Sectoral integration – long term perspective in the EU energy system

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Structure of the study

Hydrogen roadmap to 2050: Technological and market developments

- Linking the power and mobility sector & Usage of H2 in transportation
- Linking the power sector and H2-demanding industry
- Linking the power sector with transport and heating sectors
- Energy storage, integration of RES and sectorial integration
- Analysis by country

Modelling the impact of sectoral integration

- We analyse the following three scenarios:
  - H2 as a carrier
  - H2 as feedstock
  - H2 for power storage
  - and a
  - Balanced realistic scenario
  - The new assumptions add to a basic decarbonisation scenario (EUCO)

PRIMES modeling

- Full projections for each EU MS up to 2050
- Impacts on the EU energy system including costs and infrastructure investment
- Modeling market equilibrium with complete integration of demand and supply
- Explicit policy and technological drivers

Business drivers for hydrogen deployment

The need for flexibility	Limited potential of traditional storage technologies	Combine storage with production of clean fuels
• Multi-hour fast ramping to balance variable RES, in particular solar PV • Fast responding dispatchable resources to balance fluctuating RES • Storage beyond a daily cycle to cope with RES unavailability periods • Load shifting on a daily basis to avoid over-generation inefficiencies	• Hydro-pumping has limitations due to sites • Pure pumping has limited storage capacity and acts mainly as a peak device • Compressed air energy storage is expensive and has siting limitations • The batteries are small to medium scale (mostly connected to the distribution grid) and cannot cover multiple-day cycles	• Deep decarbonisation needs to replace the fossil fuels which for different reasons cannot vanish in all end-uses (e.g. gas in stationary uses, liquids in aircrafts, ships and trucks) • Carbon-free or low-carbon methane or hydrocarbons can support versatile solutions as they serve as both storage and energy carriers • Injecting H_2 to the gas grid up to a certain percentage (<15% due to the Wobbe index) reduce the average emission factor of distributed gas • H_2 can compete against direct electricity use in transport and heating depending on the future learning curve of fuel cells

Carbon-free hydrogen production

- Electrolysis powered by electricity produced using carbon-free resources, such as renewables, nuclear and carbon capture and storage
- The proton exchange membrane (PEM) technology is a promising avenue as an alternative to alkaline systems, while solid-oxide cells (SOEC) are in a development stage
- The electrolysers are not yet competitive compared to steam reforming using natural gas (which is not acceptable as it is a CO_2 emitting process) but have great potential of capital cost reductions
- As electrolysers are capital-intensive, using them at fully capacity is beneficial to reducing the average cost of hydrogen; however, if electricity prices are very volatile in a day, it may be more economical to use the electrolyser only at low load times when prices are low

Outlook for hydrogen (1/2)

Use of hydrogen as an energy carrier

- Storage of electricity in the form of hydrogen involves re-electrification of hydrogen mainly in gas turbines or combined cycle gas turbines at a lifecycle energy efficiency at best 48% (80% electrolyser and 60% the CCGT) as a potential achievement in the future
- Direct use of hydrogen in stationary and mobile energy applications can use fuel cells which can either operate at high temperature as small-scale CHP units or lower temperature for mobility
- The fuel cells are technically reliable and efficient in energy but currently expensive; the magnitude of learning potential of fuel cells is uncertain

Storage and transportation of hydrogen

- Hydrogen conditioning is necessary but inefficient for energy consumption
- Compressed H_2 can be produced directly from electrolysis with low additional energy losses
- Producing liquefied H_2 to transport over long distances implies 30-40% energy losses in liquefaction
- Road or rail transportation of compressed H_2 is expensive
- Pipeline transport of H_2 needs new infrastructure or retrofitting of gas pipelines at significant costs
- H_2 storage in pressurised tanks and line pack are probably the only practical and economic possibilities

Outlook for hydrogen (2/2)
Power-to-Gas (methane) & Power-to-Liquid (transport fuels)

Power to Gas

- Methane can be the output of methanation that uses hydrogen and carbon dioxide as inputs
- The output, synthetic gas, is fully substitutable to natural gas that provides great benefits for the use of existing infrastructure of distribution and end-use
- The methanation implies a further loss of energy efficiency over the lifecycle, getting to an overall rate below 40%, but the output can be fully stored and re-electrified in a perfectly versatile way. Thermochemical catalytic technologies for methanation are at an advanced stage of development.

