



ROADMAP 2050

A PRACTICAL GUIDE TO A PROSPEROUS,
LOW-CARBON EUROPE

TECHNICAL ANALYSIS
EXECUTIVE SUMMARY

CO₂ REDUCTION

CO₂ REDUCTION

ECONOMIC GROWTH

LESS POLLUTION

INTEGRATED EU

JOB CREATION

INTEGRATED EU

SMART ENERGY GRID

RENEWABLE ENERGY

SUSTAINABLE ENERGY

GREEN EUROPE

DEMANDSIDE MANAGEMENT



P R E F A C E

In July 2009, the leaders of the European Union and the G8 announced an objective to reduce greenhouse gas emissions by at least 80% below 1990 levels by 2050. In October 2009 the European Council set the appropriate abatement objective for Europe and other developed economies at 80-95% below 1990 levels by 2050. In support of this objective, the European Climate Foundation (ECF) initiated a study to establish a fact base behind this goal and derive the implications for European industry, particularly in the electricity sector. The result is *Roadmap 2050: a practical guide to a prosperous, low-carbon Europe*, a discussion of the feasibility and challenges of realizing an 80% GHG reduction objective for Europe, including urgent policy imperatives over the coming five years. The scientific basis and the political process behind the setting of that objective are not discussed.

This is the first of three volumes. It is a technical and economic assessment of a set of decarbonization pathways. Volume 2 will address the policy and regulatory implications arising from the analysis, and Volume 3 will address the broader implications for society. ECF strongly recommends that further work be carried out that will help stakeholders understand the required change in more detail, including the different ways in which various regions would experience the transformation.

Roadmap 2050 breaks new ground by outlining plausible ways to achieve an 80% reduction target from a broad European perspective, based on the best available facts elicited from industry players and academia, and developed by a team of recognized experts rigorously applying established industry standards.

This study is funded by ECF, which itself is funded solely by private philanthropic organizations¹. ECF does not have financial ties to EU political bodies, nor to business. Representatives of the European Commission and its services have provided strong encouragement for the development of this undertaking and have given welcome guidance regarding the objectives and the approach. Along with representatives of other EU institutions, notably the European Parliament and Council of Ministers, the European Commission has been consulted periodically throughout the course of the project. In addition, a wide range of companies, consultancy firms, research centers and NGOs have counseled ECF in the preparation of this report. These organizations can be found in the acknowledgements section.

1. ECF's funding sources are fully disclosed on its website, www.europeancimate.org

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The work on the three volumes of the Roadmap 2050 project has been undertaken by:

- Volume 1 - Technical and Economic Analysis: McKinsey & Company; KEMA; The Energy Futures Lab at Imperial College London; Oxford Economics and the ECF
- Volume 2 - Policy Report: E3G; The Energy Research Centre of the Netherlands and the ECF
- Volume 3 - Graphic Narrative: The Office for Metropolitan Architecture and the ECF

In addition, a wide range of companies, consultancy firms, research centres and NGOs have provided various forms of assistance during the preparation of this report. These organisations have provided valuable counsel that we have tried faithfully to reflect in this analysis, however their willingness to consult and to be consulted in the course of this work should not be taken to mean that each of them agrees with all of its assumptions or conclusions.

The ECF is the sole author of the Roadmap 2050 report, is solely responsible for its content and will act as a guardian of the content. The materials can be freely used to advance discussion on decarbonisation of the power sector and the broader economy. The report is made available to any and all audiences via a Creative Commons license. For details of the terms and conditions, please see www.roadmap2050.eu/cc

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For more information on Roadmap 2050:

www.roadmap2050.eu

European Climate Foundation:

www.europeanclimate.org

DEFINITION OF THE “ROADMAP 2050” STUDY

Roadmap 2050: a practical guide to a prosperous, low-carbon Europe has two primary objectives: a) to investigate the technical and economic feasibility of achieving at least an 80% reduction in greenhouse gas (GHG) emissions below 1990 levels by 2050, while maintaining or improving today's levels of electricity supply reliability, energy security, economic growth and prosperity; and b) to derive the implications for the European energy system over the next 5 to 10 years. *Roadmap 2050* addresses at a high level GHG emissions across all sectors of the economy, and it analyses the power sector in depth. The approach taken stipulates the minimum desired 2050 outcome as expressed by European leaders, and then derives plausible pathways from today to achieve them. The methodology is known as “back-casting,” to differentiate it fundamentally from forecasting: the end-state is stipulated, that is, rather than derived. A back-casting approach can help to highlight where momentum must be broken and re-directed in order to achieve future objectives, while forecasting tends to extend current trends out into the future to see where they might arrive.

