fossil oil) for mobility applications, also accounting for **8%**

Decarbonization of uses is being driven by the electrification of uses (+58% vs. 2015), mainly in **Transport (see Appendix 7 and Appendix 8), Residential and Industry.**

- Industry is the most energy-intensive sector by 2050 (**40%**), followed by Transport (**20%**) and Residential (**20%**).

- In terms of end uses, the Transport sector shows the greatest reduction in consumption (**-50%**), followed by Residential (**-38%**) compared to the counterfactual scenario (2015), thanks to the activation of energy optimization levers (see Appendix 1)

- Strong differences can occur between members state, as for instance **Germany** has a high share of **Industry representing 40-41% of total final energy demand** compared to 27% in average in the EU and covered mainly by electricity in the DE* scenario

1.2 Supply: The electrification & greening of the energy system will require the development of variable RES, whose installed capacity will be x5 between 2025-2050

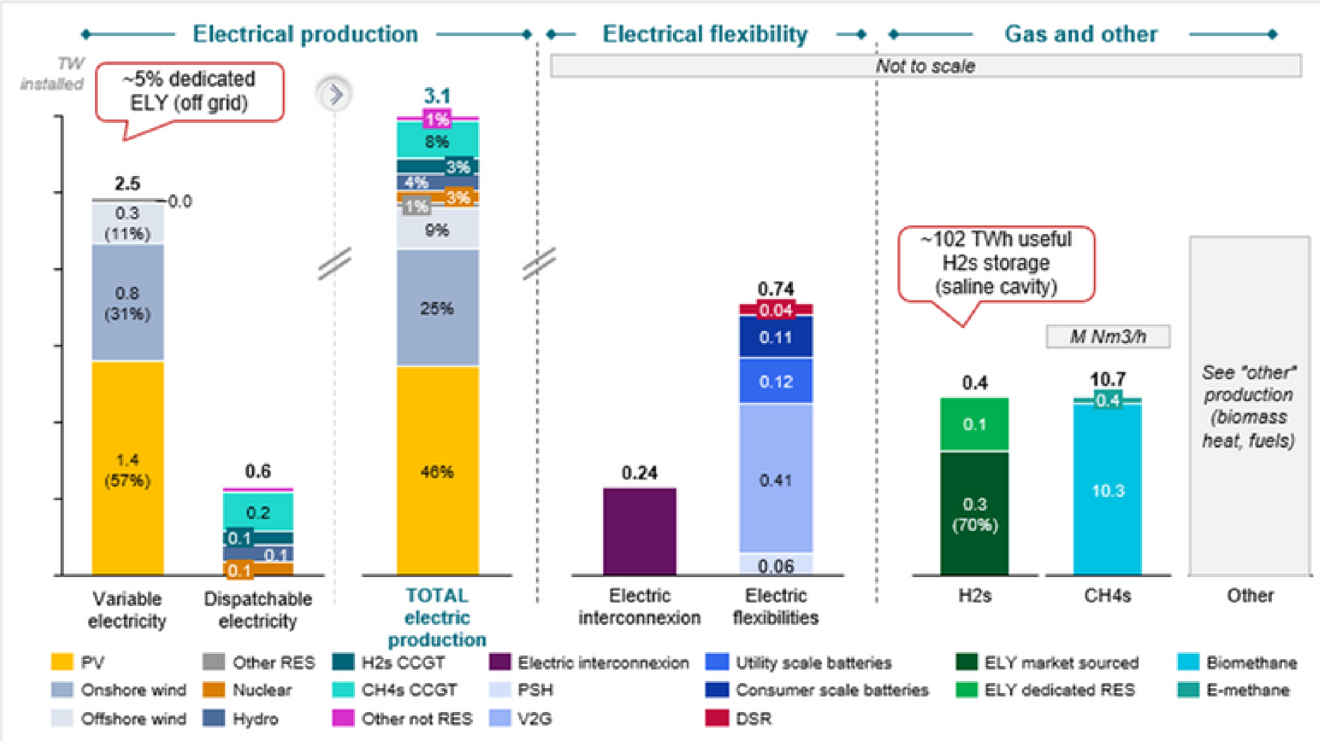

Figure 2 : Capacity mix for all energies (including flexibility capacity and excluding imports) in the DE* scenario, in TW installed in 2050(3)(4)

[3] Interconnection capacity refers to the electricity transfer capacity between EU and border countries
[4] Other RES: CHP (33 GW), biofuel (2 GW) and oil (1 GW) power plant

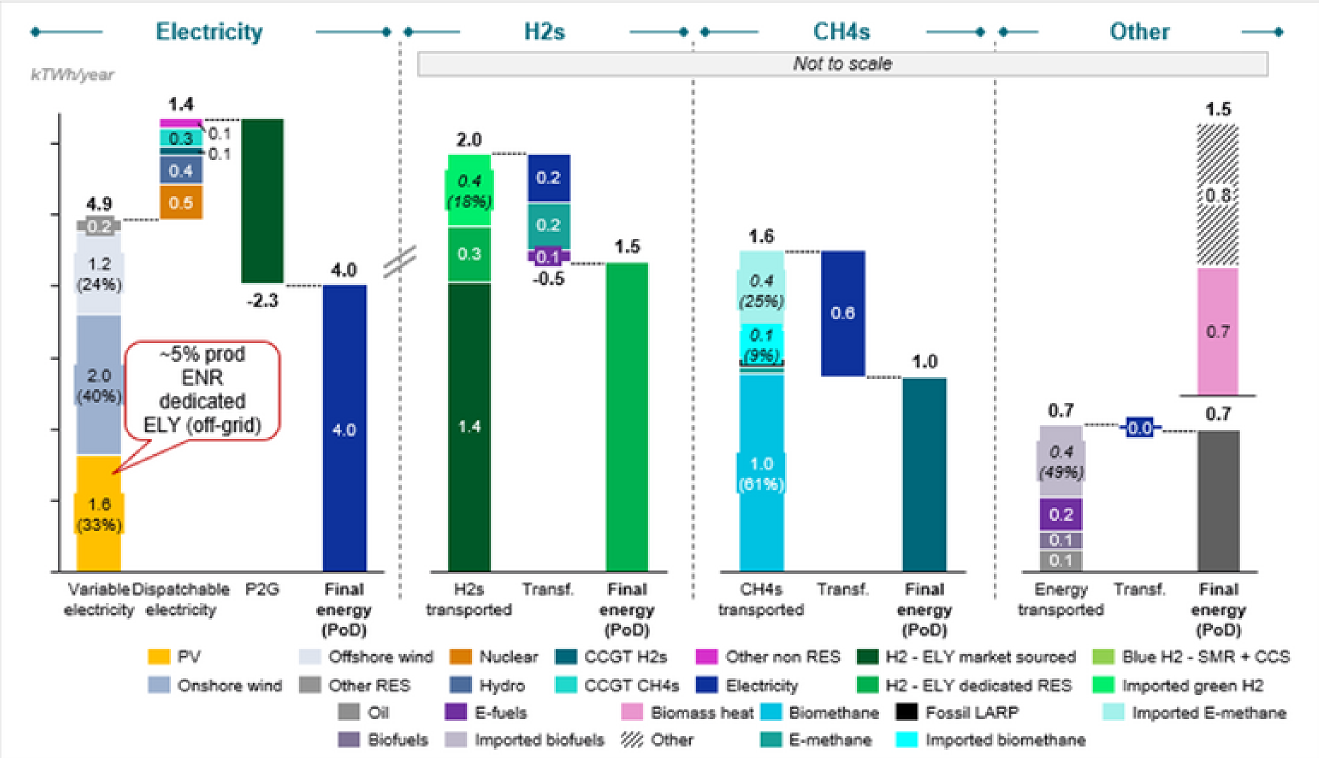

Figure 3 : Energy transported, transformed and final at the point of delivery by energy carrier in the DE* scenario, in thousands of TWh/year in 2050

Installed power generation capacity of **3.1 TW** for a production of **6.4 kTWh** used either to directly address electricity needs, or to produce e-molecules for direct use or re-electrification.

- **>80%** of the electricity produced is of RES and even up to 90% in some countries such as Germany, which requires a 5-fold increase in the RES installed capacity between 2025e and 2050 (2.5 TW), of which 5% is connected off-grid (dedicated H2 production)

- The intermittent nature of the power system calls for a strong development of **flexibility technologies**: dispatchable capacities, in particular green gas CCGT (11% of total electricity production and up to 18% in **Italy** due to strong dependency of PV system with very intermittent production and representing 80% of the RES capacity installed), intraday flexibilities (V2G[5] and batteries) and electrolyser supply (P2G) benefiting from salt cavern storage

- The increase in peak injection and withdrawal on the electricity grid, due to the growth of variable RES and electricity use, forces to **multiply by 2.3** the grid capacity before 2050 (see Appendix 4 and Appendix 5)

[5] V2G capacity corresponding to the modelled connection capacity between the distribution network and EVs

- **Strong disparities between EU member states**, with Germany and Italy, for example, importing electricity from border countries such as France, which on the other hand relies on a large nuclear base, with a positive electricity balance.

To compensate for the virtual disappearance of fossil fuels (oil, natural gas, coal) and the shift towards green gas uses in 2050, the scenario foresees a boom in Power-to-Gas (H2) and biomethane production (x10 vs 2025e), supplemented by minority imports.

- 0.4 TW of installed electrolysis capacity, 70% of which is connected to the electricity grid, accounting for **80% of domestic H2 production** (1.4 kTWh), thanks to a higher load factor than dedicated RES capacity.

- **1.0 kTWh** (equivalent to 10.3 M Nm3/h) of domestic bioCH4 production from anaerobic digestion and pyro gasification units

- Minority imports of green H2 and CH4 (18-33%) supplement domestic production

- +85,500km extension of the CH4s distribution network and the development of a 40,000km H2 network (see Appendix 8), to ensure the supply of green gas by 2050 and the connection of production sites (biomethane)

Liquid fuels are supplied half by biofuel imports and half by domestic production (biofuels, e-fuels and petrol) for use mainly in Transport.

Technical analysis of a system aiming for a greater balance between energy sources ("complementarities between energies scenario") - scenario GA*

The aim of this section is to present the main technical dimensioning results of the Global Ambition (GA*) adjusted scenario, as a scenario aiming for a greater balance between energy sources ("complementarities between energies scenario").

1.3 Final energy demand: A less electrified demand favoring the replacement of fossil gases by green gases, or fossil liquids by green gases and e/biofuels

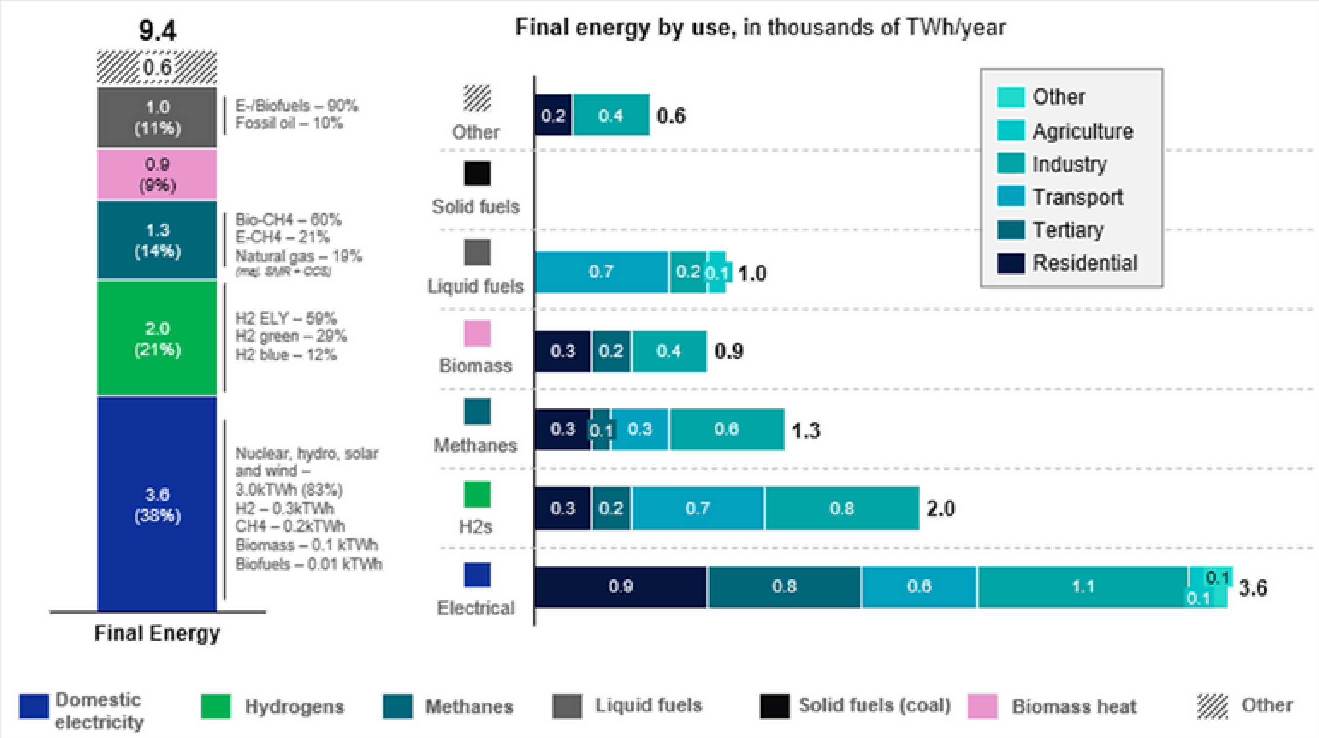

Figure 4 : Final energy supply by energy carrier and by sector in the GA* scenario, in thousands of TWh/year in 2050

In 2050, final energy consumption in the GA* scenario amounts to **9.4 kTWh/year**, i.e., a reduction of -27% compared to the counterfactual (2015) thanks to the activation of Energy Efficiency levers (See Appendix 1). Final consumption is slightly higher than in the DE* scenario (+8%), due to a slight deterioration in energy efficiency (gas & liquid fuels vs. electricity)

- Less electrified demand in the GA* scenario (38% of final demand vs. 46% DE*), due in particular to a less electrified Transport sector (25 vs. 40% DE*), and to a lesser extent Industry (34 vs. 40% DE*), Residential (46% vs. 50% DE*) and Tertiary (62% vs. 65%).

- A higher demand for decarbonated gases in the GA* scenario (35% of final demand vs. 28% DE*), favoring the replacement of fossil gases by decarbonated gases: H2s (21% GA* vs. 17% DE*) and CH4s (14% GA* vs. 11% DE*)

- Stronger demand for liquid fuels, mainly biofuels, and biomass heat due to less electrified uses (transport and heating)

Complementarity of energies is determined by a move towards decarbonized gas use in the Industry, Residential and Transport sectors (See Appendix 2 and Appendix 3)

- In the GA* scenario, the industrial sector shifts more towards the use of **green gas** (industrial furnaces and boilers), particularly CH4s, whose share is 2x higher than in the DE* scenario to 2050.

- The transport sector relies more on the complementarity of electricity/gas/liquid fuels, with the share of electricity **38% lower** than in the DE* scenario in 2050.