Power to Liquids

- Several technologies are possible, classified into two groups:
  - combined electrolysis and carbon dioxide chemical treatment (electro-reduction, co-electrolysis, reverse water gas shift) which produces methanol, dimethyl ether etc. that are further upgraded to transport fuels after hydrogenation;
  - Fischer-Tropsch conversion of syngas, produced from a treatment of H_2 as an output of electrolysis and CO_2.
- All technology pathways are energy intensive

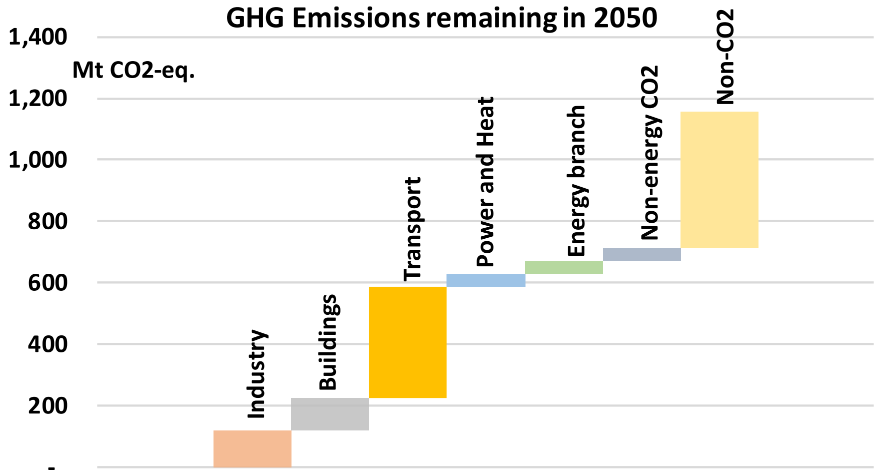
From a GHG emissions perspective, the origin of CO_2 is a challenging issue. Only CO_2 captured from ambient air guarantees full carbon-free fuels

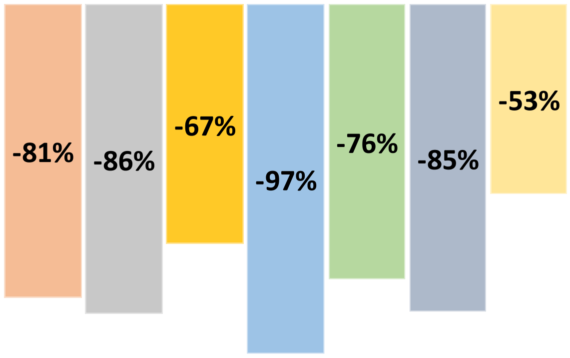
Economic challenges of a hydrogen economy

- All technology chains are energy intensive and imply that the energy output is more expensive than conventional technologies, even if the evaluation includes the full possible potential of learning
- At full learning potential a carbon price as low as € 50-80/tCO_2 would suffice to make synthetic fuels competitive. Without the learning, carbon prices above € 500/tCO_2 would be necessary
- The exploitation of the learning potential requires large-scale installations and expectation of massive production; the critical mass to trigger purely private investment is large, and thus strong policy support is necessary to make possible the initial investments
- The upfront investment costs are significant. Purely private investment is surrounded by large uncertainties. Regulation providing clear and long-lasting certainty about market prospects of the synthetic fuels is the main driver
- Back-to-back long term contracts of synthetic fuels producers and utilities providing clean electricity at a large-scale is the main business model
- The economics of large-scale power-to-hydrogen (or gas or liquid) production suggest the uninterruptible and inexpensive supply of carbon-free electricity; therefore, extending the electrical interconnections and ensuring fully coupled markets assists cost reductions and risk hedging.

The pathway towards 2050

- In 2050, 1100 Mt GHG (-80% compared to 1990 levels) are consistent with a 2°C trajectory
- By 2050, the remaining GHG (in a EUCO scenario) are 58% due to energy, of which:
  - 31% in transport
  - 20% in stationary use
  - Power and heat and energy branch account for 9%
- The challenge is to bring emissions close to zero
  - Is it possible?
  - How? When? At which cost?
  - Focus on transport: electrification? hydrogen? synthetic fuels?