The end-state stipulated for *Roadmap 2050* is an 80% reduction in GHG below 1990 levels by 2050 across the European economy (without relying on international carbon offsets²), and an energy system that delivers at least the same level of service reliability as Europeans enjoy today. The initial analysis confirmed that it is virtually impossible to achieve an 80% GHG reduction across the economy without a 95 to 100% decarbonized power sector. Three different decarbonized power sector pathways have been studied that differ in the shares of a range of low/zero carbon supply technologies: fossil fuel plus CCS, nuclear energy, and a mix of renewable technologies. In addition, a scenario with 100% electricity from renewable sources was

assessed, primarily on the dimension of maintaining the acceptable level of service reliability.

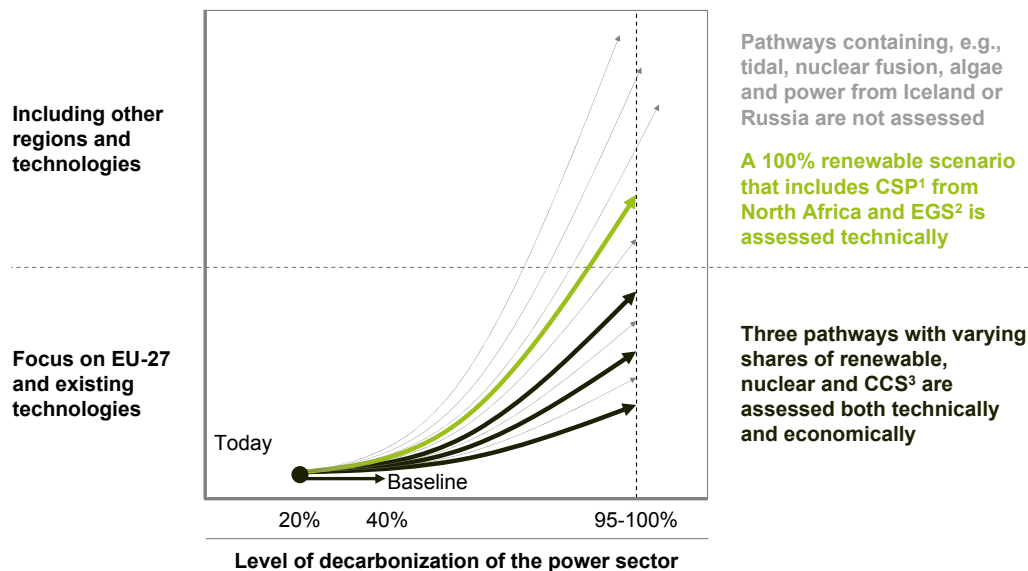
The pathways are designed to be robust; they do not depend on future technology breakthroughs or on electricity imported from neighboring regions. They are based on technologies that are commercially available³ or in late-stage development today; breakthroughs in technology will only improve the cost or feasibility of the pathways. By design a mix of technologies is used to avoid over-reliance on a few “silver bullet” technologies. This allows resource diversification as well as geographical differentiation. Consequently, the pathways are not fully optimized for lowest cost: they are not based purely on those technologies that are currently expected to be the cheapest in 2050. This approach adds to the robustness of the conclusions; if one technology fails to deliver as expected, the system still works. The technological mix also allows for the development of technologies in those locations where the required natural resource is most abundant. Constraints imposed by land use and by supply chains are taken into account. Finally, a greater diversity of resources delivers greater security of supply, which is an outcome policymakers are likely to seek in any case. A consequence of this approach is that, especially for the first decade, the back-casted technology mixes might differ from analyst forecasts.

Roadmap 2050 provides a robust analysis at a European level of the complex impacts of each decarbonization pathway on the provision of grid reliability services, ensuring that historical levels of supply reliability are maintained. Given limited time and resources, reasonable simplifying assumptions were made and tested regarding regional and local impacts; more detailed follow-on work would be required to address any actual facility planning and siting questions. The transmission grid expansion is

2. While recognizing that well-designed offsets markets can play a role in engaging developing countries and encouraging sound investment in low-cost strategies for controlling emissions in the near to medium term, the availability of CDM credits (or equivalent) to developed economies by mid-century is highly uncertain and likely to be very limited, and therefore this analysis does not rely on significant availability of offsets by 2050.

3. Although the technologies are commercially available today, it is still assumed that the costs will go down over time in real terms. The level of improvement differs by technology

EXHIBIT 0



1 Concentrated Solar Power (thermal, not photo voltaic)
 2 Enhanced Geothermal Systems
 3 Carbon Capture and Storage

optimized to lowest cost to support the exchange and sharing of renewable resources across the region, and to ensure that low-carbon resources are utilized when available. In doing this, the study makes trade-offs between adding transmission capacity, backup generation and incurring additional operating costs to balance the power system. The study also evaluates the role of “smart” grid measures in reducing the need for transmission and backup services, by allowing load to participate in balancing the system.