- In the GA* scenario, the residential sector focuses more on **H2 and biomass** use, compared with a higher share of heat network and electric pump in the DE scenario

1.4 Supply: An energy system making greater use of decarbonized gas infrastructures (H2s and CH4s) to compensate for the virtual disappearance of fossil fuels (oil, natural gas, coal) and the shift towards green gas uses in 2050

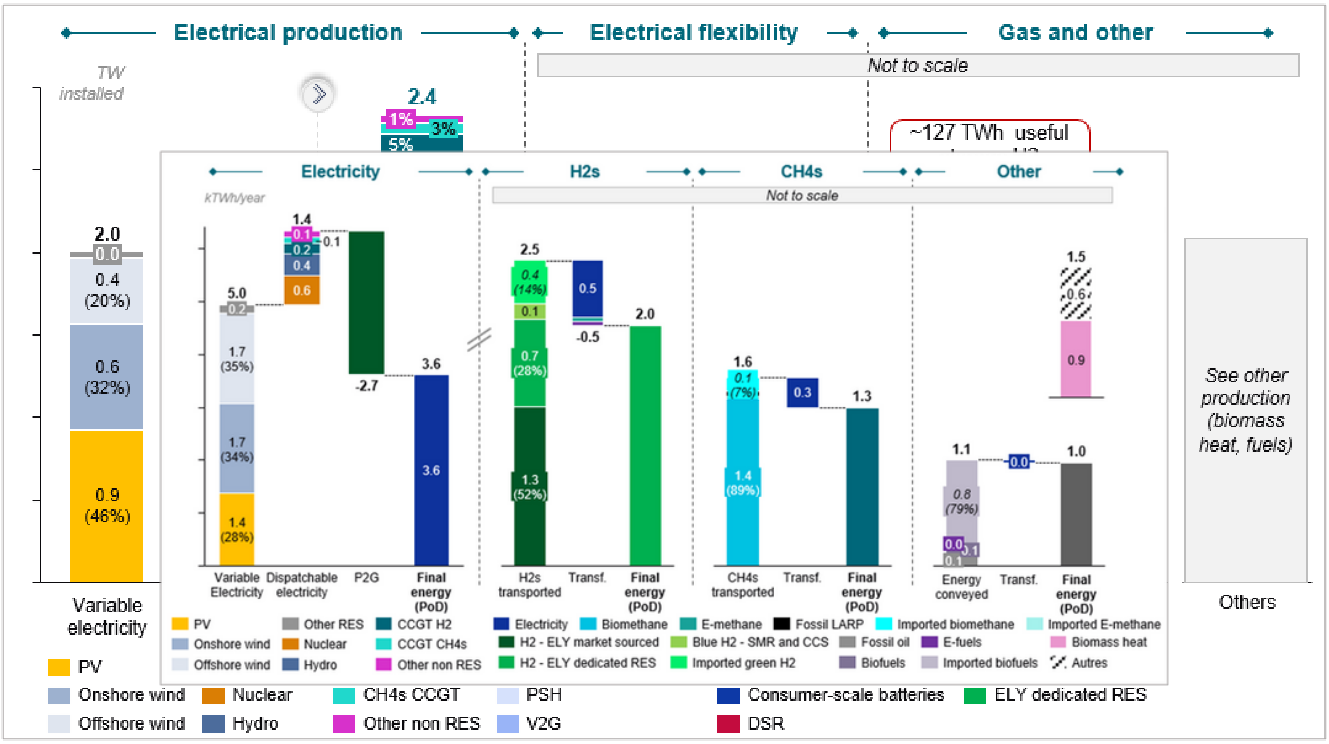

Figure 5 : Capacity mix for all energies (including flexibility capacity and excluding imports) in the GA* scenario, in TW installed in 2050

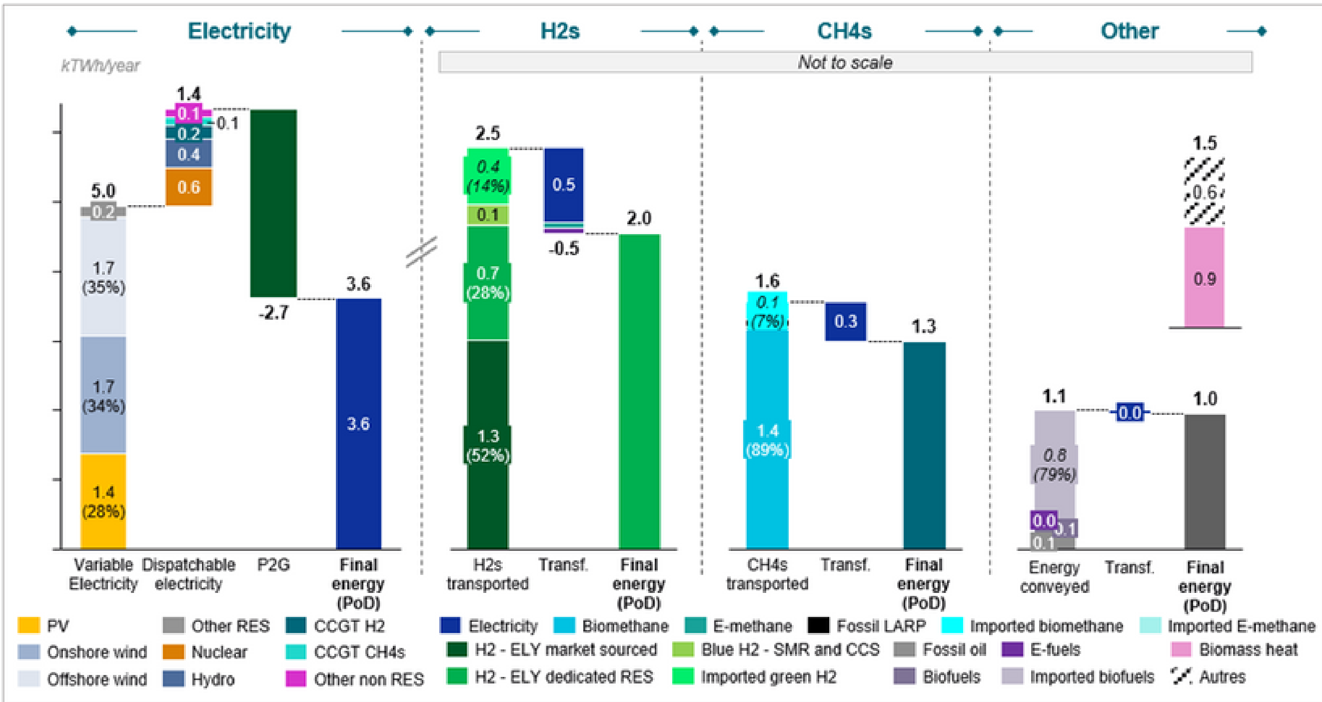

Figure 6 : Energy transported, transformed and final at the point of delivery by energy carrier in the GA* scenario, in thousands of TWh/year in 2050

Installed power generation capacity of **2.4 TW** for a production of **6.4 kTWh** used to a lesser extent to meet electricity needs (56% vs. 63% in DE* scenario) and more to produce e-molecules for direct use or re-electrification (44% vs. 37% in DE* scenario)

- **>80%** of the electricity produced is from RES, with an installed base of **2.0 TW**, 15% of which is connected to off-grid systems (dedicated H2), enabling to improve producible compared with the DE* scenario (smaller installed base, large-scale RES vs. self-consumption PV, captive RES (Power-to-H2) production deposits complementary to those mobilized for direct electricity injection, etc.)

- An installed **dispatchable electricity** capacity of 0.4 TW (vs. 0.6 TW in the DE* scenario) for an equivalent electricity production (1.4 TWh) due to an improved load factor for green gas CCGTs (CH4s and H2s) of 20% vs. 13% in the DE* scenario

- The development of electrical flexibility technologies and services (batteries, V2G, etc.) to manage **the intermittent nature** of the electrical system, for which the installed capacity is slightly lower than in the DE* scenario (0.6 TW vs. 0.7 TW in the DE* scenario), but with nearly 80% lower utilization (336 TWh of electrical energy stored and retransmitted vs. 598 TWh in the DE* scenario)

- The increase in peak injection and withdrawal on the electricity grid, due to the development of variable RES and electricity use, will force the grid's capacity to **x1.6 TW** by 2050 (see Appendix 6 and Appendix 7)

In the energy complementarity scenario (GA*), the energy system makes greater use of decarbonized gas infrastructures (H2s and CH4s) to compensate for the virtual disappearance of fossil fuels (oil, natural gas, coal) and the shift towards green gas uses in 2050.

- **0.6 TW of electrolysis** capacity installed, of which ~50% grid-connected and ~50% off-grid (dedicated RES), producing 1.3 and 0.7 kTWh of H2 respectively, due to a higher load factor than dedicated RES.

- The potential for domestic biomethane production in the EU27 is maximized with a production of **1.4 kTWh** by 2050, from anaerobic digestion and pyro gasification units (equivalent to 14.5 M Nm3/h)

- Minority imports of H2s and CH4s, representing 10% of total gas energy transported, supplement domestic production.

- +100,000km extension of the CH4s distribution network and the development of a 44,500km H2 network (See Appendix 8 and Appendix 9), to ensure the supply of green gas by 2050 and the connection of production sites (biomethane)

Liquid fuel requirements are higher (1.1 kTWh) due to less electrified transport uses compared to the DE* scenario and are supplied for almost 80% by biofuel imports and for 20% by domestic production (biofuels, e-fuels and domestic oil).

Summary of comparative performance – A UE carbon-neutral energy system that better leverages the balances & complementarities between energies in 2050 (electricity, decarbonized gases and fuels), provides significant benefits in comparison to a "power intensive" architecture

Technical performance: Improved balances and complementarities between decarbonized energies reduce the stress on intermittent renewable power sources ("RES") development, ease power grid reinforcement efforts and electricity flexibility constraints, as well as land and territorial pressure, and improve resilience to intraday and seasonal climate risks thanks to a greater share of long-term storable energy vectors

Technical performance criteria	Unit	Base	DE* 2050	GA* 2050	Comments
Share of energy demand satisfied	%	*100%*	100%	100%	• All demand covered on an hourly basis, with peak power plants sized to secure the supply of electricity
Maximum power level needed to meet instantaneous demand at annual peak	TW	*1.0*	2.3	1.6	• **+45% peak injection into electricity grid. in DE*** to 2050, offset by reinforcing CH4s and H2s networks in GA* (see economic impact)
Electrical tapping point	TW	*n/A.*	1.2	1.0	• **+20% peak demand in the DE* scenario** due to higher end-use electricity consumption (+10%)
% of prod. variable elec. total electricity	%	*15%*	66%	65%	• Substantial acceleration to the contribution of renewable energies with daily variability in the energy mix and delivered electricity, and its associated risk
% variable energy in delivered energy PoD	%	*3%*	32%	27%	
Flexibility capacities for grid injection	GW	*n/A.*	1 119	784	• **+43% capabilities of electric flexibilities** to 2050 in the sc. DE* linked to greater dependence on electricity use and the high share of RES
Primary energy produced + imports	kTWh	*16.3*	12.1	13.1	• **+8% primary energy consumption** iso-use in the GA* scenario, due to a slight deterioration in downstream energy efficiency (gas vs. electricity)
Percentage of energy supplied dependent on imports	%	*~55%*	14%	14%	• **Strengthening energy independence** for the 2 scenarios DE and GA
System energy efficiency *(final energy PoD / (primary + import))*	%	*79%*	80%	78%	• **Stable energy yield at PoD**,slightly degraded in GA because of system efficiency (PtX)
System land efficiency (domestic land consumption / primary energy)	ha / TWh	-	290	175	• **Direct land pressure 1.65x higher in the DE* case**, mainly due to utility scale PV
Technical feasibility	Qualitative	-	- -	-	• Scenarios based on **services that are not yet fully proven**, even more so in the DE scenario (e.g. V2G, electrification of heavy transport/maritime/aviation applications)

Figure 7 : Summary of technical performance of the scenarios[6]

The technical dimensioning of the two energy transition scenarios studied (DE* and GA*) makes it possible to **meet all end uses** in 2050 on an hourly basis, with several similarities:

- **Final energy consumption reduced** compared with the counterfactual (-27 to -33%), but slightly higher in the GA* scenario (+8% vs. DE*) due to the lower energy efficiency of end uses (gas and liquid fuels vs. electricity)
- System energy efficiency (primary vs. delivered energy) **stable** compared to the counterfactual and very close between scenarios (80% DE* vs. 78% GA*, limited by the efficiency of PtX and XtP systems)

[6] Performance criteria definition in Appendix 10

- **Increased energy independence** of EU supply by 2050 vs. contrafactual, with ~15% of energy supplied coming from non-EU imports in the two energy transition scenarios vs. ~55% in 2025.

DE* calls for higher installed power generation capacity (3.1 TW vs. 2.4 TW in GA*), including higher intermittent RES capacity (2.5 TW vs. 2.4 TW in GA*), of which a smaller proportion is utility scale off-grid dedicated to H2 production (0.15 TW vs. 0.4 TW in GA*). As such, DE* intensifies the sizing and the **stress on the deployment and financing of the power infrastructures (generation, transmission and distribution, storage and "flexibilities")**, and creates a system that is more **exposed to intermittent RES** with high daily variability, and therefore to climatic risks:

- **32%** of final energy delivered to the point of delivery is supplied by RES, vs. **27%** in the GA scenario*

- **+45%** of electrical grid injection capacity by 2050, thereby increasing the injection peak and thus the need to reinforce T&D electrical grids.

- **+43%** of flexibility capacity for absorption/injection in the electricity grid[7]in the scenario DE*, partially backed by technologies/services that are not yet fully proven (large scale deployment of electricity storage batteries) and leveraging high shares of aggregated pilotable Vehicle to Grid ("V2G") pools

- **In the Netherlands**, the pressure imposed by the "gas ban", offset by intense electrification, proved too heavy, and the government backed down because it jeopardized the power system (grid capacity and system resilience)[8]

GA* energy system, in comparison, increases the use of decarbonized gas infrastructures (H2s and CH4s), which provide seasonal flexibility via long-term storable energy carriers, thereby improving the **system's resilience** to climatic risks, the ability to better secure the decarbonized power system itself, and optimizing the required investments in the electricity field (see below, economic balance and performance assessment of each scenario):

- **1.4 kTWh** of domestic biomethane production (+40% vs. DE* scenario), maximizing EU biomethane potential by 2050[9] and requiring greater extension of the CH4s network (+30% in length vs. DE*) to connect biomethane production sites

[7] Intraday flexibilities (V2G, DSR, batteries, PSH) and dispatchable production (other non-RES, CCGT decarbonated gases)
[8] The Dutch gas ban and stakeholder actions, 03/2022 GRDF & Kiwa
[9] Possibility of reducing to 10% by increasing domestic production vs. biomethane imports at the same level as the GA scenario (i.e., maximum biomethane potential of 1.4 k TWh in 2050 in the EU27) - with impact on the CH4 and LCO distribution network

- 570 GW of electrolysis (+43% vs. DE*), more than half of which supplied by off-grid RES capacities directly injecting into electrolysis units, requiring larger H2 transmission and storage infrastructures (respectively ~45,000km and 125 TWhWGV[10], ie +10% / +25% vs DE*) to supply the molecules to the end consumption points.

Lastly, the **land footprint** of the energy system (direct[11] domestic land consumption / primary energy) is **1.7x higher** in the DE* scenario (290 ha/TWh vs. 175 ha/TWh in the GA* scenario) due to greater dependence on the electrical renewable technologies, particularly large PV, requiring more land than biomethane production units for instance.

[10] Working Gas Volume capacity (salt cavern storage)
[11] Area occupied exclusively by energy production facilities (electricity, H2, CH4s) and in competition with any other activity.

Economic performance: An overall improved economic equation for the "complementarities between energies" scenario, with CAPEX invested in the energy system reduced by 700 bn€ (15%) by 2050, and discounted TOTEX optimized by 1500 bn€ (7%) in terms of system set-up and operating costs over 30 years

Economic performance criteria	Unit	DE* 2050	GA* 2050	Comments
Total CAPEX invested to 2050	k €bn	5.4	4.7	• **+15% CAPEX** invested in the DE* scenario, i.e. ~€700 billion
CAPEX production *(elec + H2 + CH4 + liquefied fuels)*	k €bn	3.3 *(62%)*	3.2 *(69%)*	• Similar production CAPEX in the 2 scenarios with more investment. RES (DE*) vs electrolysis/methanization (GA*)
CAPEX flexibility *(elec + H2 storage - excluding V2G)*	k €bn	0.26 *(5%)*	0.17 *(4%)*	• **+53% investment in the DE* scenario** linked to a greater need for electric flexibility to ensure system resilience
CAPEX T&D *(elec + H2 + CH4)*	k €bn	1.8 *(34%)*	1.3 *(27%)*	• **+38% investments in the DE scenario***scenario, due to the greater need for **reinforcement of the electric system** (~1.7 vs. ~1.1 k Md€)
TOTEX (installation and operation) over 30 years	k €bn	22.7	21.3	• An **additional cost of +7%**, i.e. ~€1.5 bn in discounted TOTEX for setting up and operating the DE* vs GA* energy system
Residential TOTEX	k €bn	4.4 *(19%)*	4.2 *(20%)*	• The greater electrification of uses in the DE* scenario leads to a **5% increase in investments in** DE* vs. GA*
Tertiary TOTEX	k €bn	3.2 *(14%)*	2.9 *(14%)*	• The greater electrification of uses in the DE* scenario leads to a **10% increase in** DE* investments vs. GA*
Transport TOTEX	k €bn	5.5 *(24%)*	5.3 *(25%)*	• More balanced energy mix in the GA* case (28% elec, 33% H2, 28% comb. Liq) resulting in a **3% reduction in investments** vs. DE*
Industry TOTEX	k €bn	7.9 *(35%)*	7.5 *(35%)*	• The greater electrification of uses in the DE* scenario leads to a **7% increase in** DE* investments vs. GA*
Annualized full supply cost - standardized residential building	€/year	671	639	• **+5%** on supply costs DE* vs. GA*, mainly due to greater electrification of residential uses
Annualized full supply cost - standardized commercial building	€/year	8 940	8 100	• **+10%** on DE* procurement costs vs. GA*, mainly due to greater electrification of residential uses
Annualized full supply cost - industrial site	€/year	955 k	895 k	• **+7%** on DE* procurement costs vs. GA*, mainly due to greater electrification of industrial applications
Trade balance: import budget	k €bn	69.2	66.7	• **+4%** spent on energy imports DE* vs. GA*, mainly due to imported E-methane

Figure 8 : Summary of economic performance of the scenarios[12]

The greater complementarity of final energies enables to activate 3 major economic optimization effects for energies delivered to the point of delivery:

- On average, **higher renewable energies producible** on GA* for a smaller electrical installed base, and captive RES (Power-to-H2) production sources that complement those mobilized for direct electrical injection

- **Optimized energy transmission costs**, through a reduction in the need to reinforce the power grid and a partial transfer of transported/distributed energy volumes to gas systems (more efficient over long distances and partially existing)

- A reduction in the installed base of flexibilities needed to **balance the power system** (battery storage, "green" CCGTs)

[12] Performance criteria are defined in Appendix 11

The large **CAPEX "investment wall"** (5,400 bn€ in DE* and 4,700 bn€ in GA*) in the energy supply system by 2050 is **cut by 15% in GA***, or 700 bn€. Indeed, the reduction of 25% in investments in the electricity chain (-1,100 bn€)[13] is not offset by additional investments to develop the "green gas" and "green liquid fuels" chains in the EU (+400 bn€)[14], especially as gas transmission systems are partly existing and more efficient over longer distances to supply energies (reduced complete costs per MWh supplied).