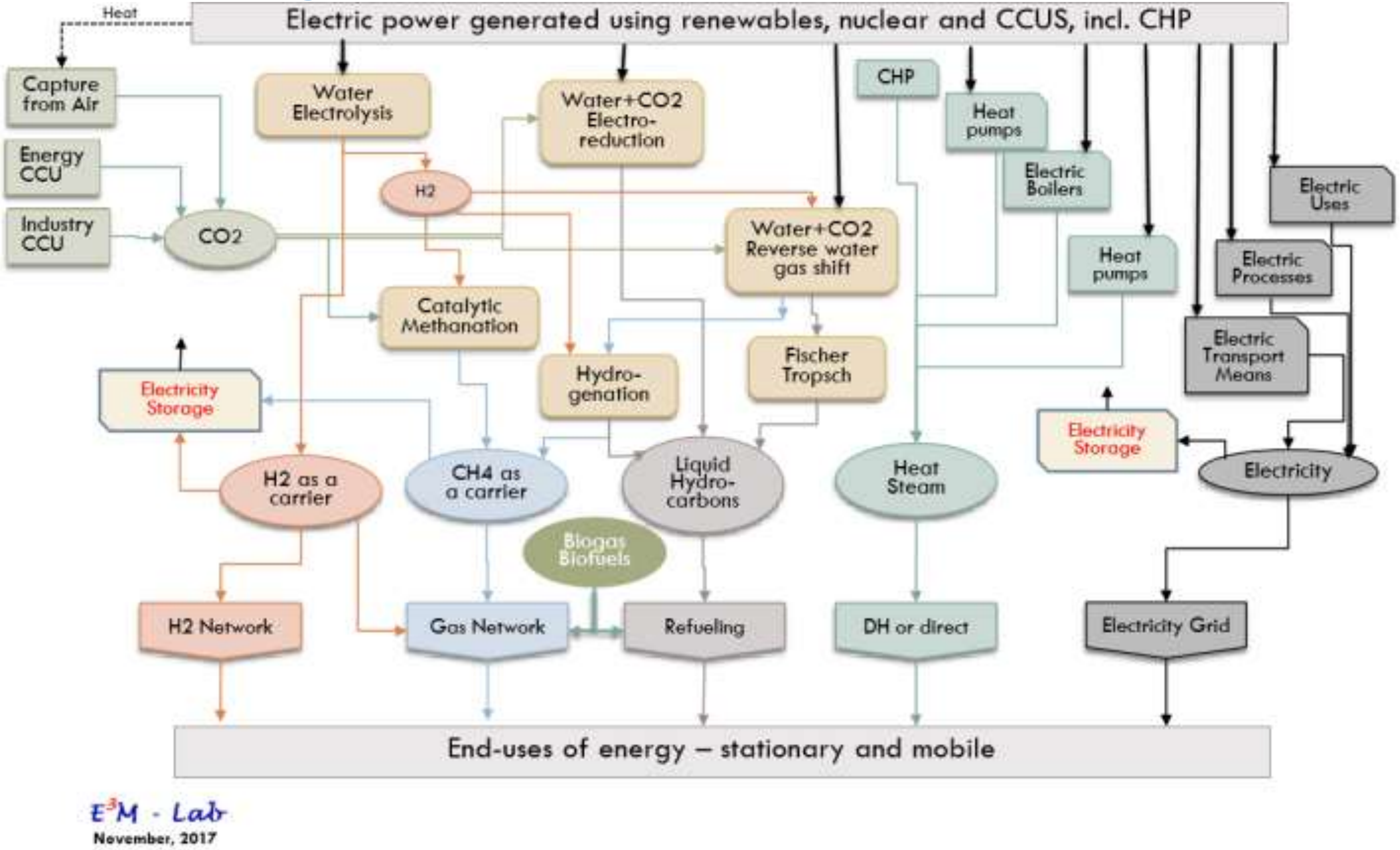


GHG Emissions reduction 2005-2050

A new special sub-model of PRIMES

- Has an horizon up to 2070, similarly to the updated main PRIMES model
- Represents the process flow with engineering and economic details
- Simulates hourly operation of a system with electricity, H_2, gas, heat, steam and synthetic fuels in a synchronized way to be able to analyze storage
- It includes an aggregate representation of the electricity, gas, heat and biomass models of PRIMES integrated into the process flow modelling (see graphical). It includes in an aggregated way fuel choice in the demand sectors, but demand for useful energy is exogenous coming from PRIMES.
- Includes all countries of Europe simultaneously to capture trade of the carriers, location of new factories and infrastructure (power grids, gas, H2 network and distributed heat)
- Includes three non-linear mechanisms:
  - Cost-potential non-linear curves for exhaustion of resources (increasing slope)
  - Learning non-linear curves (technology) and economies of scale (factory), both with decreasing slopes
  - Uncertainties and heterogeneity implying hidden-perceived costs which non-linearly depends on enabling conditions (such as a carbon price)
- Optimizes under perfect foresight assumptions