The report addresses the implications of electrification in buildings and transport on final power demand, but it does not attempt a detailed analysis of the decarbonization pathways for either sector. As such the assumption regarding the extent of electrification in transport (vs. biofuels, e.g.,) or regarding the extent of electrification of buildings (vs. biogas heating or zero-carbon district heating, e.g.,) should not be taken as expressing a view that these are the preferred solutions. These assumptions can rather be viewed as presenting a conservative case for the amount of electric demand that must

be decarbonized. Should other (non-electric) decarbonization solutions emerge for some portion of either sector, these will only make the power challenge that much more manageable.

Roadmap 2050 is the first of its kind to provide a system-wide European assessment, including a system reliability assessment. It is also the first study to develop its analysis in cooperation with the NGOs, major utility companies, TSOs, and equipment manufacturers across technologies and throughout Europe. The project built on several previous studies, including country specific analyses and technology assessments. It presents new facts, but also leaves room for further fact finding. The report provides insights from fact-based analysis on the technical feasibility of an 80% emission reduction by 2050, on the potential and cost of low-carbon power generation and transmission, and on the impact on the different sectors in the economy. It does not address the costs of distribution network reinforcements incremental to the distribution investments already required in the baseline; however a preliminary effort has been made to gauge the likely magnitude of these investment

needs. Beyond imposing reasonable technical constraints, *Roadmap 2050* does not attempt to make judgments on the relative political or social feasibility of implementing various components of the pathways (e.g., for the transmission expansion or extent of new nuclear construction). Neither does the report analyze in detail the potential cost of transition risks. These could be significant if bad policies damage the economy, or investments fail in terms of budget or technology delivery. Finally, *Roadmap 2050* will need to be supplemented by further work to clarify the implications for countries or regions, while preserving an integrated EU perspective.

Evaluation criteria taken into account include a combination of power system reliability, total energy costs, economic and employment growth, security of supply, sustainability and GHG emission levels.

SUMMARY OF FINDINGS

By 2050, Europe could achieve an economy-wide reduction of GHG emissions of at least 80% compared to 1990 levels. Realizing this radical transformation requires fundamental changes to the energy system. This level of reduction is only possible with a nearly zero-carbon power supply⁴. Such a power supply could be realized by further developing and deploying technologies that today are already commercially available or in late stage development, and by expanding the trans-European transmission grid. Assuming (i) industry consensus learning rates for those technologies; (ii) increased emission reduction efforts in the rest of the world; (iii) market demand for low-carbon investments; (iv) IEA projections for fossil fuel prices; (v) a significant expansion of grid interconnection between and across regions in Europe; and (vi) an *average* carbon price of at least € 20-30 per tCO₂e over 40 years, the cost of electricity and overall economic growth in the decarbonized pathways would be comparable to the baseline over the period 2010-2050⁵. In the shorter term, the cost of electricity in the decarbonized pathways is higher than the baseline, more so in the pathways with higher shares of renewable supply. Over the medium and longer term these differences disappear. Because the average costs of the decarbonized pathways over 40 years differ from the baseline cost by less than 15%, other factors, like risk tolerance, technology development, legacy infrastructure, resource availability and security of supply become more important in planning for and implementing a decarbonized power system.

Achieving the 80% reduction means nothing less than a transition to a new energy system both in the way energy is used and in the way it is produced. It requires a transformation across all energy related emitting sectors, moving capital into new sectors such as low-carbon energy generation, smart grids, electric vehicles and heat pumps. These investments will result in lower operating costs compared to

the baseline. Dramatic changes are required to implement this new energy system, including shifts in regulation (e.g., to provide effective investments incentives for capital-intensive generation and transmission capacity), funding mechanisms and public support. Despite the complexities, the transformation of the European power sector would yield economic and sustainability benefits, while dramatically securing and stabilizing Europe's energy supply.

Realistically, the 2050 goals will be hard to realize if the transition is not started in earnest within the next five years. Continued investments in non-abated carbon-emitting plants will affect 2050 emission levels. Continued uncertainty about the business case for sustained investment in low-carbon assets will impede the mobilization of private-sector capital. Waiting until 2015 (or later) to begin to build the large amount of required infrastructure would place a higher burden on the economy and the construction industry. Delay would also increase the challenges in transforming policies, regulation, planning and permitting. At the same time, the project to transform Europe's power sector will need to take into account feasible ramp-up rates across all sectors, particularly in the current financially constrained context. In the decarbonized pathways, the capital spent in the power sector goes up from about € 30 billion in 2010 to about € 65 billion a year in 2025. When delayed by ten years, the required annual capital spent goes up to over € 90 billion per year in 2035. This would require steep scale up of supply chains, potentially leading to short term shortages of building capacity, materials and resources. Furthermore, the cumulative emitted CO₂ between 2010 and 2050 would increase substantially. The project requires closer transnational cooperation in transmission infrastructure, resource planning, energy market regulation, and systems operation. Taking all this into account, it is not difficult to see that technological,

4 .Defined as a power sector that emits 5% or less of baseline GHG emission levels.