- In the DE* scenario, **5,400 bn€2023 of total CAPEX** will be invested in the energy system by 2050 for production, transmission and energy flexibilities for all sectors - excluding DSM (demand side management) and "usage" investments - of which 83% of investments will be for the electricity sector[15], with around 1/3 of total CAPEX solely for reinforcing the electricity grid.

- Reduced dependence on electricity use (around -10% reduction in final electricity demand in GA* scenario) means a 35% reduction in peak electricity injection and a 32% reduction in the installed RES base for direct electricity grid injection, resulting in a **25% reduction in CAPEX invested** (-1,100 bn€2023)[16] in the electricity chain (production, grids and flexibilities)

- Savings in GA* are **not offset by additional investment** to develop the "green gas" and green liquid fuels chains in the EU[17]: +€214 bn investment in H2s, +€132 bn in CH4s and -€8 bn in green liquid fuels (biofuels/e-fuels)

- The greater use of **decarbonized gas vectors offers infrastructure that is less expensive** to develop: DE: €1,700 bn (Elec grid) + €100 bn (H2 grid and storage) + €15 bn (CH4s grid) vs GA: €1,100 bn (Elec grid) + €130 bn (H2 grid and storage) + €20 bn (CH4s grid)

[13]Total 1,100 bn€ savings split as: 600 bn€ from T&D electrical grids, 300 bn€ from intermittent RES capacity (excl. RES dedicated to H2) and 200 bn€ from intraday flexibilities and dispatchable production
[14]Total 400 bn€ additional investment split as: ~240 bn€ from H2 production capacities (incl. dedicated RES), ~30 bn€ from H2 T&S infrastructures, ~130 bn€ from CH4s production capacities (biomethane) and ~5 bn€ from CH4 distribution infrastructures
[15] Excluding V2G CAPEX considered as 'usage' investments
[16]Total 1,100 bn€ savings split as: 600 bn€ from T&D electrical grids, 300 bn€ from intermittent RES capacity (excl. RES dedicated to H2) and 200 bn€ from intraday flexibilities and dispatchable production
[17] Total 1,100 bn€ savings split as: 600 bn€ from T&D electrical grids, 300 bn€ from intermittent RES capacity (excl. RES dedicated to H2) and 200 bn€ from intraday flexibilities and dispatchable production

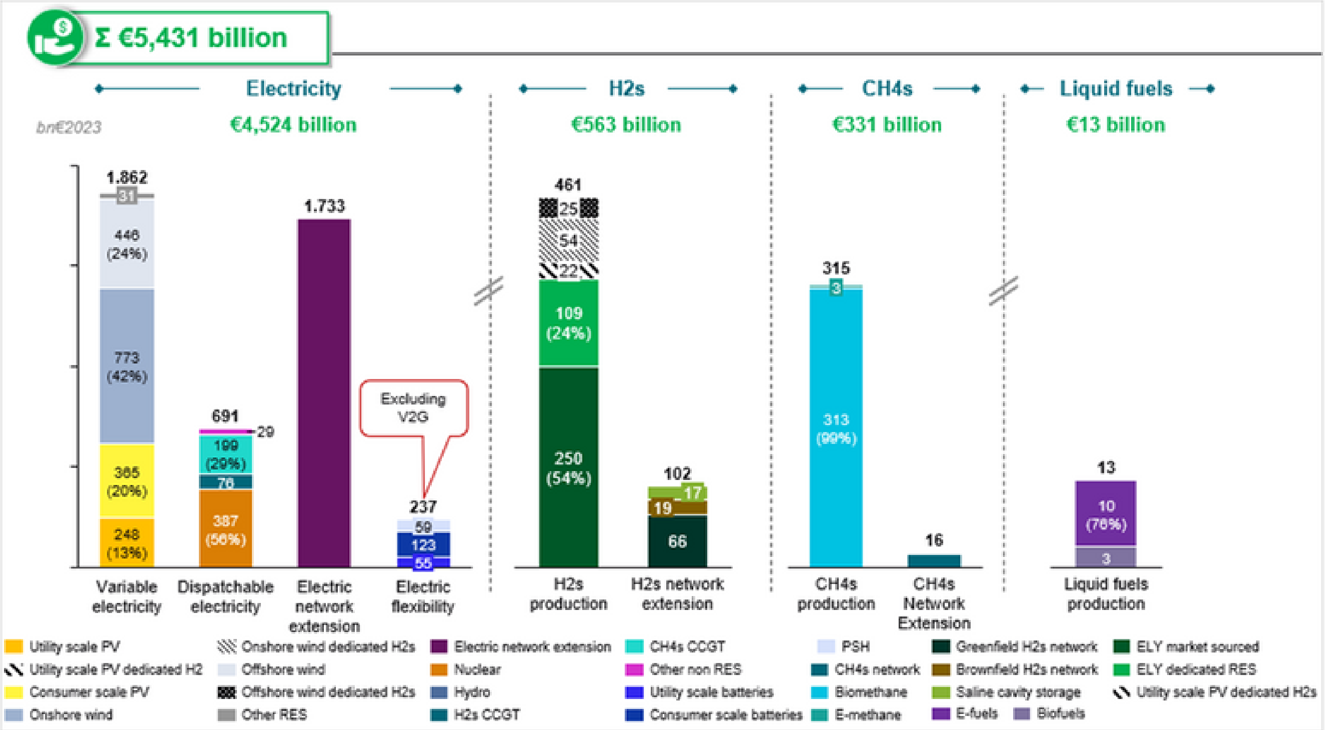

Figure 9 : Total CAPEX invested in the energy system by 2050 in scenario DE*, in €bn [18]

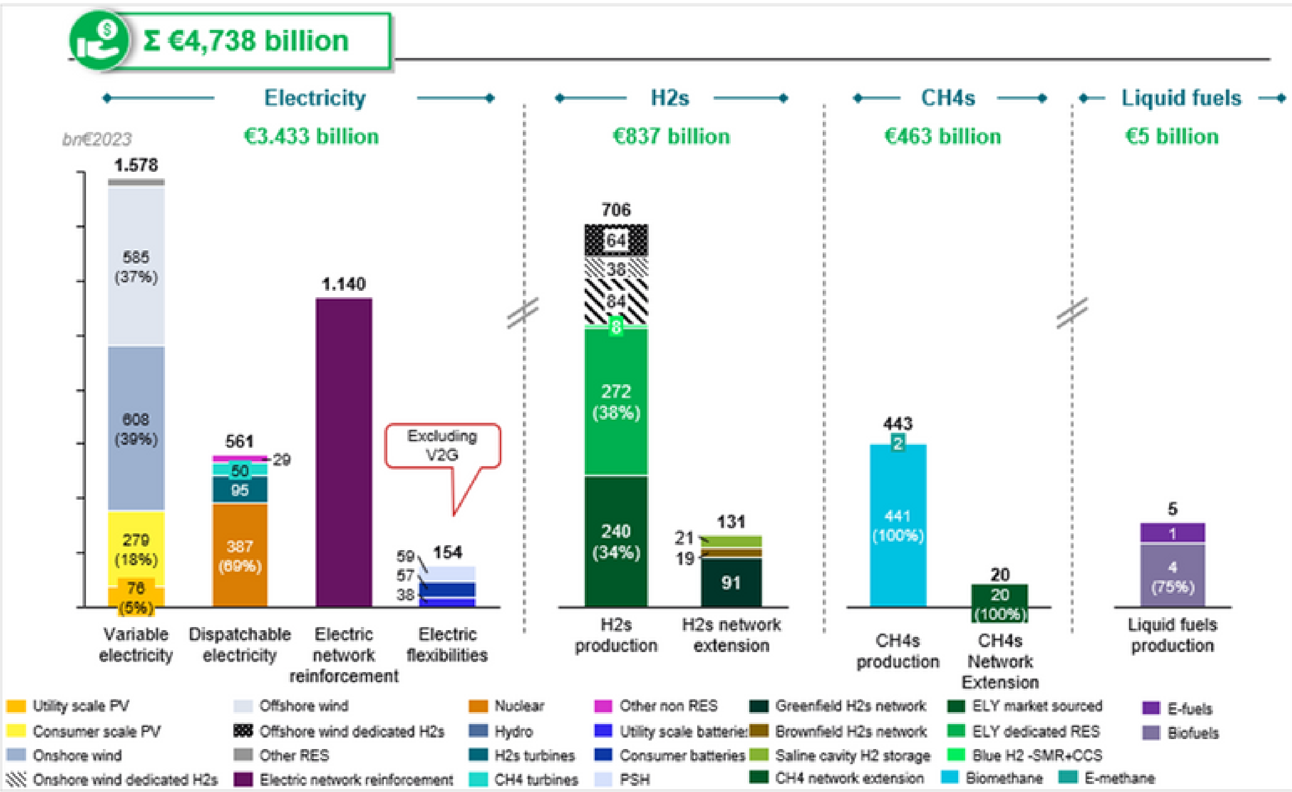

Figure 10 : Total CAPEX invested in the energy system by 2050 in scenario GA*, in €bn

[18] Electric CAPEX does not include RES dedicated to H2 production (off-grid capacities)

Furthermore, although downstream energy efficiency is slightly downgraded in GA*, the discounted **TOTEX for setting up and operating the energy system over 30 years is decreased by 7 to 8%**, or 1,500 bn€

- A reduction in final demand of elec. (-10%), reducing TOTEX associated with the electricity system by 30% (-2.9 trillion€2023)[19]
  - Reduction of 32% in the installed base of RES for direct grid injection, optimizing the installed base in the GA* scenario by tapping into higher yields in average and thus reducing the average LCOE RES production by 10 to 15% (onshore and PV)
  - Reduction of electrical flexibilities use, and dispatchable capacities (green gas CCGTs) required to ensure system resilience.
  - Reduction of peak injection by 35% with a 35% impact on the T&D elec LCO (-€6/MWhe) - Optimization of reinforcements
- An increase in the share of other energies in the GA* mix, notably CH4s (+35% of end uses) and H2s (+28% of end uses), which require relatively lower installation and operating costs (CH4s / H2s / Liquid fuels: +0.6 / +0.6 / +0.3, i.e., +1.5 trillion€2023 in discounted TOTEX compared to DE* scenario)
- Mainly thanks to more attractive transport and storage costs than for the electricity system: +0.2 trillion€2023 for H2, although infrastructure costs remain uncertain/less controlled at this stage, and +15 bn€2023 for CH4s network reinforcement.

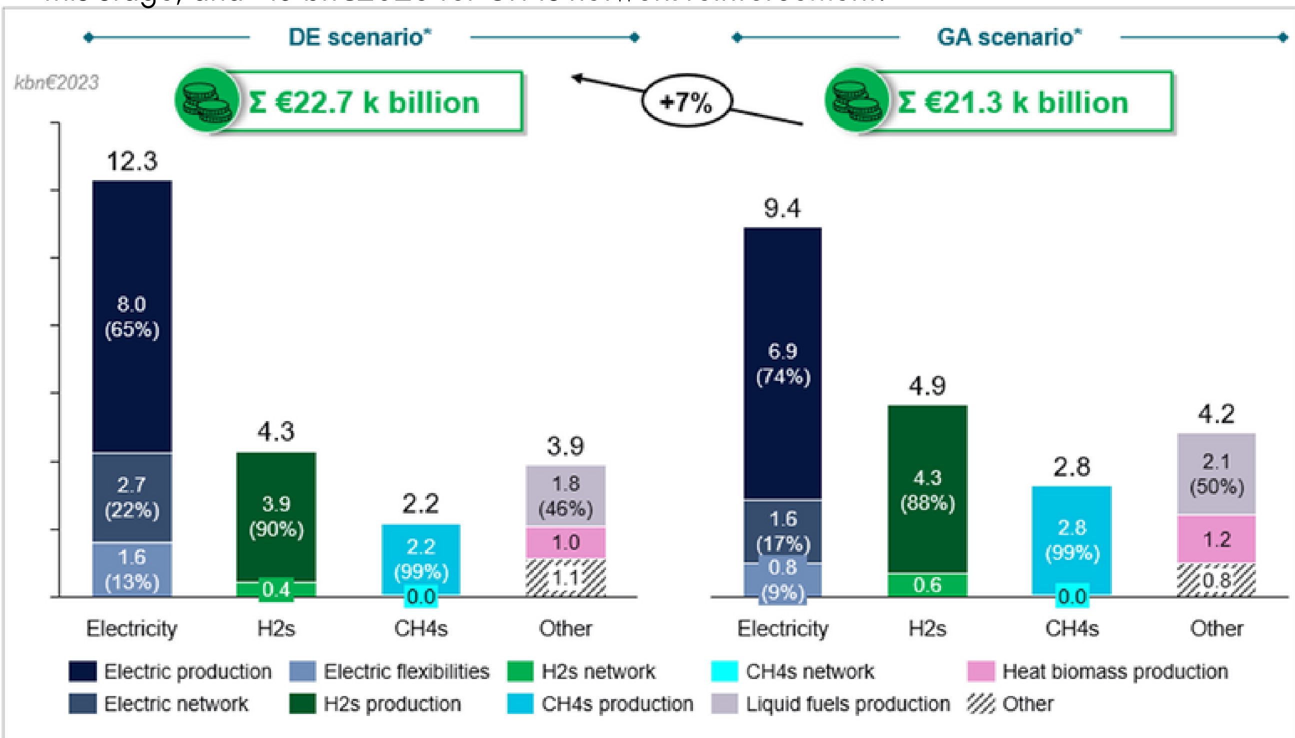

Figure 11 : TOTEX for all energies updated over 30 years for both scenarios at point of delivery, in trillion of €2023

[19] Excluding TOTEX linked to the production of H2

As a result, the total **cost of supply is optimized for all sectors**, averaging -10% in Tertiary and -7% in Industry, boosting **competitiveness and available income** for end-users, with a further impact on the preservation and growth of economic activities, and therefore on jobs and purchasing power of economic players

- An initial additional cost at the point of delivery for all sectors combined of +16% per MWh of energy extracted (+10€/MWh), reduced to +7% on the average complete cost of supply, due to the improved efficiency of electrical equipment and a reduced final energy balance.