A process flow diagram



Modelling the impact of sectorial integration on the energy system towards 2050

- Begin using the EUCO30* as a basis; a scenario that assumes the existence of the enabling conditions of decarbonisation, with a further constraint to get energy-related emissions close to zero shortly after 2050
- The stylized scenarios explore the following contrasted pathways:
  - Scenario A - H_2 as an energy carrier
  - Scenario B - H_2 as feedstock for the production of synthetic clean fuels
  - Scenario C – H_2 as a means of electricity storage
- All three scenarios assume technology success and adequate policy enablers, but differently per scenario
- The projections evaluates indicators for the comparisons, covering costs for consumers, investments needed, reliability, security and an analysis of uncertainties

*EUCO: a scenario developed in the context of the Winter Package

Pros and Cons of each stylized scenario

	Main uncertainties	Main advantages
H_2 as a carrier	• Distribution and transport network specifically for H_2 • Cost of fuel cells • H_2 storage	• H_2 is an energy carrier valid for the entire system • High energy efficiency maintained • No excessive increase in power generation • Can accommodate H_2 to fuel processing if technology reached maturity in the future
H_2 as feedstock	• CO_2 capture from air • Poor energy efficiency • Too high increase in demand for electricity • Costs	• Continued use of existing distribution infra for gas and liquid fuels • Convenient energy applications, equipment and processes • No major disturbance of transport system
H_2 for power storage	• Electric aircrafts, ships and long distance trucks • Electrification of all industrial processes • Electrification of all residential energy uses	• High efficiency of electricity in end-uses • Feasible from power system perspective • Power-to-H_2 used mainly for storage purposes can develop without major uncertainties and can achieve low costs

A combined – realistic scenario achieving zero emissions

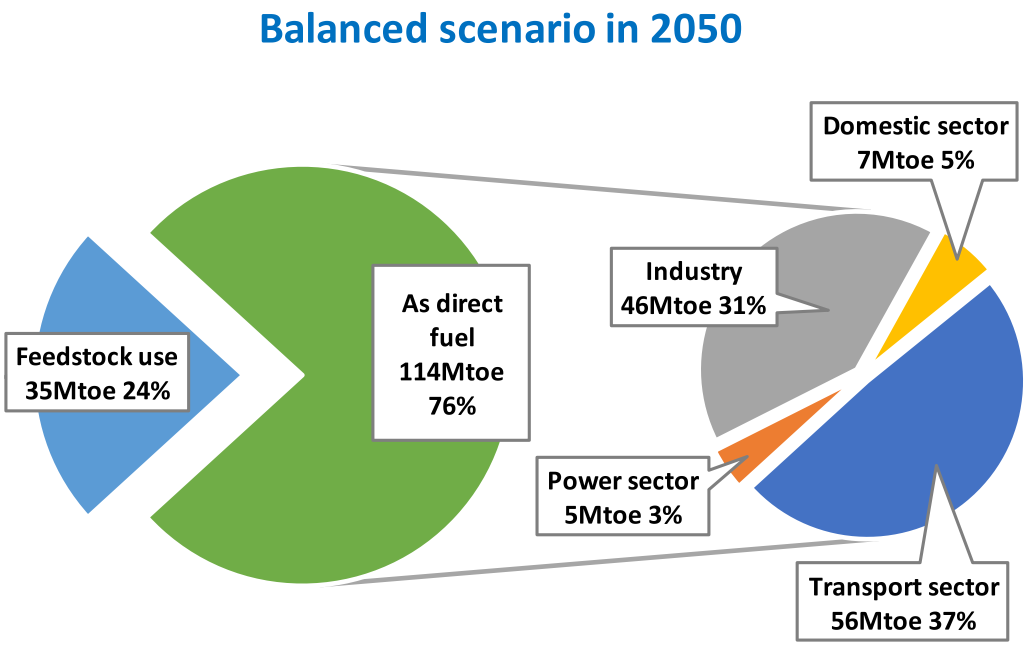
Hydrogen uses

- Mix up to 15% in gas distribution
- Use fuel cells using H2 in vehicles that cannot run in batteries, such as trucks, buses, taxis, duty vehicles. Combine with large-scale H2 refueling stations, which may include electrolysis and H2 storage.
- Use H2 directly in high temperature furnaces in industry combined with local electrolysis and storage
- Produce clean methane in methanation plants using CO2 captured from air, integrated in power utility facilities well interconnected. H2 produced in these locations also serve electricity storage.