5. Levelized cost of electricity (LCoE) was calculated without a projected carbon price; a price of €20-30 per tCO₂e would effectively equalize the baseline LCoE with the LCoE of the decarbonized pathways. A significantly higher CO₂ price may be required to provide incentives for new investments. Volume 2 will address the policy implications

regulatory and collaborative activities have to start now in order to ensure a realistic pathway towards achieving the 80% GHG reduction by 2050.

DEPLOYMENT OF EXISTING TECHNOLOGIES COULD REDUCE GREENHOUSE GAS EMISSIONS IN EUROPE BY 80% BY 2050

By deploying technologies already commercial today or in late development stage, Europe could reduce greenhouse gases emissions by 80% by 2050 compared to 1990 and still provide the same level of reliability as the existing energy system. Assuming no fundamental changes in lifestyle, this transition nonetheless requires that all currently identified emission abatement measures⁶ in all sectors will be implemented to their maximum potential. These include energy efficiency measures; decarbonization of the power sector; a fuel shift from oil and gas to power and biomass; afforestation; and many others. Specifically, this means that:

- *Energy efficiency* improvements up to 2% per year are realized. This project assumes that energy efficiency measures like those identified in the McKinsey 2030 Global GHG Abatement Cost Curve for Europe are implemented fully and in all sectors. These include aggressive energy efficiency measures in buildings, industry, transport, power generation, agriculture, etc. It also assumes that the energy efficiency measures identified in the 2030 GHG abatement curve penetrate further as the timeframe continues to 2050.
- Nearly full *decarbonization of the power sector* is achieved by relying to varying degrees on renewables, nuclear and carbon capture and storage (CCS), along with a significant increase in transmission and distribution investments.

- *Fossil fuels are replaced* in the buildings and transport sectors by decarbonized electricity and low CO₂ fuels (e.g., 2nd-generation biofuels).
- All *other identified emission abatement* measures are implemented, such as CCS in industry and afforestation.

Prerequisites assumed in *Roadmap 2050* for a reliable and affordable decarbonized power sector include: to have a geographical distribution of supply technologies and resources that have sufficient potential in the aggregate to meet projected demand; to use a mix of technologies rather than a few; to allow sufficient time for the implementation of the pathways to avoid stranded costs due to early retirements (yet to retire plants at the end of their assumed economic lives); and finally to deploy these resources across a transmission and distribution grid capable of fully meeting demand for electricity in all places at every hour of the year to the current reliability standard of 99.97%⁷.

Decarbonized electricity consumption in 2050 is estimated to be about 4,900 TWh per year (including Norway and Switzerland), which is approximately 40% higher than today. In the baseline (consistent up to 2030 with IEA WEO 2009), the overall power demand would also grow by about 40% by 2050. *Roadmap 2050* assumes that this “business as usual” growth in demand is avoided almost completely by applying the aggressive energy efficiency measures described above. However, because of growth in new sources of power demand (for electric vehicles and heat pumps in buildings and industry), the overall quantity of demand for electricity in 2050 is roughly the same as it would have been without decarbonization⁸ (though overall energy consumption is lower because of the higher efficiency of electric vehicles and heat pumps compared to what they are replacing).

6. This report leverages the extensive work done by McKinsey on the technical GHG abatement potential up to a maximum cost of €60 per tCO₂e (and assumes further abatement potential up to €100 per tCO₂e). For more details please refer to its report available on its website (“Pathways to a low carbon economy: Version 2 of the Global Greenhouse Gas Abatement Cost Curve”).

7. This reliability means that over the course of a year 99.97% of the total electricity demand is delivered. Any demand that is not met is generally managed through contracted “interruptible loads” rather than through brown-outs or black-outs.

8. This is the net sum of economic growth, energy efficiency measures and electrification of transport and heating; if the energy efficiency targets were not met and electrification were still to be pursued as modeled, electricity demand would increase by 80 % compared to today’s levels.

Power generation technologies (and the associated primary energy resources) capable of producing the required 4,900 TWh per year of decarbonized power exist today, either commercially available or in late stage development. Several mixes of power technologies have proven to be feasible, providing reliable power at all times at an economic price on average over the 2010-2050 period. The technologies include hydro; coal and gas plants with CCS; nuclear plants; wind turbines (onshore and offshore); solar PV and CSP; biomass plants; and geothermal plants. The supply mixes tested cover a share of renewable energy between 40% and 100%, a share of nuclear energy between 0% and 30%, and a share of fossil fuel plus CCS plants between 0% and 30%. For both CCS and nuclear a sensitivity up to 60% was assessed on cost and reliability. A supply of solar power from outside Europe (based on commercial CSP technology) as well as breakthrough in technology with enhanced geothermal was assumed for the 100% renewable energy pathway.