- A proven cost premium for each sector, with variations of between +3% and +24% on the average annual complete supply cost and depending on the energy mix consumed, with, for example:

  - +5% on all-energy complete supply costs for an EU standard household (100m2): 671€/year in DE* scenario vs. 639€/year in GA* scenario[20]

  - +7% on all-energy complete supply costs for a small industrial site[21] in EU: €955k/year in DE* scenario vs. €895k/year in GA* scenario

  - +10% on all-energy complete supply costs for a standardized commercial building in EU (570m2): €955k/year in DE* scenario vs. €895k/year in GA* scenario[22]

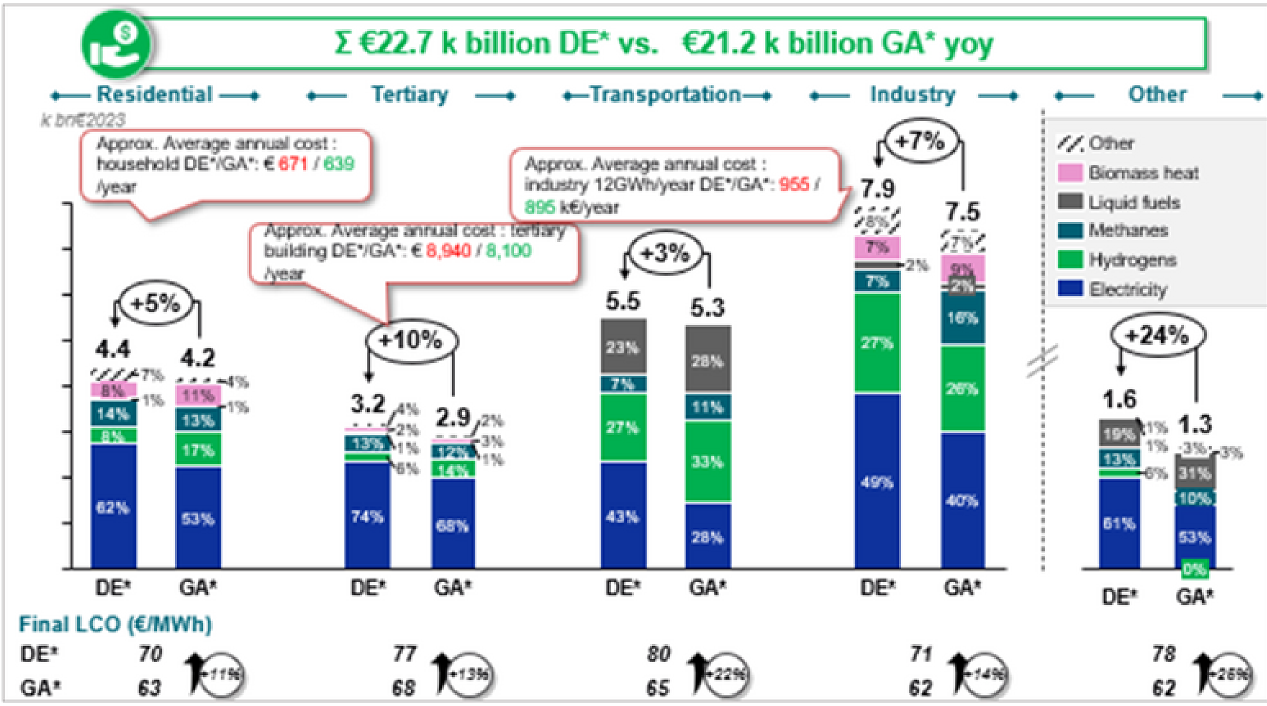

Figure 12 : TOTEX actualised over 30 years broken down by use sectors
for the scenarios DE* and GA*, in trillions €2023([1])

[20] Total residential area EU27: 20 billion m2; Standard residential: 100 m2
[21] On the real example of the energetic consumption a rail wagon manufacturer in France
[22] Total tertiary area EU27: 6.8 billion m2; Average tertiary building: 570 m2
[23] Total residential area EU27: 20 bn m2; Standard residential: 100 m2 and Total tertiary area EU27: 6.8 billion m2; Average tertiary building: 570 m2

Social performance: Complementarities between energies generates improved social value (economic, employment, acceptance to change

Social performance criteria	Unit	DE* 2050	GA* 2050	Comments
Constraints of changing living standards, energy use and behavior	Qualitative	+	+	• **Maintaining the uses and practices of different economic players** " without constraints " with demand satisfied in the 2 scenarios to 2050
Intensity of direct consumption of additional land	M ha	3.5	2.3	• **Increased risk of conflicts of use in the DE* scenario due to greater land consumption in the DE* scenario** DE* scenario (+1.2 Mha), mainly due to greater RES development, particularly PV
Job creation in the new energy system	M years FTE	35.9	36.6	• **+0.7 M FTE years created** in GA* scenario thanks to more permanent operation and maintenance jobs
Permanent jobs	M years FTE	21.6	24.1	• **+12% more permanent jobs** created in GA* due to increased consumption of biomethane and biomass heating, O&M demand
Temporary jobs	M years FTE	14.4	12.5	• **+15% temporary jobs** equipment installation and manufacturing **for the DE* scenario** more CAPEX-intensive (ENR)
Share of system Value Added (VA) generated by activities in the EU	%	61%	62%	• The **majority of investments** to set up the energy system came from **activities in the EU**

Figure 13 : Summary of social performance of the scenarios ([24])

Both scenarios assume that the uses and practices of the various economic players will be maintained "without constraints» and manage to satisfy demand. However, the GA* scenario generates greater social value than the DE* scenario, for several reasons:

- Improved economic performance in GA* reduces the cost of energy for all end-users, improving the population's **purchasing power**
- A bigger part of the **value creation** could potentially be retained in the local or European territory during construction due to the provenance of RES equipment and reduced budget of green gas import to manage intermittency over the years
- GA* strengthens **permanent jobs creation** with +12% FTEs created in comparison with DE*, thus sustaining local jobs over the long run and limiting negative externalities from non-permanent job creations waves (intense workforce recruitment, training, mobilization and post-wave reallocations complexities across industrial chains)
- GA* puts less constraints on assumed **changes in behavior** of energy consumers, related to substitution in equipment or energy sources and changes in consumption patterns (electric mobility charging, “V2G” pools, massive electrification of homes, …)
- GA* puts less constraints on social acceptability of local environment disturbances: **landscape changes, strong changes in land allocation structures, noise pollution**

[24] Performance criteria definition in Appendix 12

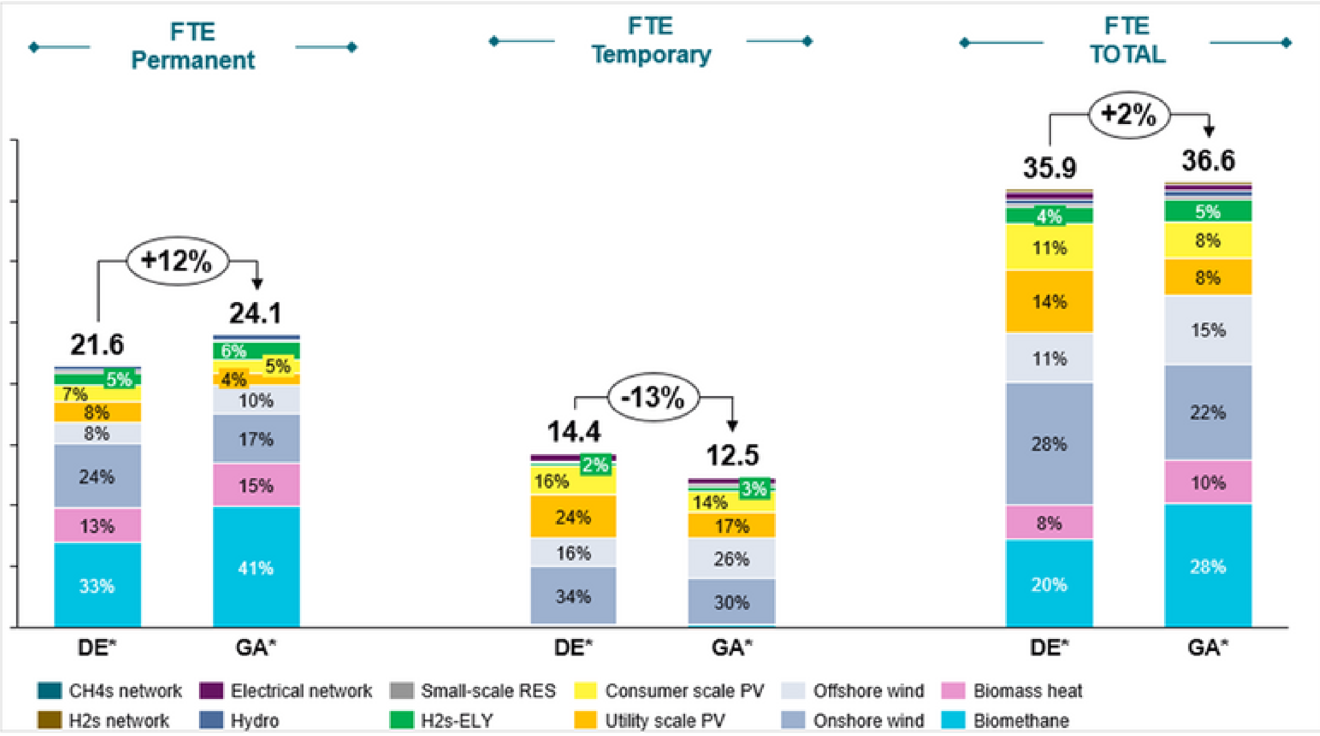

Figure 14 : Jobs created by technological sector for the implementation and operation of the system over 30 years, in millions of full-time equivalent (FTE) years

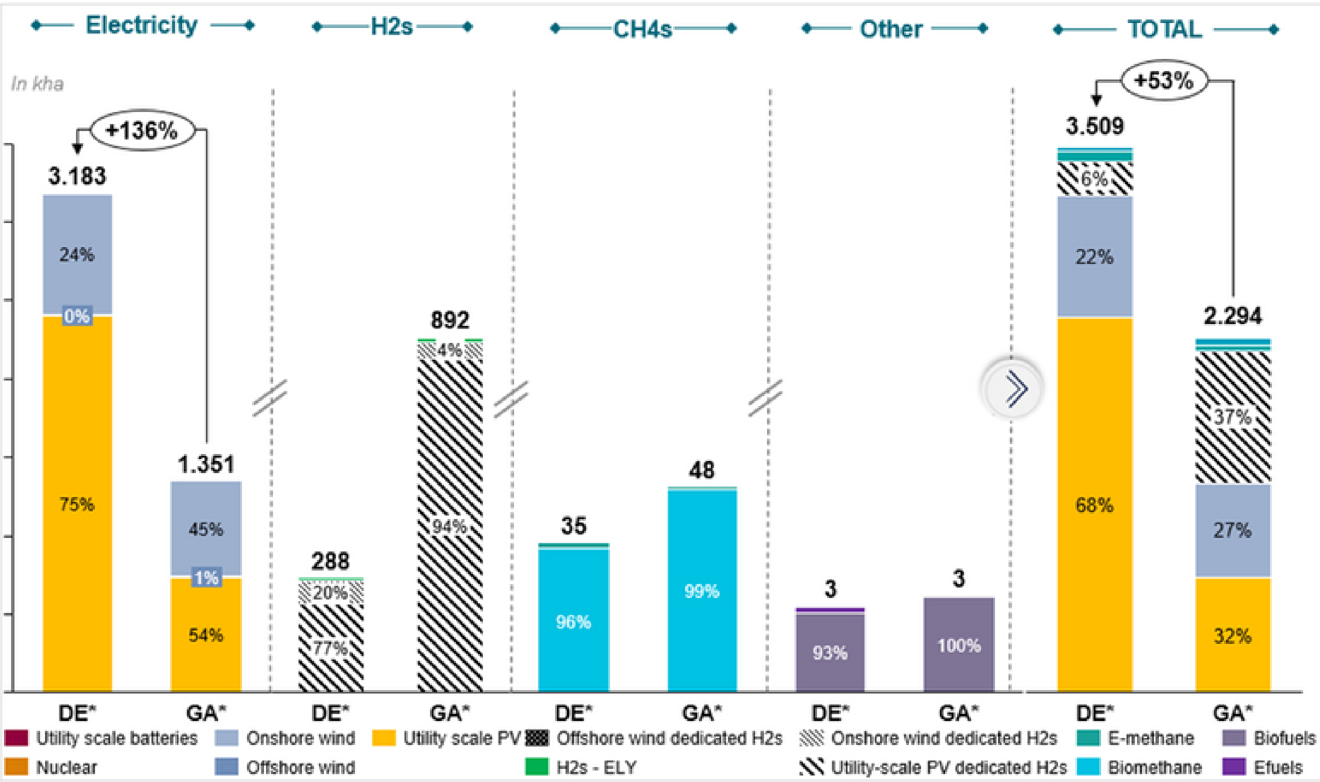

Figure 15 : Direct land pressure by technology in the DE* and GA* scenarios to 2050, in kha

[24] Performance criteria definition in Appendix 12

Ecological and environmental performance: Carbon neutrality is achieved by 2050 for both scenarios, with a reduced land footprint and increased value for the agrarian system in the GA* scenario

Eco/env. performance criteria.	Unit	Base	DE* 2050	GA* 2050	Comments
GHG scope 1 assessment and performance	MtCO2e q./year	*4 474*	0	0	• Scenarios designed to achieve **neutrality by 2050.** Potential to go further by integrating CCS and DAC capabilities (not integrated)
GHG assessment and performance in LCA	MtCO2e q./year	*n / A.*	365	360	• **+1% GHG emissions in the DE** scenario in LCA accounting, due to the increased installation of renewable energy capacities with degraded productivity. **Challenge for renewable energies in terms of decarbonization,** particularly PV, mainly sourced outside the EU
Additional land consumption	MHa	-	3.5	2.3	• **+53% direct land pressure** mainly due to the greater development of renewable energies, particularly PV, in the DE scenario
Other externalities / synergies	Qualitative	-	+	++	• Strong growth in **biomethane** (+40% production in the sc. GA*), with a **positive impact on the agrarian system** (soil stability, organic fertilizers, etc.)

Figure 16 : Summary of the ecological and environmental performance of the scenarios[25]

Both scenarios are in **line with the Paris Agreement, achieving carbon neutrality** in scope 1 by 2050 (excluding the additional potential of CCS and DAC, enabling a negative annual balance)

- In full LCA, both scenarios remain comparable, with disparities depending on the energy carriers (See Appendix 15) The higher DE* emissions in the electricity system (notably due to CCGTs and PV) and the production of market-sourced H2 are offset in the GA* scenario by the greater development of dedicated RES (notably PV), biomethane production and increased use of liquid fuels

The increased installation of RES capacities (grid injection and dedicated renewable energy electrolysis) in the DE* scenario (+25% vs. GA* scenario) degrades its ecological and environmental performance:

- **Land usage** is strongly reduced compared to the power-centric (more PV-intense) system, which consumes +53% more land by 2050, or +1.2 M ha (2.3 vs. 3.5 M ha), in competition with other activities and with increased risk of destruction of carbon 'sinks' or other negative externalities (landscape impacts, noise pollution, etc.)

- Furthermore, massive biomethane domestic production (+40% domestic production), from intermediate energy crops for instance, will positively impact the **EU agricultural ecosystem and support its transition**: soil stability and protection, organic fertilizers production, waste management

[25] Performance criteria definition in Appendix 14

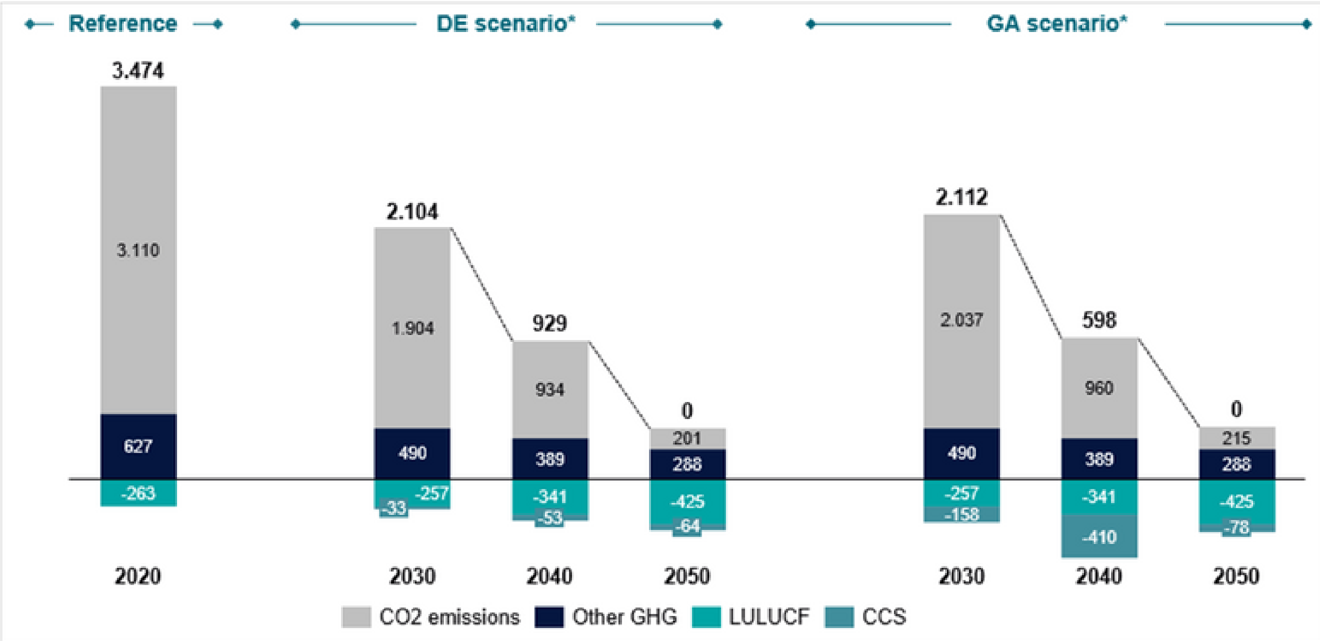

Figure 17 : Scope 1 greenhouse gas emissions x scenarios – in Mt CO2eq/year([26],[27])

[26] TYNDP's version of GA* scenario reaches a negative carbon balance (-584 MtCO2eq.) due to additional CCS capacities combined with biomethane burning industrial facilities. This was not integrated here to maintain homogeneity between scenarios
[27] Scope 1 emissions, on European soil (based on primary energy used)

Additional risk as a direct consequence of scenario performance - Increased risks arise in the implementation and operation of the energy system in DE*, linked to degraded technical, economic and social performance.