Rest of Options

- Fully decarbonize power generation using maximum contribution by RES, dispersed and centralized, complemented by nuclear and CCS where possible. Direct storage and chemical storage, as well as interconnections, succeed to balance the RES.
- Exploit to maximum possible potential energy efficiency in buildings and industry
- Electrify car mobility and heating
- Develop advanced sustainable biomass feedstock to produce fungible jet fuels and ship fuel, as well as bio-methane mixed in the gas grid

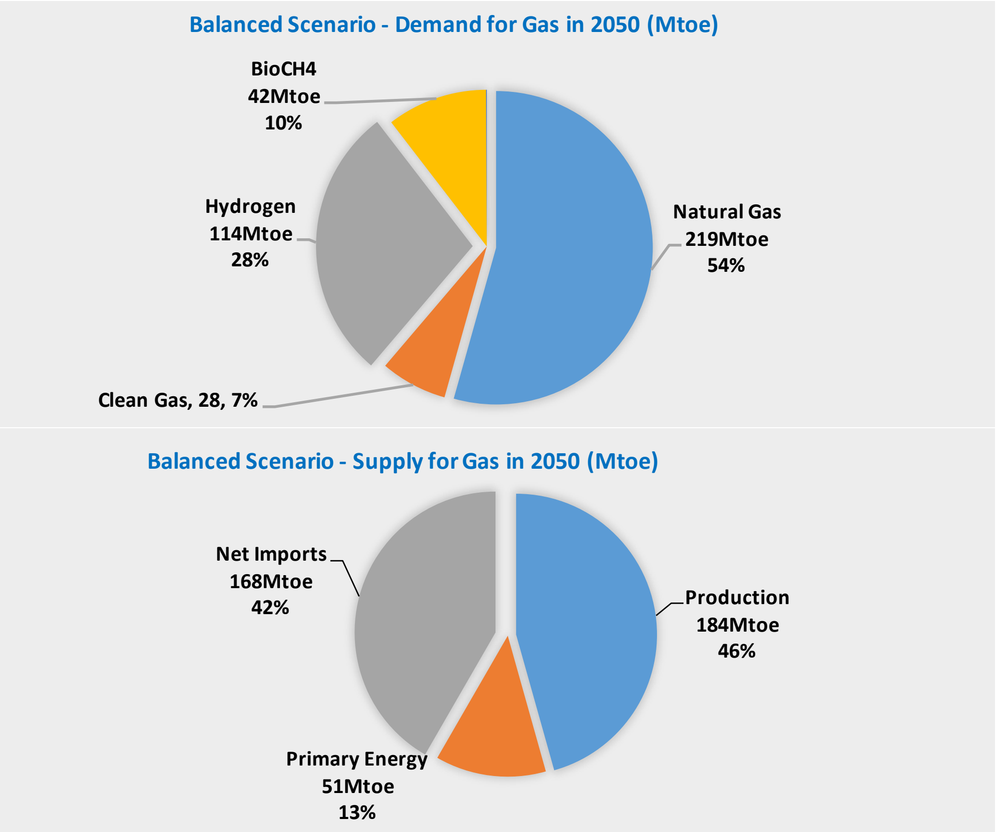
Uses of hydrogen in the balanced scenario



- Mainly used (3/4 of total) directly in final consumption
  - 15% mixed in gas distribution
  - Directly in high temperature furnaces in industry
  - In transport via fuel cells
- Used directly in power generation as electricity storage (chemical storage)
- As a feedstock (1/4 of total) to produce clean methane (CH4), which is mixed in gas distribution and is used in the power sector as electricity storage

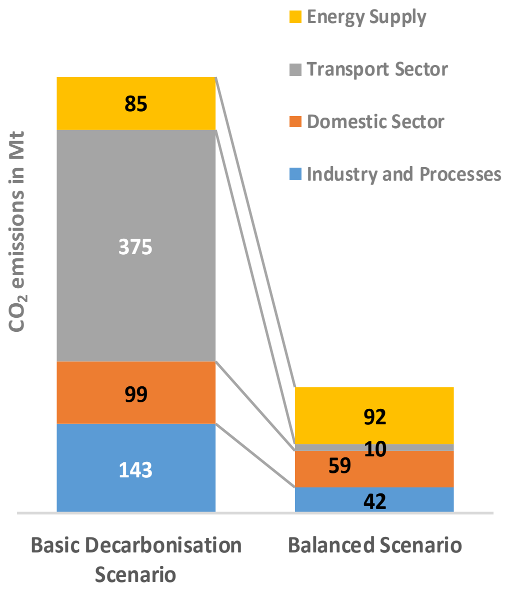
Gaseous fuels in the Balanced scenario

- Natural gas (fossil) covers only 54% of a total of 404Mtoe consumption of gaseous fuels in 2050
- Natural gas is roughly the only remaining fossil in the system, being used in the power balancing and mostly in CCGT-CCS plants
- Methanation and bio-energy plants produce 184Mtoe (45% of total gaseous)
- Tremendous independence from natural gas imports by 2050