The rationale for using a mix of sources rather than a few technologies in each of the pathways is that a) most technologies do not have sufficient theoretical capacity to supply all demand, b) a mix of technologies is more robust against delivery risks, and c) different technologies can be utilized to a greater extent in those regions where they are most suitable. A diversity of resources also enhances supply security. While the three main pathways employ some quantity of nuclear and coal-with-CCS plants operating in customary fashion, neither nuclear nor coal-with-CCS is necessary to deliver decarbonization while maintaining the current standard of reliability (as described in chapter 7 on Further opportunities, with the 100% RES being fully reliable), nor was the combination of nuclear or coal-with-CCS incompatible with high renewable shares. In each pathway, CCS is required to achieve significant abatements in industry. It should be noted that the resulting technology mix is not always similar to the forward-looking projections of industry associations and analysts, especially in the short term.

Implementation of new policies and regulations, orderly construction of new plants, and a smooth build up of the new technology supply chains requires the full period of about forty years available between now and 2050. Existing (CO₂ emitting) plants are assumed to be able to operate to the end of their economic lives⁹, at which point their retirements, along with load growth, will create the market demand required for investments in low carbon technologies to deliver the projected learning potential. However, if the new energy system would be delayed significantly at first and then implemented at an accelerated pace later, the risk of a forced retirement of high-emitting plants increases. This would be the result of new plants being built at the beginning of the period, to compensate the slower implementation of low-emitting technologies, that would be replaced by such technologies later but before the end of their economic life. A significant delay in building out the new system could also create a risk of temporary supply chain shortages, which would increase the cost of transition.

Compared to today, all of the pathways, especially those with higher RES penetrations, require a shift in the approach to planning and operation of transmission systems. Electricity demand is no longer fixed and unchangeable. 'Smart' investments that make demand more flexible and responsive to the available supply of energy can significantly reduce system costs and implementation challenges. Expansions of transmission system capacity are a crucial and cost-effective way to take full advantage of the low-carbon resources that are available, when they are available¹⁰. Inter-regional transmission must develop from a minor trading and reserve-sharing role to one that enables significant energy exchanges between regions across the year, enabling wider sharing of generation resources and minimizing curtailment. Operation of the grid must be based on greater collaboration over wider areas. To achieve this, it is paramount that planning and evaluation of transmission investments and operational decisions consider wider regional benefits than is currently the case.

9. The economic lives assumed here are approximations of the average depreciation lifetimes of the various plant types.

10. A detailed assessment of distribution system investments is outside the scope of this report. Distribution investments in the future are likely to be significant, but the extent to which they will be incremental to the baseline, rather than investments already required in the baseline, is unclear.

A significant challenge is the provision of low load factor dispatchable capacity that can be available, for example in winter when there is less solar production and demand is higher. Roughly 10% to 15% of the total generation capacity would be needed to act in a backup arrangement with low load factors. The preferred technologies for the backup service are yet uncertain, and the attractiveness of the various options needs to be assessed in more depth. Currently, likely options include: extensions of existing flexible plants but limited to very low utilization rates¹¹; new gas-fired plants (e.g., open-cycle gas turbine plants without CCS)¹²; biomass/biogas fired plants; and hydrogen-fueled plants, potentially in combination with hydrogen production for fuel cells. The implications for gas or hydrogen networks have not been studied in detail. Storage is optimized to create additional flexibility. The study has not assumed any additional large-scale storage capable of shifting large amounts of energy between seasons but with new technology this may become an economic alternative. Neither has vehicle-to-grid storage been assumed. If proven economic and feasible, this could enhance the balancing capability of the system.

DECARBONIZATION WOULD ENHANCE GROWTH AND SECURITY OVER THE LONG TERM

While the unit cost of *electricity* over the 2010-2050 period could be 10-15% higher than in the baseline (excluding carbon pricing), the overall cost of *energy* in the decarbonized pathways declines by 20-30% over the period relative to the baseline, due primarily to greater energy efficiency and a shift from oil and gas to decarbonized electricity in the transport and buildings sectors. In the pathways, GDP growth is slightly higher as a result this improvement in

productivity, though the impact is likely to differ from region to region. Reliance on fossil fuels declines significantly in the decarbonized pathways and the use of indigenous energy sources with low or zero fuel costs expands significantly, which together increase the security and stability of Europe's energy supply.