Technical risks		
System implementation	**Stress on the deployment of the infrastructures,** especially the power ones	• **Industrial ramp-up risks and challenges** in simultaneously carrying out projects of unprecedented scope, and timely availability of a trained workforce in investment sectors (especially for temporary jobs)
	Stress on component supply (especially imports beyond EU)	• **Increased pressure on the supply chain and prices of materials** essential to the production of batteries (cobalt, lithium, etc.) and wind turbines (rare-earth elements) for instance, requiring critical efforts in sourcing security, equipment design, recovery and recycling processes
System operation	**System resilience**	• **More exposed to intermittent RES** with high daily variability, and therefore to climatic risks • **Less leveraging of decarbonized gas infrastructures** (H2s and CH4s), with seasonal flexibility (long-term storable energy carriers)
	Technical demonstration of solutions	• Relying on **power-centric technologies not deployed at scale** today with strong assumptions: V2G techno and behaviors, heavy transport electrification (aviation, maritime, heavy duty mobility solutions)
Economical risks		
System implementation	**Stress on the financing of the infrastructures,** especially the power ones	• Ability **to finance this extra effort** ('CAPEX investment wall'): need for public funds, difficulty in raising private funds if other risks are not reduced, etc.
System operation	**Electricity wholesale market price volatility**	• **System balancing and dominance of intermittent RES** leading to **greater variation and hence volatility in electricity market prices,** making it more difficult to control value for stakeholders.
	Competitiveness of the industry	• **Deteriorating competitiveness of industries**, impacting on the preservation (risk of relocation) and growth of economic activities, and therefore on employment and purchasing power
Social risks		
System operation	**Limited social acceptability**	• **Risk of social unrest** due to limited acceptability (land footprint, nuisance, impacts on biodiversity, energy price volatility / level, and reduced purchasing power, etc.).

[26] TYNDP's version of GA* scenario reaches a negative carbon balance (-584 MtCO2eq.) due to additional CCS capacities combined with biomethane burning industrial facilities. This was not integrated here to maintain homogeneity between scenarios
[27] Scope 1 emissions, on European soil (based on primary energy used)

Conclusion – A system that better leverages complementarities between energies (power, decarbonized gases and fuels) provides significant economic as well as non-economic benefits, and calls for policy actions

Based on the two technical systems comparison, energies complementarity provides clear advantages to the EU Communities, not only technical (system resilience…) and economical (CAPEX and TOTEX reduction…), but also social (permanent jobs…), environmental (land preservation…), and related to risks (industrial risk management and complexity of execution).

Collaborating at EU level to reconsider improved energies equilibrium and optimal mixes for energy transition is recommended, to avoid putting too much pressure on the power system with negative impact. This would call for several specific actions:

- EU energy system strategic planification, based on detailed and neutral techno-economic modelling, and results appropriation by political stakeholders

- Definition of clear quantified objectives, and optimal target mix of energies (from usages to primary energy production and imports): maintaining an optimal share of decarbonized gases and fuels usages that can be greenified (heavy transport, industrial and domestic heat, etc.)

- Support in securing strategic renewable gas energy sources, especially for biogas production scale-up, which appears as a critical lever to reach these improved equilibriums

- Collaboration in the development of mass-scale green H2 system design and construction, favoring optimal RES designs, dedicated H2 transmission networks, and centralized H2 storage

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Contacts :

CVA : robin.eline@corporate-value.com
matthieu.crest@corporate-value.com

Confrontations Europe : bhallouet@confrontations.org

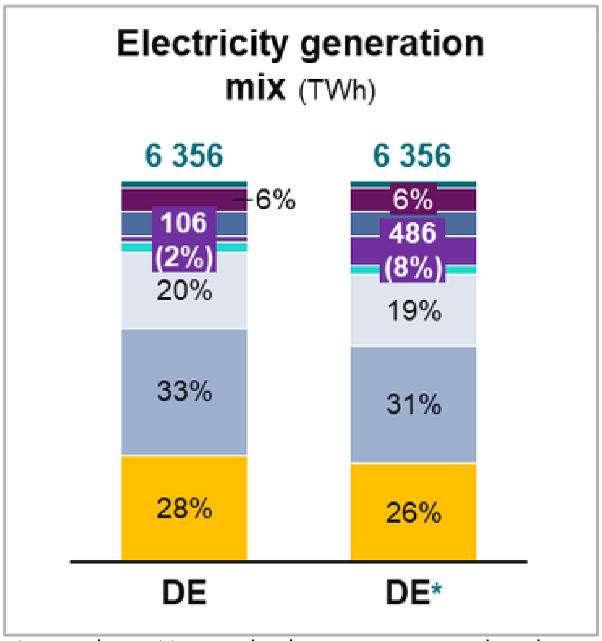
Appendices

Marginal adjustments on nuclear base integrated to DE* scenario to ensure a balanced comparison 'all other things being equal'

- **Critical review of TYNDP's DE scenario in light of the objective of the study carried out**: near-disappearance of the nuclear share in the DE scenario, activating possibly unjustified recourse to new RES capacities (unjustified imbalance between scenarios)

- **Principle of adjustment:** maintaining a significant proportion of nuclear power in the mix, to limit RES constraints on the energy system (power grid, flex, land).

- **Approach and assumptions used to adjust the DE scenario:** Balance the installed nuclear base at the same level as the GA scenario by replacing new RES capacities (at pro-rata by TWh) in order to re-establish a symmetrical balance between the scenarios



Appendix 1 : Marginal adjustments on nuclear base integrated to DE* scenario

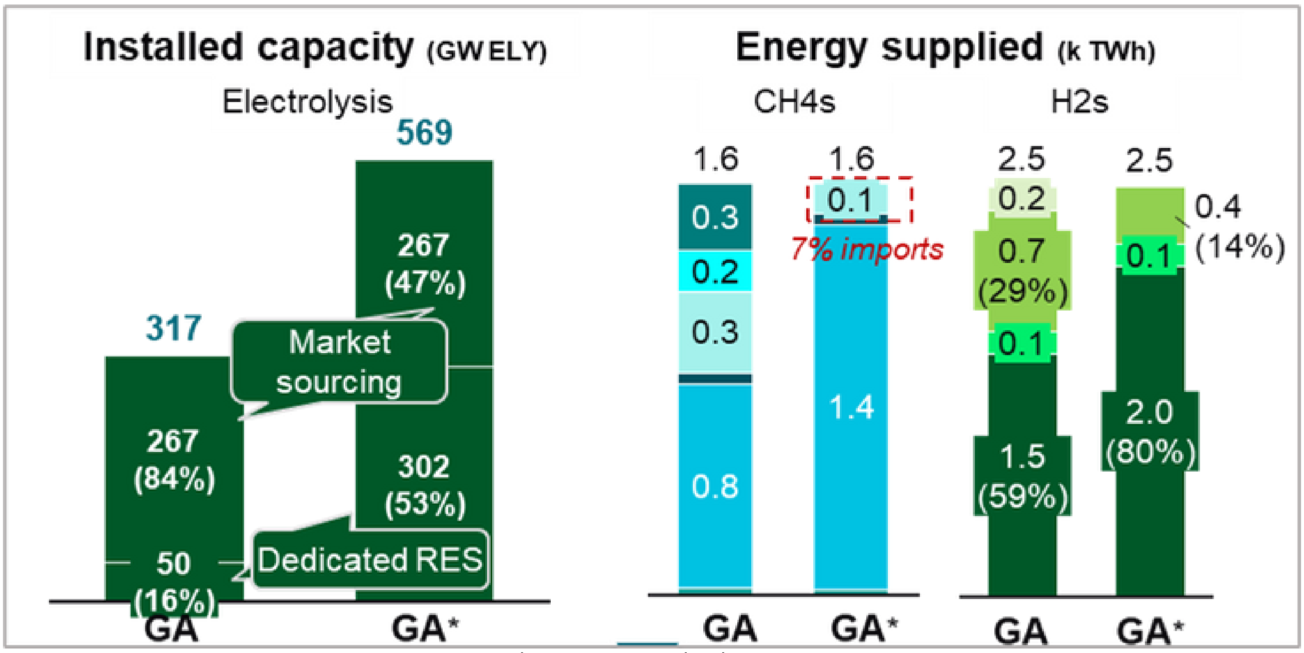
- **Technical impact on the electricity generation mix** in the adjusted scenario DE* compared to initial DE scenario from TYNDP:
    - **Nuclear base adjustment from 19 TW to 86 TW** of capacity installed in 2050 (same as GA)
    - **Increase from 106 TWh of electricity produced** from nuclear installation (2% of total electricity generated) to **486 TWh** in the adjusted scenario DE* (8% of total electricity generated)

Marginal adjustments on decarbonated gas imports integrated to GA* scenario to ensure a balanced comparison 'all other things being equal'

- **Critical review of TYNDP's DE scenario in light of the objective of the study carried out:** Low share of domestic green gas in the GA scenario (TYNDP), which activates possibly unjustified recourse to green gas imports (cheaper source)

- **Principle of adjustment:** Stronger mobilization of domestic sources of biomethane, electrolysis and H2 capacity (with dedicated ENR supply: off-grid)

- **Approach and assumptions used to adjust the DE scenario:**
  - **Biomethane production potential in EU 27 by 2050 of 1400 TWh**[28], ie +600 TWh increase compared to initial GA scenario (TYNDP)
  - **Balance the need for H2 imports between the two scenarios**, by reducing the volume imported in the GA scenario to the level of imports in the DE scenario, and managing domestic production through dedicated RES (PV



Appendix 2 : Marginal adjustments on decarbonated gas imports integrated to GA* scenario

Hydrogène décarbonné importé | Hydrogène bleu (SMR + CCS) | Imported natural gas | Imported e-methane | Domestic biomethane | Hydrogène vert importé | P2G (électrolyse) UE | Imported biomethane | Domestic Natural gas | Domestic e-methane

[28] ENGIE (2021), Geographical analysis of biomethane potential and costs in Europe in 2050

- **Technical impact on the gas energy supplied** in the adjusted scenario GA* compared to initial scenario from TYNDP:
  - **+600 TWh of domestic biomethane production,** substituting imported natural gas and biomethane
  - **+0.5 kTWh of domestic green H2 production** (P2G through electrolysis with 33% load factor), from dedicated RES, thus increasing the electrolysis installed capacity connected to dedicated RES from 50 to 302 GW and the total capacity from 317 to 569 GW

TECHNICAL ANALYSIS OF THE SCENARIOS STUDIED

	Types of levers considered	Sub-levers	Sector	Energy vector impacted	Quantitative elements
Passive EE levers	Thermal insulation of buildings (attic, walls, windows...)	Reduction of heat losses, and therefore energy needs (eg heating, air conditioning)	Residential, tertiary and industrial	All (electricity, methane, biomass...)	• N/A
Passive EE levers	Replacement of generation systems (boilers, heat pump, LEDs, hot / cold networks, household appliances)	Increased energy efficiency of generators/consumers, and therefore decreased energy consumption	Residential, tertiary	Mainly electricity	• ~50% of individual dwellings equipped with electric and hybrid heat pumps in 2050 in the DE scenario vs. 10% in the counterfactual scenario • From ~10% share of district heating in EU27 to ~20-25% in 2050 in the DE* scenario
Passive EE levers	EE processes in industry (boilers, variable speed motors, equipment with better efficiency)	Increased energy efficiency of industrial processes (new generation technology, electrification / motorization, ...)	Industrial	All (electricity, methane, biomass...)	• +1% energy efficiency in industry per year (source: TYNDP report authors)
Passive EE levers	Replacement of consumer equipment and energy change	Equipment replacement and greening of energy carriers (e.g. ICE→ EV)	Residential, tertiary	All (electricity, methane, biomass...)	• More than 75% of passenger cars and heavy-duty vehicles with combustion engines (ICE) in 2030 (DE scenario) vs 1-2% for passenger cars and 2-10% for heavy-duty vehicles in 2050
Active EE levers	"Smart" residential and industrial equipment, energy management and sobriety	Decrease in use (sobriety), change in behaviour (e.g. public transport), and development of self-consumption	Residential, tertiary and industrial	All (electricity, methane, biomass...)	• 399 GW (DE) of rooftop PV by 2050
Active EE levers		Reduction of demand with unchanged load curve – by access to consumption data, equipment control and consumption management (light intensity, heating control)	Residential, tertiary and industrial	All (electricity, methane, biomass...)	• N/A
Leviers CoP	Equipment of end sites with energy management solutions - reduction of power requirements	• Peak shedding (behavior modification, home automation, demand-response) • Self-consumption (PV roof) • Prosumer with storage (residential battery, V2G)	Residential and industrial	Electricity	• 32 TWh (GA) of residential batteries by 2050 • 144 TWh (GA) of V2G service to 2050

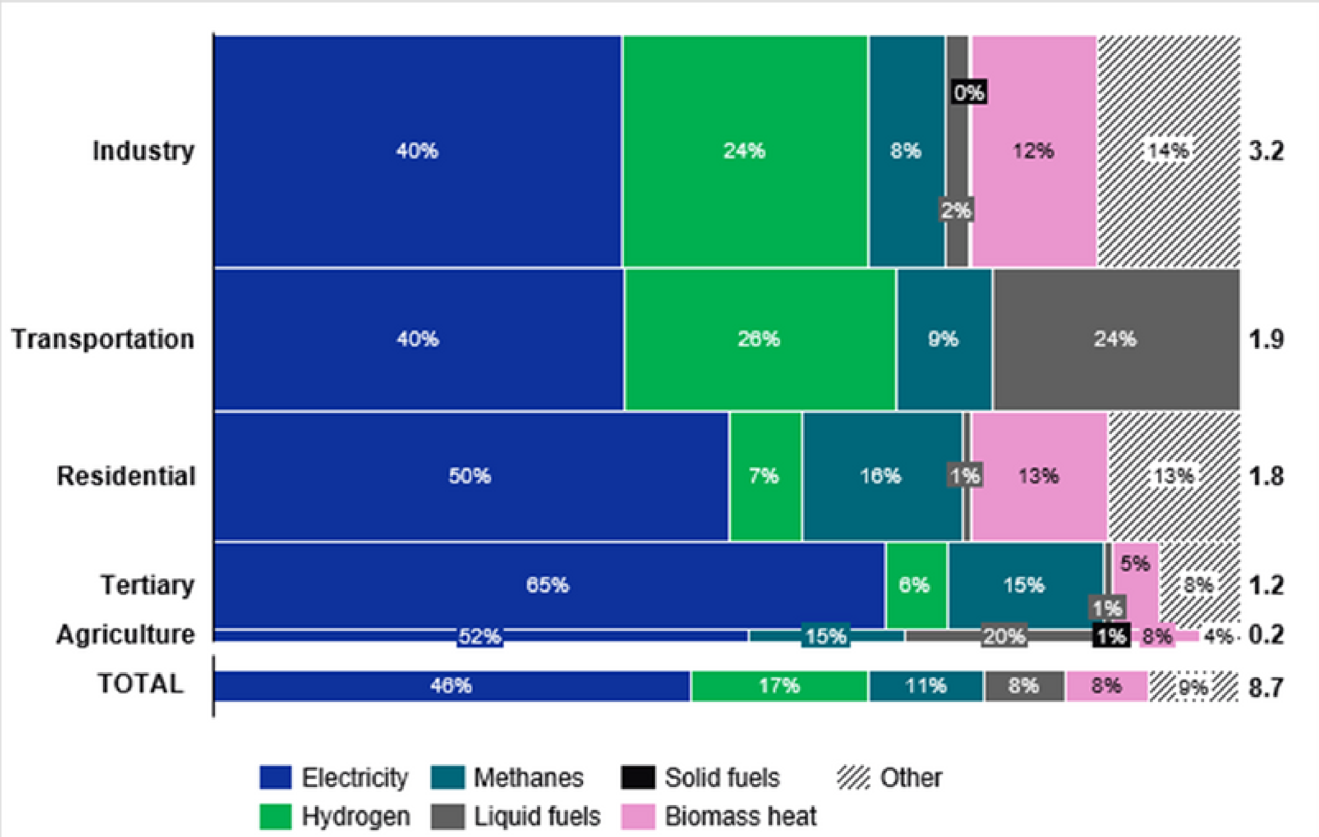
Passive EE levers — Active EE levers — Control of power levers