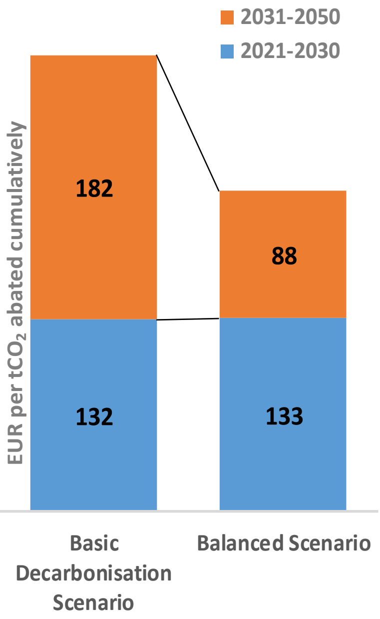


Emissions and costs in the Balanced Scenario

PRIMES projections



Remaining CO_2 Emissions in 2050

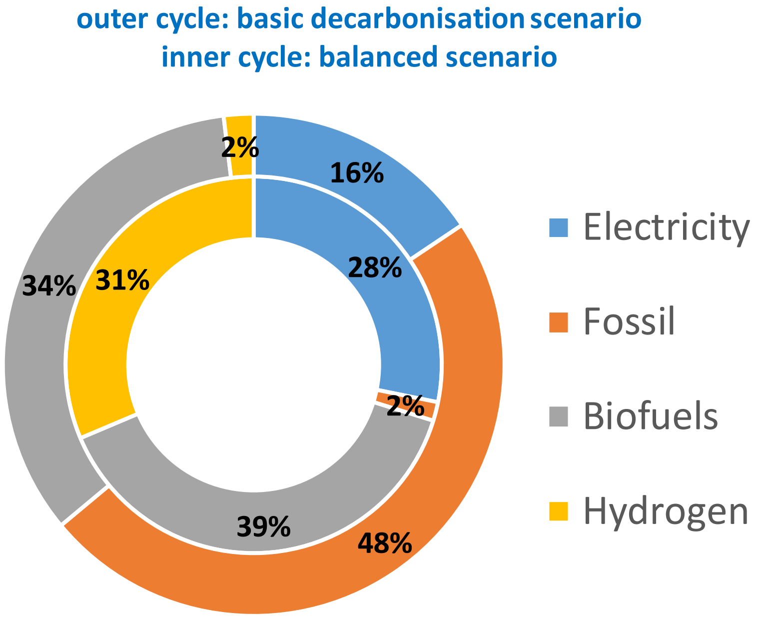


Average unit cost of emissions reduction

- 96% CO_2 emissions reduction in 2050 (relative to 1990)
  - 12 percentage points more than in the basic decarbonisation scenario (-84% CO_2 in 2050)
- The balanced scenario abates CO_2 at an average cost of €88/t CO_2 (cumulatively in the period 2030-2050)
  - Which is less than half of the cost in the basic decarbonisation scenario (€182/tCO_2 abated)
- The performance owes to the multiple roles of hydrogen in sectoral integration, and its particular role in the transport sector