- **Across the energy system** (electricity, oil, gas and coal, supply and demand sectors), the cost of energy per unit of GDP decreases in 2010-2020 by ~15% in the baseline and ~25% in the decarbonized pathways (mostly due to increased efficiency). After 2020, the cost of energy per unit of GDP continue to decrease more strongly in the decarbonized pathways, resulting in a 20-30% benefit in energy cost per unit of GDP in 2050. This is mostly an effect of more energy efficiency and a shift away from oil and gas to power, as well as lower GHG emissions which reduce the exposure to carbon prices. The benefit of the decarbonized pathways is equivalent to a lower total cost of energy of € 350 billion per year by 2050, or € 1,500 per year per household.
- **Within the power sector**, the levelized cost of electricity of the decarbonized pathways is about 10-15% higher than in the baseline. This difference would be bridged with an *average* CO₂ price of at least € 20-30 per ton¹³. A significantly higher CO₂ price may be required to provide incentives for new investments. Volume 2 will address the policy implications. In the decarbonized pathways, the levelized cost of electricity is relatively higher in the 2010-2020 period and relatively lower in the period 2030-2050. This cost evolution reflects an increase in capital invested, offset by a decrease in the overall running costs. The capital costs for the power sector are about 70% higher than in the baseline, with an additional €25 billion per year of investment on average over the 2010-

11. The costs of converting and maintaining an existing fossil plant for this purpose may in most cases be prohibitive relative to alternatives, such as OCGT.

12. In case of gas-fired backup plants, an increase in generation capacity will require an increase in gas transport and storage capacity (to be able to deliver the gas at peak times); however, parts of the current gas transport and storage system might become available for this use, as the system has been dimensioned for winter peak demand for heating from commercial and residential customers which will no longer be needed if all buildings have electric heating.

13. Input assumptions moderately affect these conclusions: an increase in the real after-tax cost of capital from 7% to 9% increases electricity costs by 15% in the decarbonized pathways and by 10% in the baseline. If RES cost reductions fall behind the learning rate assumptions by 50%, the cost of electricity increases by 15% in the decarbonized pathways, and by 2% in the baseline. A 25% higher fuel price increases the cost in the baseline by 10% compared to 5% in the decarbonized pathways.

2050 period compared to the baseline. A market and regulatory environment that offers investors sufficient incentives is required to trigger the required investments in capital-intensive generation and transmission capacity.

While these numbers represent less than 1% of annual GDP over that period, the change is significant for the energy sector. The power sector will require more capital to finance the investments in low/zero carbon generation, transmission and back up capacity. Longer term, the coal, gas and oil sectors may see investments decline by 50% due to lower demand, which can have large implications for certain countries. Clearly, this number depends on the extent to which the lower demand displaces imported vs. domestically produced fuels and to what extent the decline would have happened anyway in the baseline. Notwithstanding a possible decline, fossil fuels still play a significant role in all pathways. Natural gas in particular plays a large and critical role through the transition.

In the 2010 to 2020 period, the slightly higher electricity costs would reduce the growth rate in GDP by 0.02% compared to the baseline. This means that the same 2020 GDP levels would be reached about one month later in the decarbonized pathways than in the baseline. Such macro-economic modeling should be seen with its usual limitations: it is not meant as a forecast but only as a tool to better understand the potential impact of such measures. The results show that the likely impact on GDP growth is lower than the customary margin of error for macro-economic forecasts. Higher electricity prices may reduce competitiveness for sectors that compete globally and have a high share of energy costs, though can be offset to some extent by investments in energy efficiency. If Europe is able to build and maintain a leading position in clean technology, increased exports could contribute about €25 billion per year to GDP in this first decade, similar to the contribution of about 10 of the largest European technology providers. This is equivalent to a contribution to GDP growth of about 0.04% per year.

From 2020 to 2030, the cost of energy (power and primary energy) per unit of GDP is already lower than

in the baseline, as more energy efficiency is realized and oil and gas demand is shifted to electricity, which is lower cost and results in greater energy efficiency. Annual GDP growth could be slightly higher than in baseline, by about 0.03%.

In the 2030 to 2050 period, the cost of energy per unit of GDP output could be about 20 to 30% lower in the decarbonized pathways than in the baseline. The lower cost is due to the large implementation of energy efficiency levers and a significant shift away from oil and gas in transport and buildings, with electric vehicles, fuel cells and heat pumps being both more efficient than current technologies and using lower-cost energy sources. Though the total bill for electricity in the decarbonized pathway is similar to the baseline, on an overall energy system level (power, oil, coal and gas), the annual cost advantage could grow to €350 billion per year in 2050. As a result, the annual GDP growth rate in the decarbonized pathways is about 0.07% higher than in the baseline. Achieving the energy efficiency reductions is of critical importance: if only half of the desired energy efficiency measures were achieved, and the cost doubled, GDP in the decarbonized pathways would be €300 billion lower by 2050, eroding the improvements in productivity and imposing additional investment requirements for generation and transmission.

The changes in the energy system would have an impact on overall employment. New jobs are created to implement energy efficiency measures (e.g., building insulation) and to develop and install new technologies (e.g., heat pumps, electric cars and hydrogen fuel cells, capital investments in power generation and transmission). Sectors that benefit most are construction and mechanical engineering. The total number of these new jobs by 2020 could range from 300,000 to 500,000. At the same time, employment in some primary energy supply chains may erode, depending whether it is European fossil fuel production or imports that are displaced. Demand for oil, coal and gas may decrease by 60 to 75% between 2010 and 2050 compared to the baseline. Over 250,000 jobs could be at stake, both in the baseline and the decarbonized pathways. Clearly, some regions will be hit harder in this respect than others. Short-term interventions could ensure that employees in vulnerable industries and

regions are appropriately supported, both in financial assistance and in skills retraining, in the transition years 2010-2020¹⁴.