Appendix 3 : Energy efficiency levers used in scenario DE in 2050

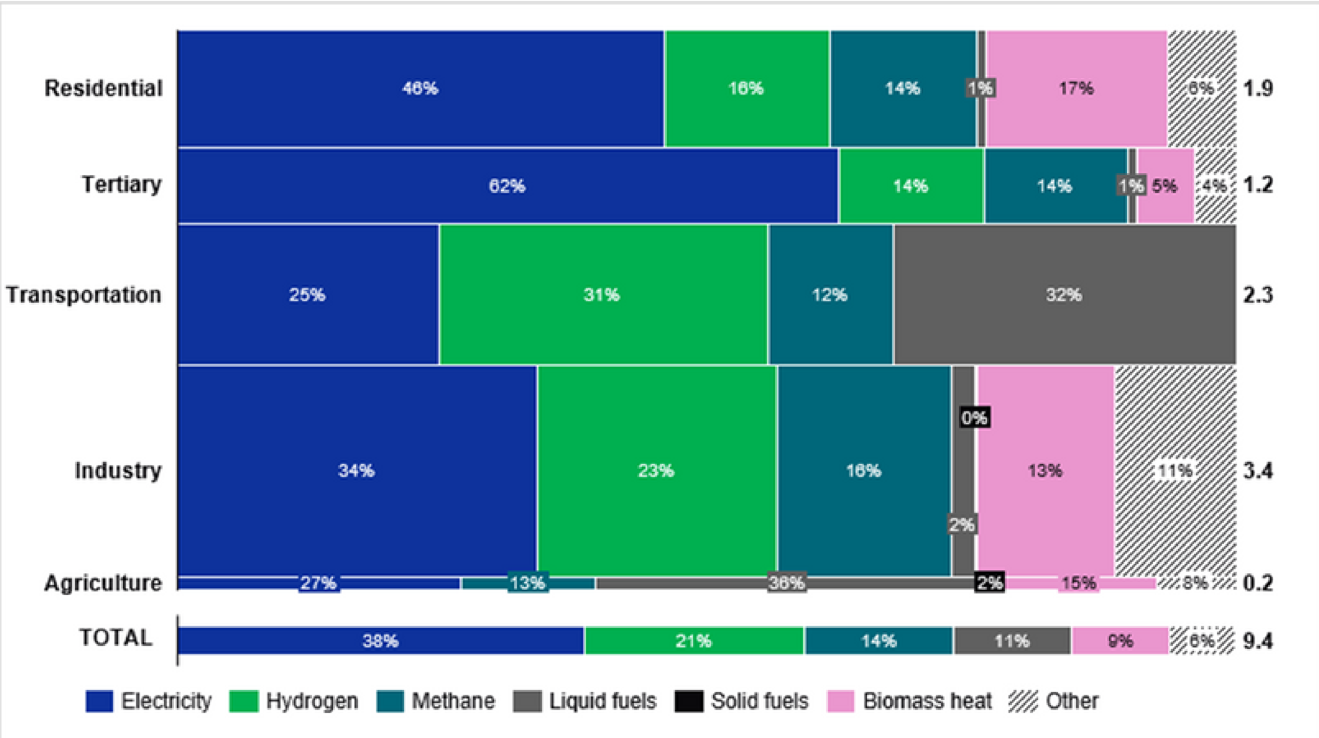
	Types of levers considered	Sub-levers	Sector	Energy vector impacted	Quantitative elements
Passive EE levers	Thermal insulation of buildings (attic, walls, windows...)	Reduction of heat losses, and therefore energy needs (eg heating, air conditioning)	Residential, tertiary and industrial	All (electricity, methane, biomass...)	• N/A
Passive EE levers	Replacement of generation systems (boilers, heat pump, LEDs, hot / cold networks, household appliances)	Increased energy efficiency of generators/consumers, and therefore decreased energy consumption	Residential, tertiary	Mainly electricity	• ~50% of individual dwellings equipped with electric and hybrid heat pumps in 2050 in the DE scenario vs. 10% in the counterfactual scenario • From ~10% share of district heating in EU27 to ~20-25% in 2050 in the DE* scenario
Passive EE levers	EE processes in industry (boilers, variable speed motors, equipment with better efficiency)	Increased energy efficiency of industrial processes (new generation technology, electrification / motorization, ...)	Industrial	All (electricity, methane, biomass...)	• +1% energy efficiency in industry per year (source: TYNDP report authors)
Passive EE levers	Replacement of consumer equipment and energy change	Equipment replacement and greening of energy carriers (e.g. ICE→ EV)	Residential, tertiary	All (electricity, methane, biomass...)	• More than 75% of passenger cars and heavy-duty vehicles with combustion engines (ICE) in 2030 (DE scenario) vs 1-2% for passenger cars and 2-10% for heavy-duty vehicles in 2050
Active EE levers	"Smart" residential and industrial equipment, energy management and sobriety	Decrease in use (sobriety), change in behaviour (e.g. public transport), and development of self-consumption	Residential, tertiary and industrial	All (electricity, methane, biomass...)	• 399 GW (DE) of rooftop PV by 2050
Active EE levers		Reduction of demand with unchanged load curve – by access to consumption data, equipment control and consumption management (light intensity, heating control)	Residential, tertiary and industrial	All (electricity, methane, biomass...)	• N/A
Leviers CoP	Equipment of end sites with energy management solutions - reduction of power requirements	• Peak shedding (behavior modification, home automation, demand-response) • Self-consumption (PV roof) • Prosumer with storage (residential battery, V2G)	Residential and industrial	Electricity	• 32 TWh (GA) of residential batteries by 2050 • 144 TWh (GA) of V2G service to 2050

Passive EE levers — Active EE levers — Control of power levers

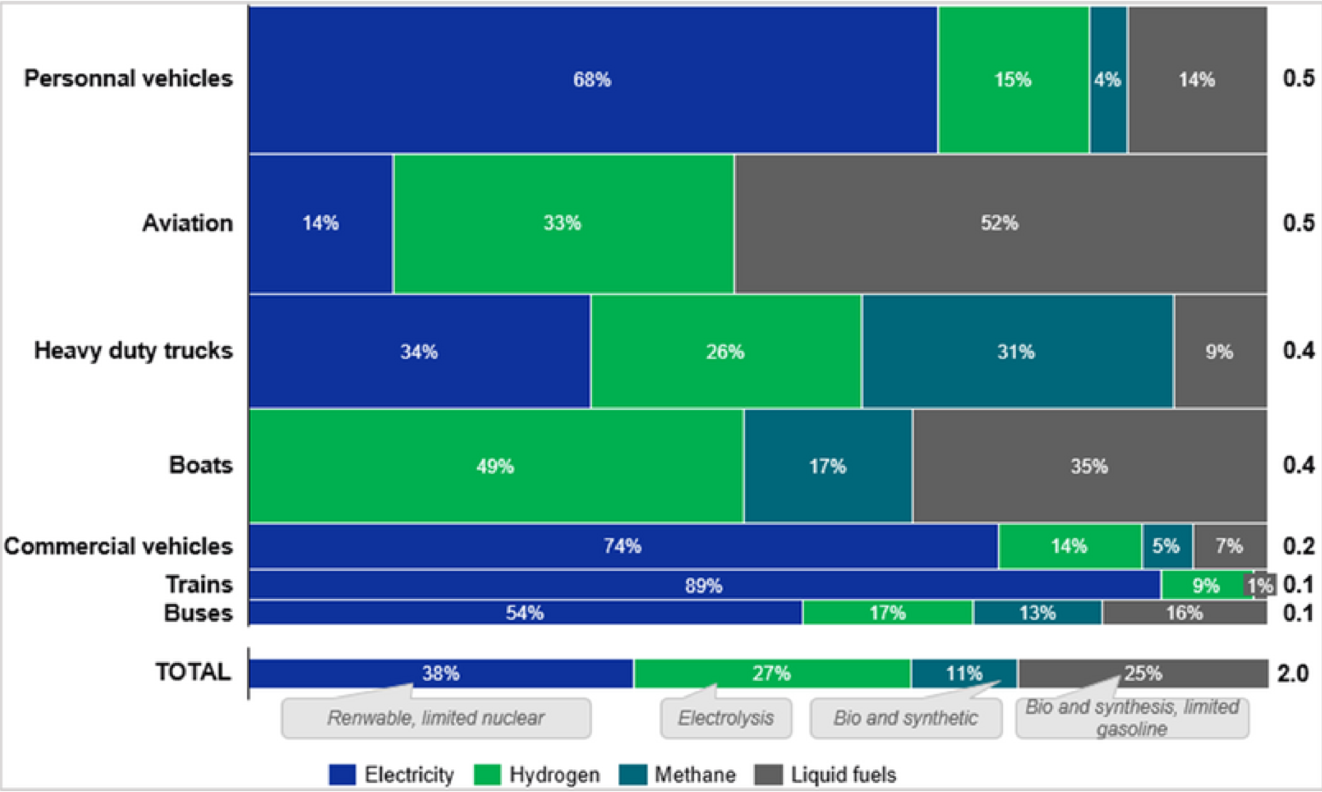
Appendix 4: Energy efficiency levers used in scenario GA in 2050



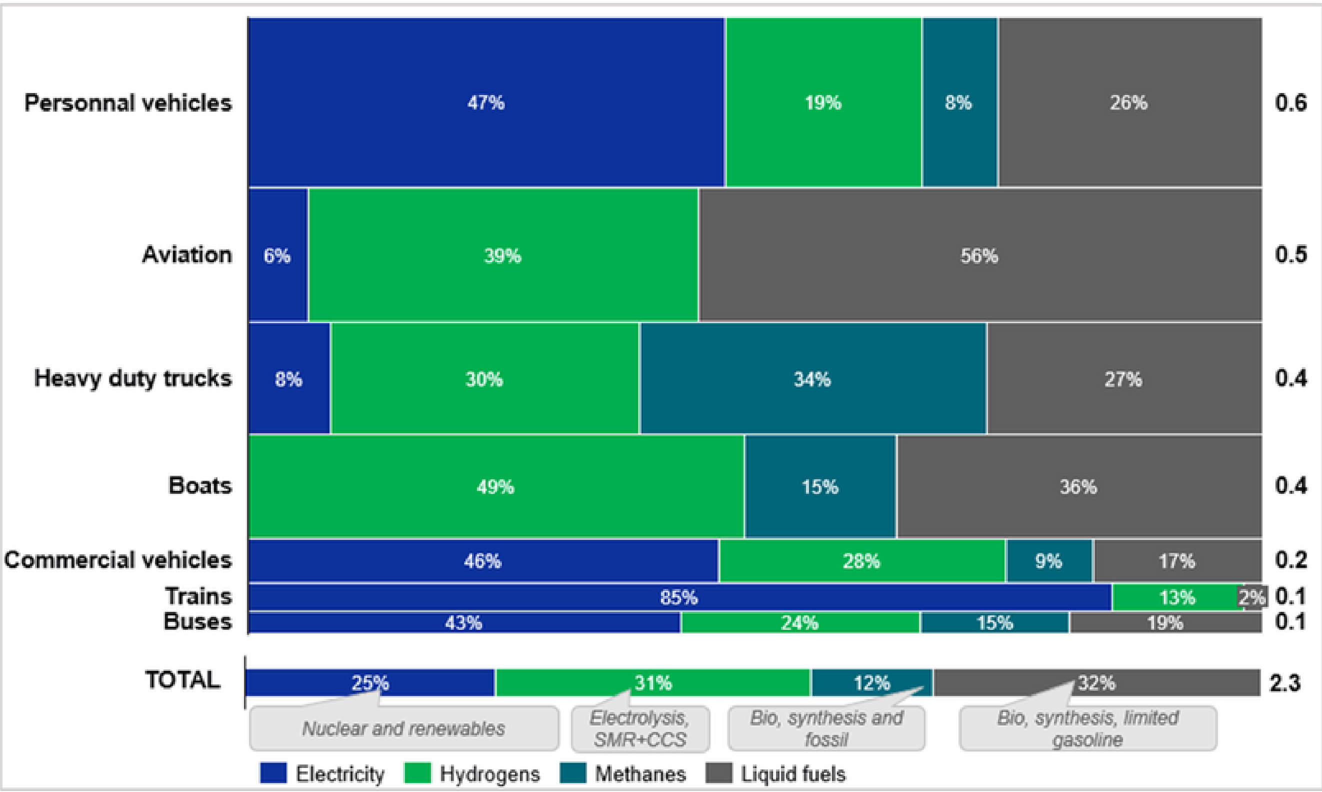
Appendix 5: Final use of energy by sectors x energy vectors, scenario DE*,
in thousands of TWh/year in 2050



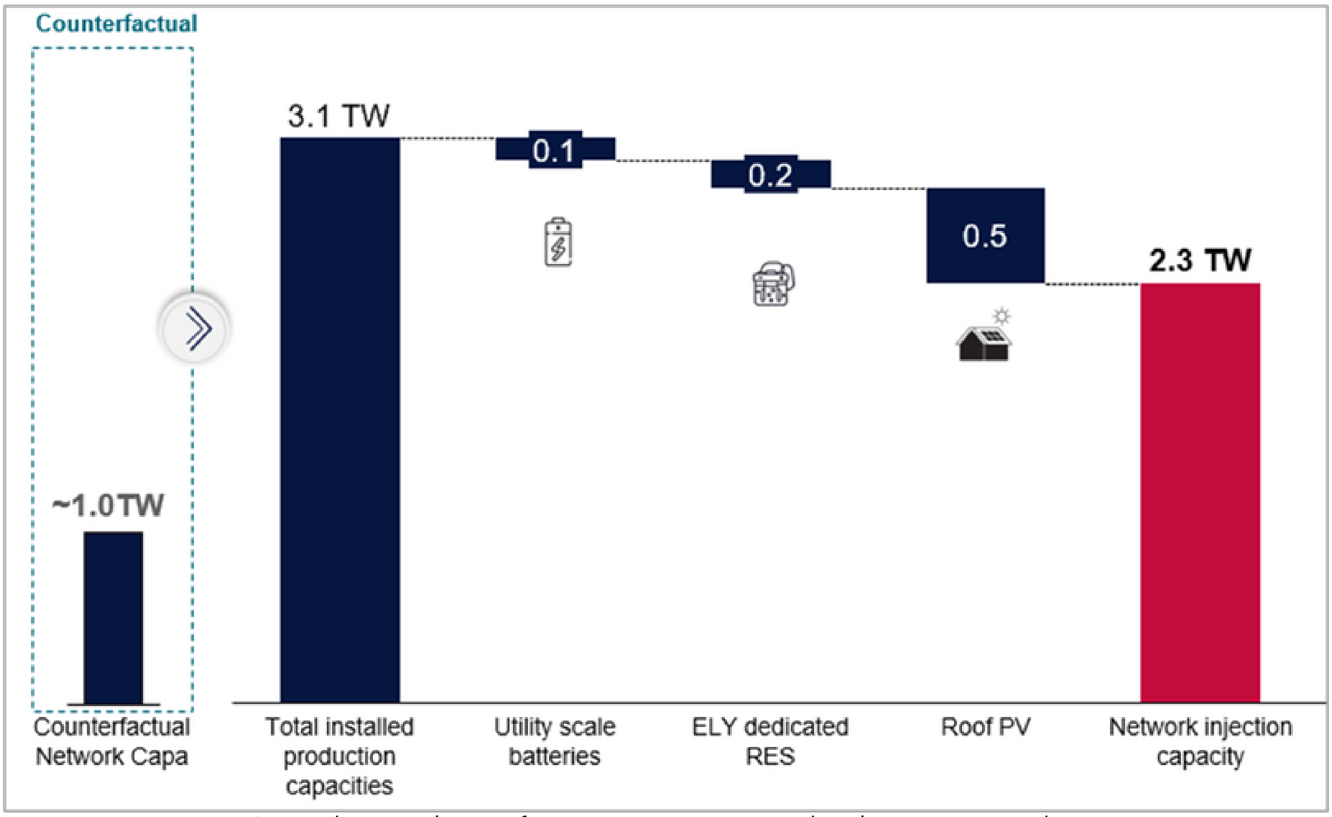
Appendix 6: Final use of energy by sectors x energy vectors, scenario GA*
in thousands of TWh/year in 2050