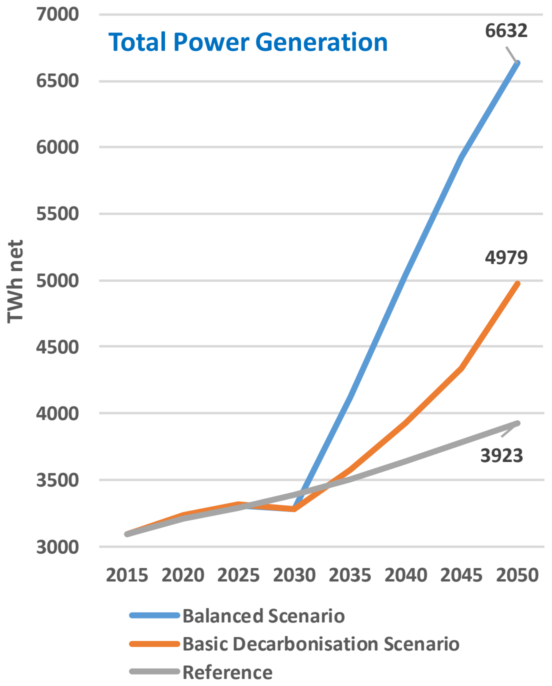
Fuel mix in Transport in 2050

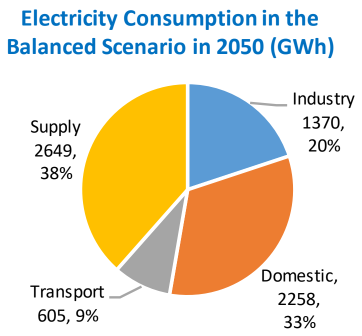
PRIMES projections

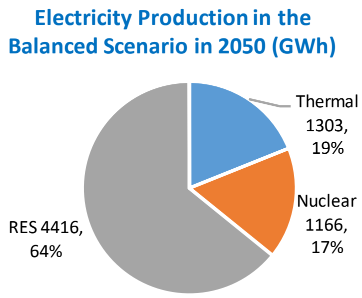


- In the balanced scenario
  - Almost no fossil fuels
  - Complementary market segments for battery and fuel-cell vehicles
    - Battery-charged cars in cites and short-medium distance trips
    - Fuel cells heavy duty vehicles and cars with high mileage
  - Lower total amounts of biofuels than in the basic decarbonisation scenario
    - The fuel cells move biofuels from trucks to aircrafts and ships
  - Optimistic learning assumptions, both for batteries and fuel cells, allow for full substitution of fossil fuels in the car market at lower total cost, compared to the basic decarbonisation scenario

Hydrogen further enhances the role of electricity

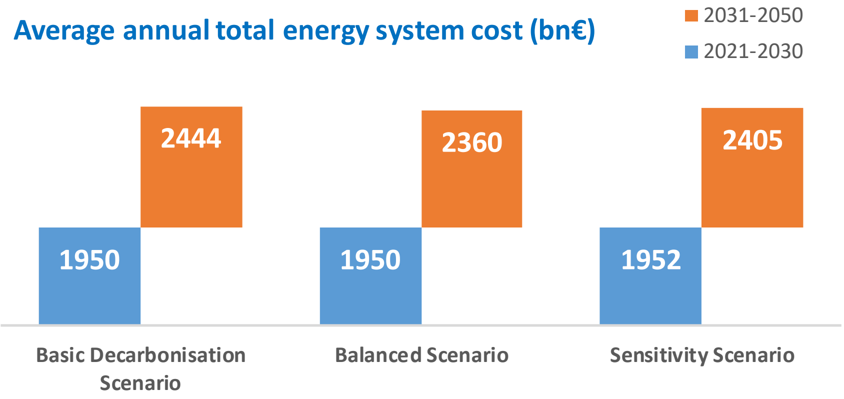


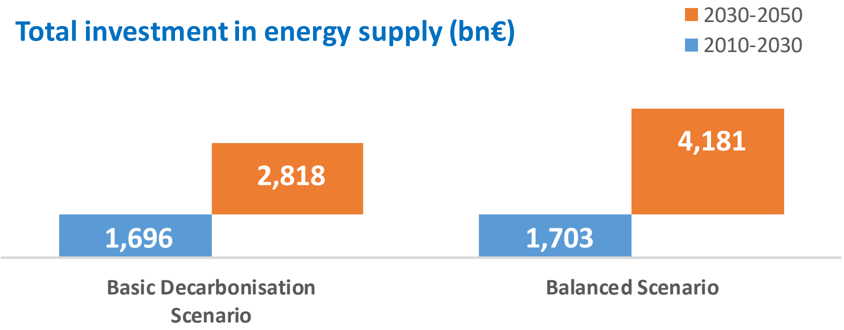




- Electricity producing hydrogen and clean gas becomes a large sector
- Economic optimality in this sector requires a large scale and a non-interrupted supply of electricity
- Therefore, RES from different origins, with complementary production profiles and nuclear are the optimum input portfolio
- Consequently, large scale interconnections and the full completion of the internal market matter for cost-efficiency
- The power sector thus combines dispersed generation (prosumers) and centralized generation over a mesh grid
- In 2050, RES-power increase by 36%, nuclear by 20% and gas-CCS by 37% in the balanced scenario compared to the basic decarbonisation scenario