The security of Europe's primary energy supply is improved in the decarbonized pathways. Substantial benefits can be expected in terms of the resilience of the economy to volatility in fossil fuel prices. A spike in oil and gas prices has often been the spark that ignites a recession. On a total economy level, the demand for coal, oil and gas would be reduced significantly. Fuel sourced from non-OECD countries for power supply could decrease from 35% of total fossil fuels in the baseline down to 7% of total fossil fuels in the pathway that relies on 80% renewable energy sources. Moreover, the absolute volume of fossil fuels is lower in the high renewable energy pathways. At the same time, local control of power supply for each member state in the EU remains similar to what it is today, as significant capacity in backup plants ensures sufficient local production is available to cover most of the local demand for electricity. Sufficient grid and back up investments can ensure that the increased intermittency of the decarbonized pathways delivers reliable power.

IMPLEMENTATION IS THE BIGGEST CHALLENGE

Although the decarbonization pathways seem feasible from a technical and economic viewpoint, the feasibility of implementation is less obvious. The magnitude of change required in the sectors affected is substantial in all of the decarbonization pathways tested. Between now and 2050, a decarbonized economy will have to achieve the following milestones:

- On average, the pathways require the installation of about 5,000 square kilometers of solar panels over 40 years equaling about 0.1% of the area of the European Union (assuming 50% of these being rooftop solar panels). This requires
- significant project management efforts and (spatial) planning and permitting at large scale. The new installation and replacement of close to 100,000 wind turbines (of which half could be at sea), equaling 2,000 to 4,000 new wind turbines per year. This is about the same pace as the wind sector has built over the past decade, albeit that the new wind turbines are significantly larger (up to 7-10 MW), with a large share offshore in challenging conditions.
- The addition of significant new transmission capacity, with several thousands of kilometers of new inter-regional transmission infrastructure required. The overall expansion required over 40 years is a factor-three increase from today's level of inter-regional transmission capacity. In some corridors the expansion will be even greater, such as, for example, in Iberia to France, where capacity is currently less than 1 GW and the required increase would range from 15 to 40 GW (high end of the range with 80% RES penetration). Clearly this will not be possible unless the historical pattern of public opposition is addressed; among other things, this will involve reconsideration of public planning processes to bring greater clarity of purpose and remove barriers. Alternative solutions to overhead lines over the Pyrenees may need to be considered¹⁵, as well as alternative generation mixes with higher wind and lower solar generation. Additionally, enhanced local distribution networks and IT applications for smart grid functionality must be implemented on top of the baseline maintenance, expansion and upgrades already anticipated.
- Approximately 190 to 270 GW of backup generation capacity is required to maintain the reliability of the electricity system, of which 120 GW already in the baseline. This represents 10 to 15% of total 2050 generation capacity (the high end being the 80% RES pathway). This capacity would be required on a regional basis and will be run at load factors of less than 5% for

14. However, concerns about carbon leakage through the potential relocation of industry due to stringent emission regulations seem to be often overplayed: external research indicates that less than 1% of industrial production could potentially relocate. While many factors influence such decisions, further research is required to clarify what level of carbon penalty could affect the share of industry affected.

15. E.g., underground and sub-marine cables; in costing new transmission needed in the decarbonized pathways, it has been assumed that a mix of AC and DC, overhead, underground and sub-marine technologies will be deployed, which reflects in part the assumption that transmission cost levels between Iberia and France are based on deploying a disproportionately high percentage of underground and/or sub-marine cables.

the 40%/60%/80% pathways and up to 8% in the 100% RES pathway.

- In each of the pathways, CCS is required. The three main pathways include CCS for power generation and all scenarios require CCS to abate industrial emissions, e.g., for steel, refining, chemicals and cement. The realization of an extensive CO₂ transportation and storage infrastructure across certain regions in Europe, depending on where and how CCS will be most intensively deployed.
- In the 40% RES pathway, about 1,500 TWh per year of nuclear production is required, compared to approximately 1,000 TWh per year today. Approximately 200 GW of new nuclear plants would need to be built, representing approximately over a hundred new nuclear plants entering construction by 2040. The 80% RES pathway requires that about half of the current level of nuclear production is replaced.
- The deployment of potentially up to 200 million electric and fuel cell vehicles and potentially around 100 million heat pumps for buildings or city districts across Europe. Achieving these goals would require a fundamental transformation of the automotive supply chain as well as a large construction effort in buildings and associated infrastructure.