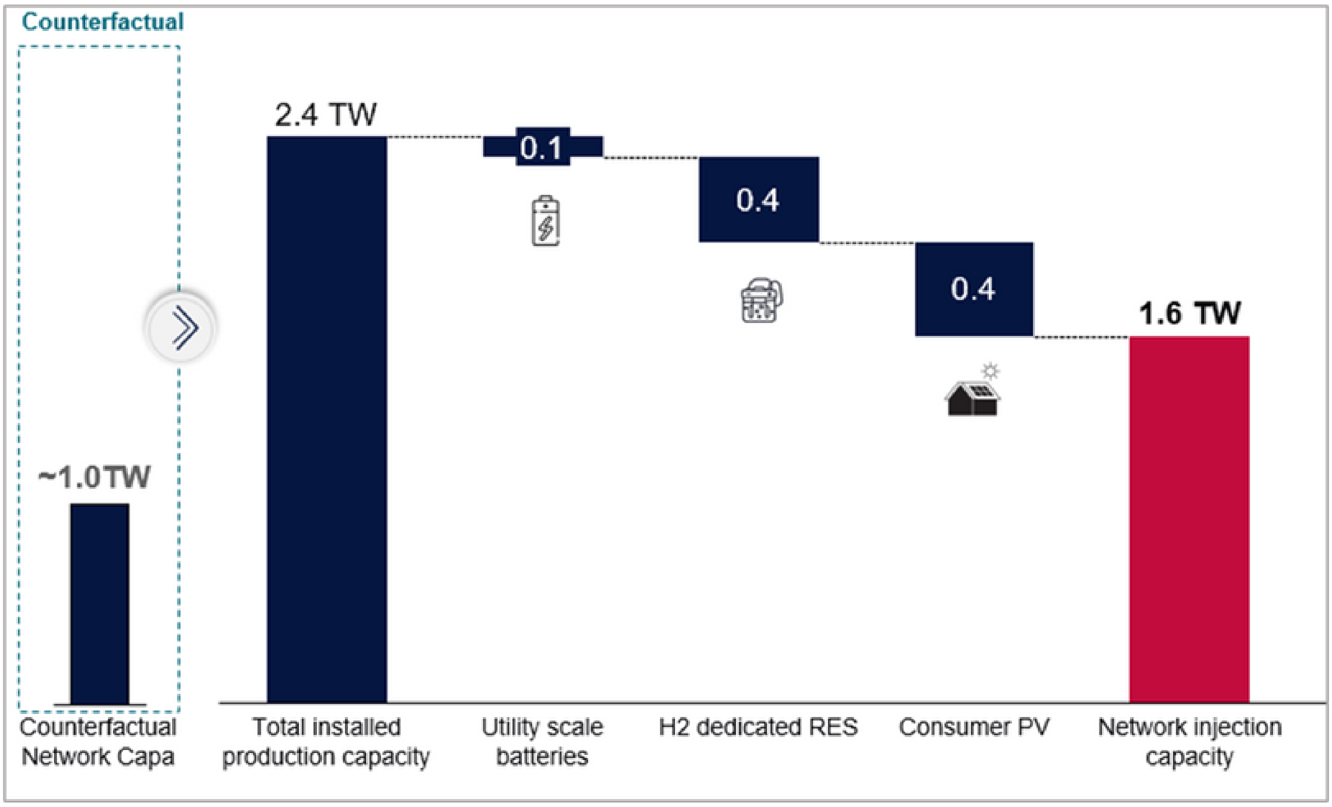
Appendix 7 : Transport types x energy carriers, scenario DE*, in thousands of TWh/year at 2050



Appendix 8 : Transport types x energy carriers, scenario GA*, in thousands of TWh/year at 2050

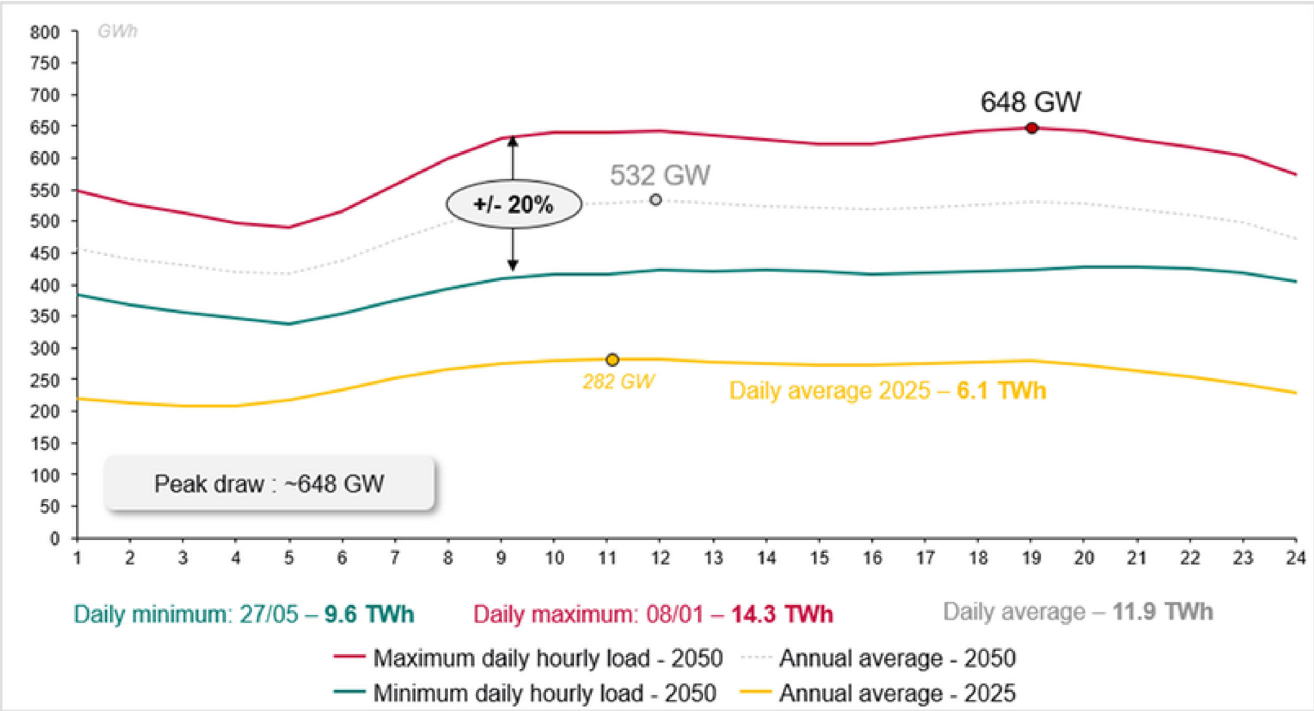


Appendix 9: Evolution of injection capacities on the electricity network in 2050 for DE*, in TW([29],[30])

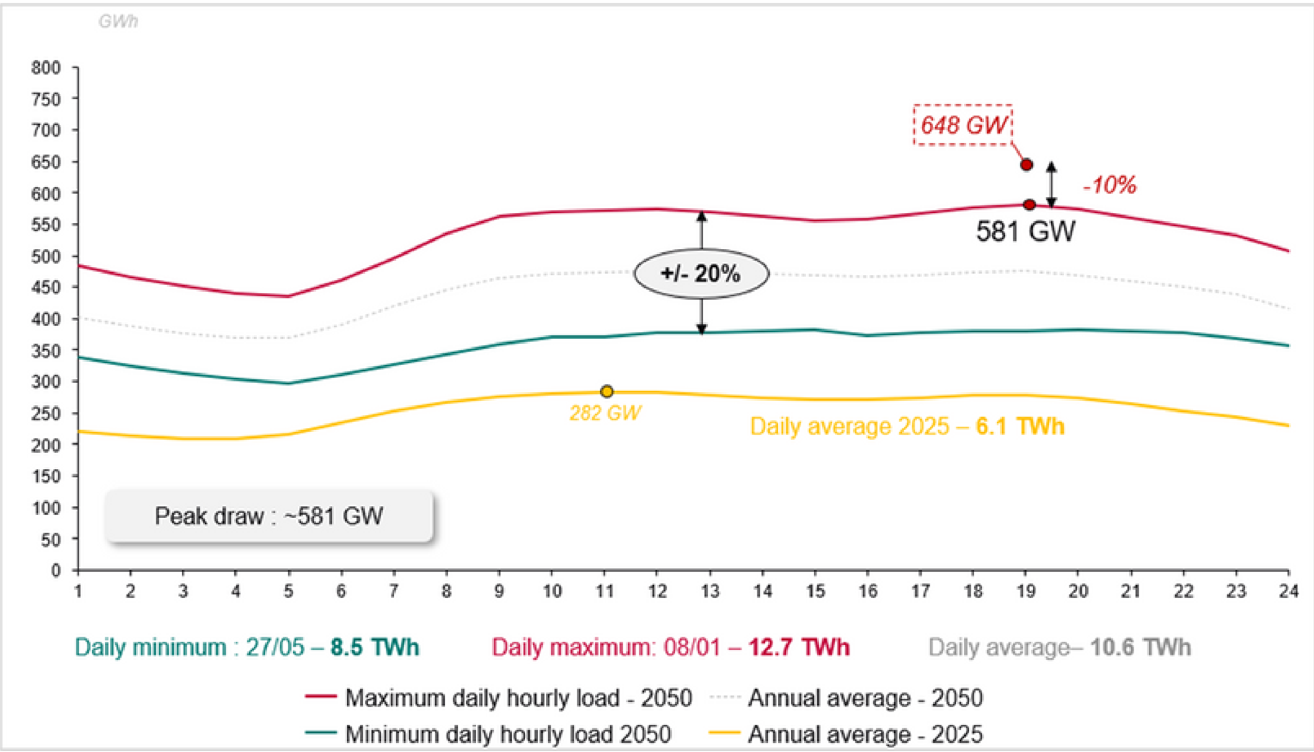


Appendix 10: Evolution of injection capacities on the electricity network in 2050 for GA*, in TW

[29] Counterfactual scenario in 2025
[30] Actual injection capacity = total production capacity-Roof PV – H2 dedicated ENR – Batteries

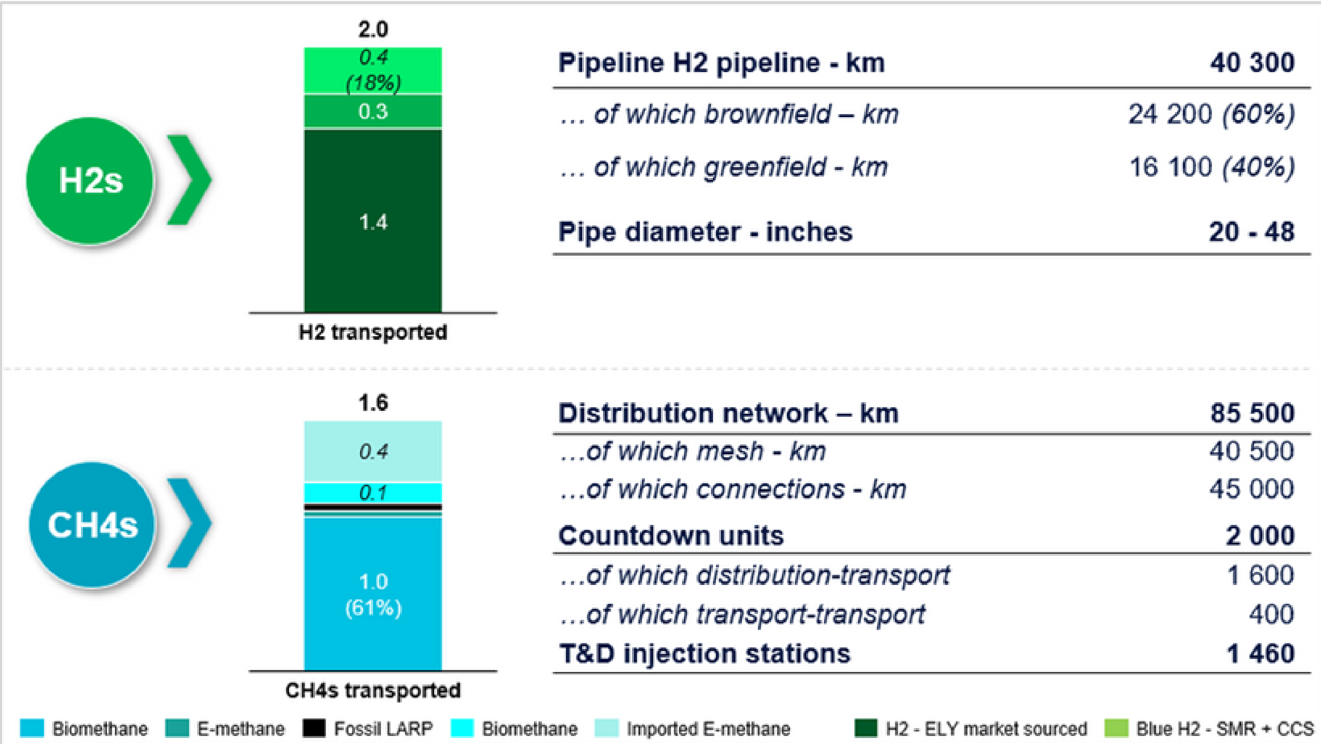


Appendix 11: Load curve of final hourly electricity consumption for scenario DE*, max and min over 24 hours – in GWh in 2050[31]

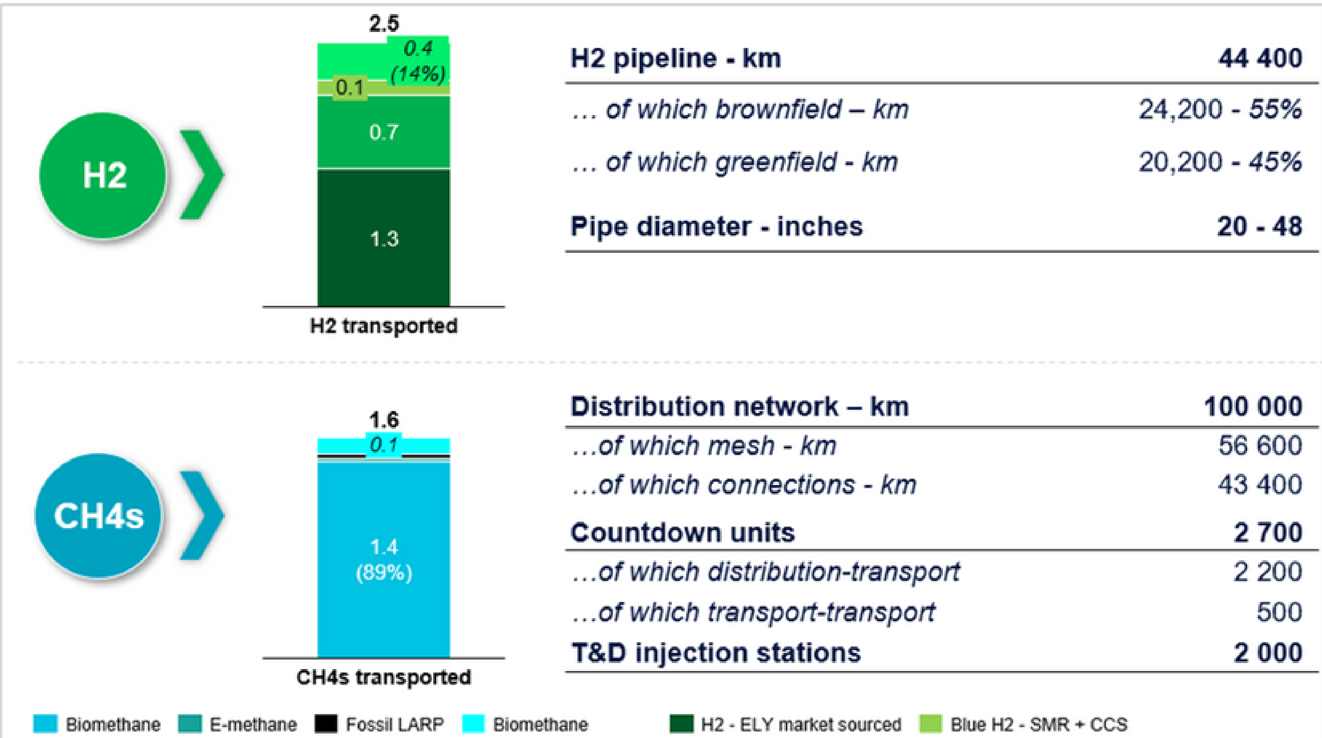


Appendix 12: Load curve of final hourly electricity consumption for scenario GA*, max and min over 24 hours – in GWh in 2050