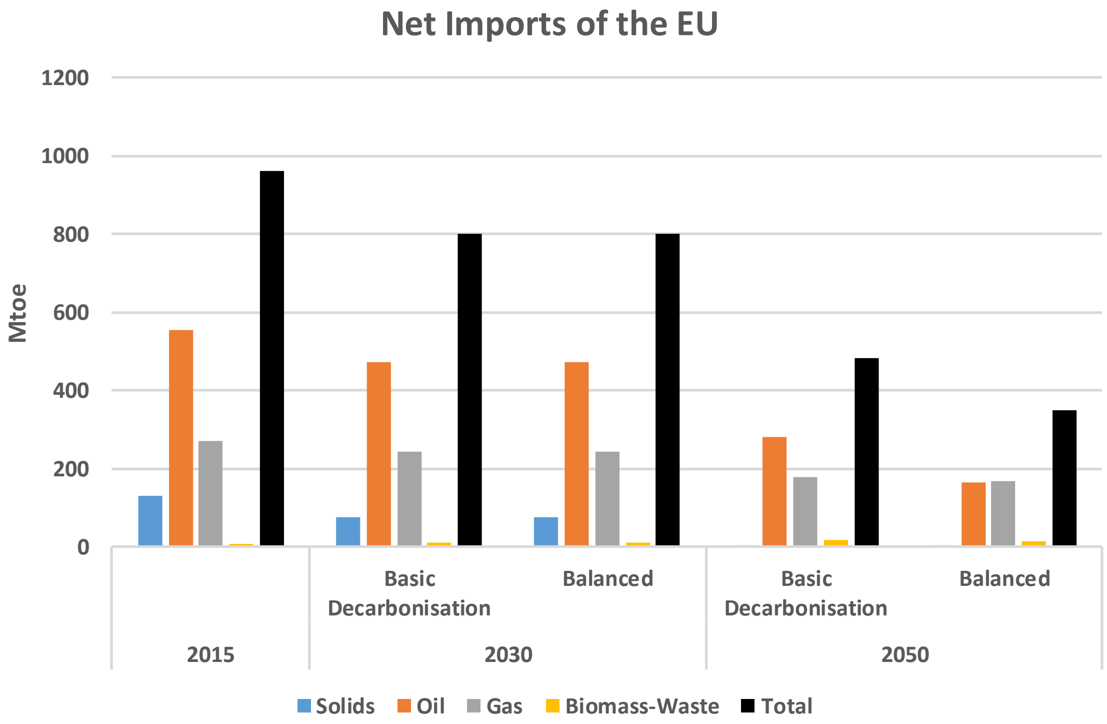
Cost impacts





- Total costs are lower in the balanced scenario, despite higher emissions reduction than in the basic decarbonisation scenario
- A sensitivity analysis scenario involving less optimistic cost assumptions for the hydrogen technologies remains cheaper and achieves 91% emissions reduction in 2050
- The electricity prices remain stable despite the significant increase in total power generation
- The cost reductions owe to the assumptions about availability of the new hydrogen technologies and the string learning effects.
- However, the balanced scenario is significantly more demanding in investment funds in the supply system in the period 2030-2050 (48% increase)

Tremendous benefits for import independence



- In the balanced scenario by 2050
  - Oil imports are used almost exclusively in petrochemicals, as they are fully substituted in transport
  - Natural gas imports are only slightly lower than in the basic decarbonisation scenario, but they are used in large majority in the power sector
  - Biomass imports do not increase relative to the basic decarbonisation scenario and remain reasonable, as biofuels are used in 2050 only in aircrafts and ships (being advanced and fully fungible)

Concluding remarks

- Sectoral integration enabled by electricity and in the long-term by hydrogen are powerful strategies to decarbonize the energy system in a cost-effective manner
- The hydrogen technology chain, as an add-on of the EUCO decarbonisation approach, can bring CO_2 emissions down close to a 95% reduction at an affordable cost
- The H_2 value chain includes clean H_2 from electricity, Power-to-Gas producing clean gas, and direct uses of H_2 in gas grids, high temperature furnaces and in fuel cells for heavy duty and high mileage travelling vehicles
- All extreme stylized scenarios present serious uncertainties, as for example a full hydrogen, a full electric or a full synthetic-hydrocarbon economy
- The modelling, based on an enhanced version of PRIMES, illustrated that a balanced scenario towards deep emissions reduction by mid-century is feasible technically and economically
- However, to achieve the expected cost reductions in the technologies, large-scale investments are necessary and an effective market coordination of different actors, including infrastructure and technology developers
- As a next step, not addressed in this study, we put emphasis on the assessment of suitable energy policy instruments which could enable emergence and widespread of the technologies