[31] Load curve includes V2G but not electricity dedicated to H2 production (P2G)

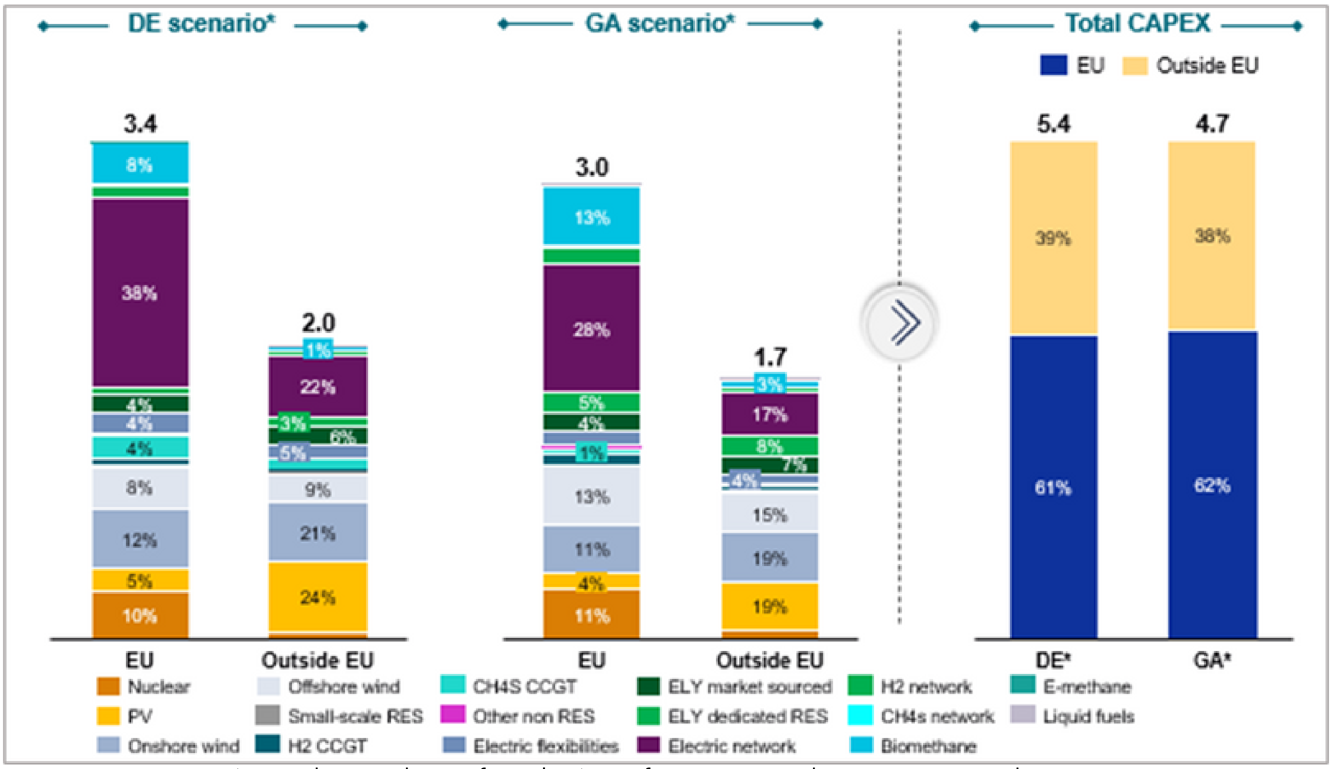


Appendix 13: H2 and CH4s network extensions necessary in scenario DE* to meet the needs of the energetic system ([32],[33],[34],[35])

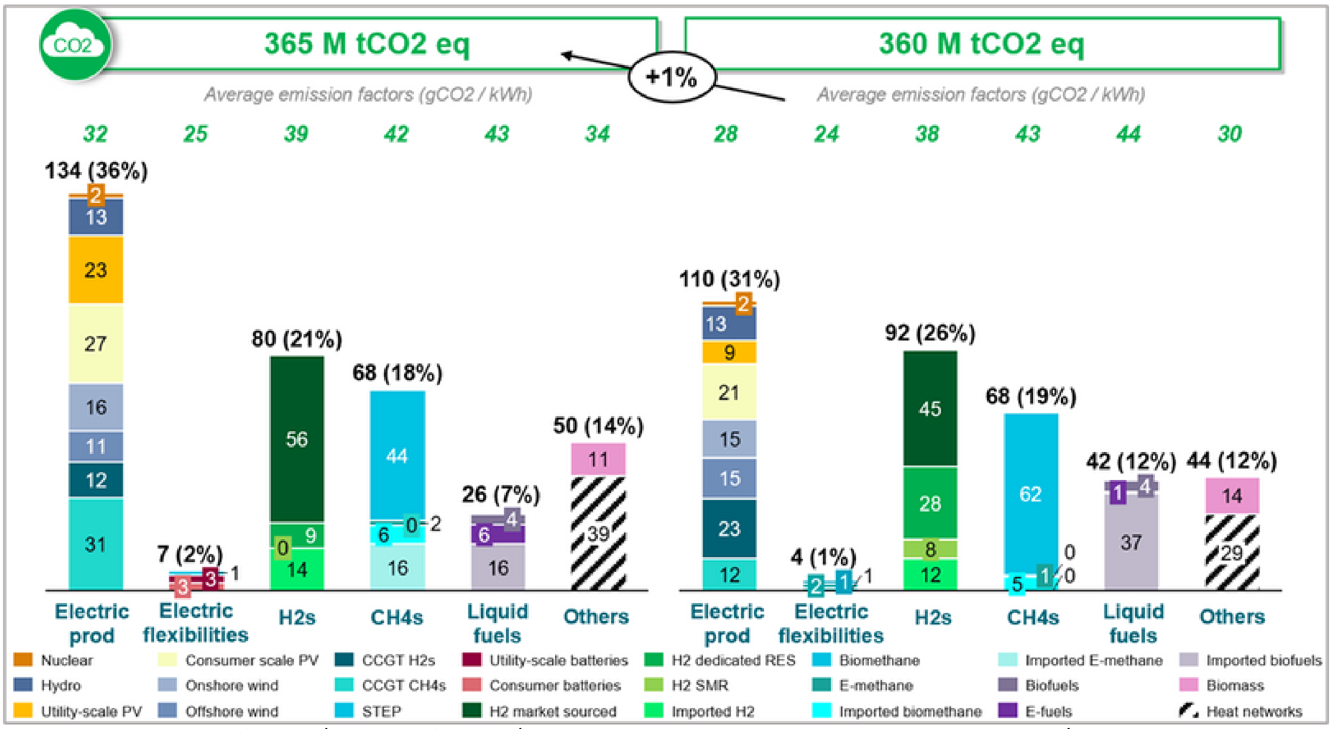


Appendix 14: H2 and CH4s network extensions necessary in scenario GA* to meet the needs of the energetic system

[32] Energy transported = before losses
[33] Ratio number of biomethane units/GW : 145#/GWh in France vs 28#/GWh in the EU27
[34] CAVEAT: Length of CH4 networks extrapolated FRàEU ((source CRE): linear relationship between prod. domestic bio-CH4, reverse units and T&D meshes; ratio adjusted proportionally to the average size of green gas production projects France vs EU for T&D & injection stations
[35] CAVEAT: Pipeline length based on EHB backbone sizing (constant for brownfield, linear relation flow H2 x greenfield)



Appendix 15 : Share of total CAPEX for setting up the energy system by 2050
from activities in the EU in trillions €2023



Appendix 16 : LCA greenhouse gas emissions x scenarios – in Mt CO2eq/year

PERFORMANCE CRITERIA

Technical performance criteria	Comments
Share of energy demand satisfied	• Capacity of the energy system to respond to end uses at an hourly mesh and considering different climatic reference years (security of supply)
Maximum power level needed to meet instantaneous demand at annual peak	• Power level to be mobilized for the electric system to absorb all variable production at peak (electric system resilience)
Electrical tapping point	• Ability of the electric network to respond to power calls / peaks of electricity consumption (security of electricity supply)
% of prod. variable elec. total electricity	• Share of final uses satisfied by variable energies and subject to daily production hazards (electricity supply at risk)
% variable energy in delivered energy PoD	• Share of final energy demand met by variable energies and subject to daily production hazards (total supply at risk)
Flexibility installed capacity for grid injection	• Dimensioning of the capacity of electrical flexibilities (intraday and dispatchable production) to ensure the security of the electricity system with hourly mesh vs the variability of its production
Primary energy produced + imports	• Primary energy and import requirements to meet end uses 2050 – all energy carriers
Percentage of energy supplied dependent on imports	• Independence of the EU energy system by 2050 (domestic production vs. dependence on imports)
System energy efficiency *(final energy PoD / (primary + import))*	• Efficiency of the energy system in terms of resource use – transformation losses between energy carriers (P2G, P2M, P2L, XtP etc.)
System land efficiency (domestic land consumption / primary energy)	• Efficiency of the energy system in terms of direct use of land; Ability to avoid overconsumption of territory
Technical feasibility	• Mastery of services / technologies deployed in 2050 scenarios (e.g. V2G, etc.)

Appendix 17 : Definition of technical energy performance criteria

Economic performance criteria	Comments
Total CAPEX invested to 2050	• Intensity of the total investment effort (all upstream and midstream stakeholders) to deploy a carbon-neutral energy system by 2050 (m€)
CAPEX production *(elec + H2 + CH4 + liquefied fuels)*	• Intensity of producers' investment effort (electricity, H2s, CH4s, liquid fuels)
CAPEX flexibility *(elec + H2 storage - excluding V2G)*	• Intensity of the investment effort in batteries, WWTPs, salt cavities H2 (excluding V2G because of downstream meter investment)
CAPEX T&D *(elec + H2 + CH4)*	• Intensity of the investment effort of TSO/DSO electra and gas
TOTEX (installation and operation) over 30 years	• Levelized costs of setting up and operating the energy system at 2050 pre-PoD (CAPEX and OPEX) total and by main sectors of use (Residential, Transport, Tertiary, Industry)
Residential TOTEX	
Tertiary TOTEX	
Transport TOTEX	
Industry TOTEX	
Annualized full supply cost - standardized residential building	• Annualised final total energy cost for an average standardised household (100m2) in EU27 to 2050, excluding mobility
Annualized full supply cost - standardized commercial building	• Annualised final total energy cost for an average standardised tertiary building (570 m2) in EU27 to 2050
Annualized full supply cost - industrial site	• Annualised final total energy cost for a manufacturing industrial site (12 GWh) in EU27 to 2050
Trade balance: import budget	• Annual expenditure on energy imports (H2s, CH4s, liquid fuels, etc.)

Appendix 18 : Definition of economic performance criteria

Social performance criteria	Comments
Constraints of changing living standards, energy use and behavior	• Coherence and viability of the evolution of energy uses and behaviours in relation to maintaining the standard of living in 2050
Intensity of direct consumption of additional land	• Direct land impact from additional facilities necessary for the decarbonisation of the energy system (production assets, flexibilities, etc.) and which may lead to conflicts of use (food, housing, etc.)
Job creation in the new energy system	• Impact in terms of total job creation (permanent and temporary) on the main upstream PoD technology sectors for the implementation and operation of the energy system over 30 years
Permanent jobs	• Main jobs created for the operation and maintenance of the facilities over 30 years
Temporary jobs	• Main jobs created for the installation and manufacture of energy production and transmission equipment by 2050
Share of system Value Added (VA) generated by activities in the EU	• Share of total CAPEX for energy system implementation at 2050 - excluding MDE investments and "uses" - from activities in the EU and to measure the economic benefits for the EU

Appendix 19 : Definition of social performance criteria

Performance criteria ecological/environmental	Comments
GHG scope 1 assessment and performance	• Ability of TE scenarios to achieve carbon neutrality by 2050, considering a scope 1 calculation of GHG emissions and integrating the reduction of emissions related to CCS and LULUCF
GHG assessment and performance in LCA	• Full carbon impact of technology sectors and remaining challenge in terms of decarbonization by measuring the full cycle carbon footprint (LCA) of TE to 2050 scenarios
Additional land consumption	• Direct land impact of additional installations necessary for the decarbonisation of the energy system (production assets, flexibilities, etc.) and which may lead to the destruction of carbon 'sinks' or other externalities (landscape impacts, noise pollution, etc.)
Other externalities / synergies	• Other impacts of the scenarios in terms of value brought to the local ecosystem (e.g. agrarian system, air or water quality, etc.)

Appendix 20 : Definition of environmental and ecological performance criteria

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Glossary

- **CAPEX:** Capital expenditure
- **CCS:** Carbon Capture and Storage. Process of sequestrating CO2 and storing it in such a way that it won't enter the atmosphere.
- **CCGT:** Combined Cycle Gas Turbine. Power plant generating electricity from gas.
- **CH4s:** methanes, including natural gas, biomethane, e-methanes.
- **DAC:** Direct Air Capture. Technology that captures carbon directly from the atmosphere to reduce CO2 levels.
- **DE:** Distributed Energy scenario
- **DSR:** Demand Side Response. Changes in power consumption by end-use consumers to reduce pressure on electric system during high load periods.
- **ENTSOE/ENTSOG:** European Network of Transmission System Operators for Electricity/GAS. Organizations that coordinate and facilitate the integration of the European electricity and gas markets respectively, authors of TYNDP report.
- **EV:** Electric Vehicle
- **ELY:** Electrolysis, production of hydrogen using electricity to splitting water molecules between H2 and O2
- **H2s:** Green hydrogen from RES and decarbonated hydrogen (e.g. from CCS or nuclear)
- **GA:** Global Ambition scenario
- **gCO2eq:** Greenhouse gas emission equivalent to that of one gram of CO2
- **GHG:** GreenHouse Gas
- **ICE:** Internal Combustion Engine
- **LCA:** Life-Cycle Analysis. Method to evaluate environmental impact of a product or process through its entire life cycle, from raw materials production to disposal and recycling.
- **LCOE:** Levelized Cost Of Energy. Net present cost of producing a unit of electricity over the entire lifespan of a power generation asset.

- **LULUCF:** Land Use, Land Use Change and Forestry. Sink of CO_2 made possible by the fact that atmospheric CO_2 can accumulate as carbon in vegetation and soils in terrestrial ecosystems.
- **Mha:** millions of hectares
- **OPEX:** OPerational EXpenditure
- **RES:** Renewable Energy Source
- **P2G:** Power to Gas. Technology that uses electricity to produce gas: first by electrolysis to produce hydrogen, then either using it directly, or combining H2 with CO2 to get synthetic methane. Other gas energy carriers can be obtained in the same way.
- **P2L:** Power to Liquids, process to obtain liquid fuel from hydrogen electrolysis.
- **P2M:** Power to Methane, process to obtain methane from hydrogen electrolysis.
- **PoD:** Point of Delivery
- **PtX/XtP:** Conversion of X form of energy to or from electricity
- **PV:** Photovoltaic
- **SMR:** Steam Methane Reforming, industrial process to produce hydrogen with natural gas.
- **Prosumer:** a person who participates in the production of the object they are going to consume and thus becomes a responsible actor in shaping the world they live in
- **PSH:** Pumped-Storage Hydroelectricity. Type of energy storage that uses 2 water reservoirs of different heights: when electricity is abundant, pumps pull water to the upper reservoir, which can be used to produce electricity on its way down when demand is high.
- **T&D:** Transport and Distribution
- **TOTEX:** Total Expenditure
- **TWh:** Terawatt hour
- **TYNDP:** Ten Year Network Development Plan
- **V2G:** Vehicle to Grid, electric flexibility that allows electric vehicles to connect to the grid and reduce charging consumption during high load periods and serve as storage capacity