The fundamental transformation of all energy-related sectors requires steep growth of supply chains for engineering, manufacturing and construction of power generation, transmission infrastructure, energy efficiency measures, new car types, etc. Yet the required rate of growth is not without precedent, and it is considered feasible by industry experts. Funding requirements shift substantially. Within the power sector, about € 30-50 billion per year of additional funds are required for more capital-intensive generation capacity and grid investments. Capital for oil, gas and coal supply in Europe may come down by 30%. Funding is required for new investments in energy efficiency measures, heat pumps and alternative drive trains, which may add up to over € 2-3 trillion over 40 years.

All decarbonization pathways explored in Roadmap 2050 confront profound implementation challenges.

Some challenges – like the need for large and rapid additions of transmission capacity between and within regions – are common to all pathways, though they differ in scale from one pathway to the next. Other challenges tend to emerge within some pathways more than others – for instance, one pathway relies heavily on a large, sustained nuclear construction program, while others rely heavily on deployment of “smart” demand-side technologies and practices to manage high levels of intermittent supply. Apart from the implementation challenges, the pathways also face large public acceptance challenges. These affect all scenarios, but differ significantly between them across the various dimensions.

Recognizing the current challenges in achieving new licenses and rights of way for transmission lines, a sensitivity was investigated with substantially less transmission than the capacity reached in the optimized case. The alternative to transmission was modeled as additional storage capacity within the system. The analysis shows that there would be a need to add more than 125 GW of new storage capacity (approximately 3 times the existing EU storage capacity) with an associated 50 TWh of energy storage (equivalent to about 50% of the average storage in Norway) spread across all of the regions. An alternative approach could be to supply the additional power required from generation when transmission constraints limit energy import and to allow the curtailment of output from renewable sources when export potential is limited. This approach requires about 40 GW of additional generation capacity and leads to a curtailment of renewables of nearly 10%, three to five times the level of curtailment in the cost optimized case. In both of the alternative cases the overall costs would be significantly higher than those for the cost-optimized transmission investment case.

Delivery risks exist for most technologies. Nuclear and to some extent CCS carry public acceptance risks. Nuclear faces proliferation concerns and issues with handling and disposal of high-level radioactive waste. The quantity of long-term storage capacity that will be feasible for CCS is still unclear, while a CO₂ transport infrastructure will need to be constructed. Onshore wind also faces local public acceptance issues, while offshore environments

make the construction and maintenance of offshore wind installations challenging. For biomass, the development of a reliable logistics infrastructure is challenging, as is avoiding competition with food and water and negative effects on biodiversity. Learning for most of the required technologies, particularly for solar and CCS, will need to be achieved through continued R&D, demonstration and/or deployment investments.

Arguably the toughest challenge of all is to obtain broad, active public support for the transformation, across countries, sectors and political parties. Transnational cooperation is required for regulation, funding, R&D, infrastructure investments and operation. Societal enthusiasm for the changes is also needed to draw talent and energy, much as the high-tech sector did in recent decades, to innovate, plan and execute these massive changes in power supply and consumption. Resilience to overcome inevitable setbacks will be required, including initiatives to change public attitudes regarding the construction of large-scale overhead transmission infrastructure.

In summary, the challenge in implementation is not “the same, but more.” Europeans possess the skills, the technology, the capital and the industrial wherewithal to deliver this transformation, but the policies and regulations required to mobilize those vast resources to the extent required do not yet exist. If European leaders are serious about achieving an 80% reduction in GHG emissions by 2050, then a heavy burden falls upon policymakers, in Brussels and in member states, to re-shape the energy landscape through enhanced markets and effective regulation.

PRIORITIES FOR THE NEXT 5 TO 10 YEARS

Five priorities must be set for 2010-2015 in order for Europe to progress towards implementation of an 80% reduction target for greenhouse gas emissions by 2050:

1. Energy efficiency – The case for transition relies to a large extent on a marked improvement on financial incentive structures and the current pace of delivery of energy efficiency improvements across the economy. It is well established that

vast potential exists for cost-effective energy efficiency measures, less costly than supply measures required to replace them. The costs of the transition rise significantly if implementation of energy efficiency measures falls behind. Innovative programs will be needed to eliminate information barriers, reduce transaction costs and mobilize investment capital.

2. Low carbon technology – The case presented here does not rely on technology breakthroughs, but it does rely on steady, in some cases dramatic improvements in existing technologies. Coordination of support for development and deployment of, e.g., CCS, PV, offshore wind, biomass, electric vehicles, fuel cells, integrated heat pump and thermal storage systems, and networked HVDC technologies, including adoption of common standards, will be critical. R&D support for, e.g., enhanced geothermal systems, large-scale electrochemical storage and other new, potential breakthrough technologies will enable the transition faster and at lower cost.

3. Grids and integrated market operation – A large increase in regional integration and interconnection of electricity markets is key to the transition in all pathways and is urgently required even for the level of decarbonization already mandated for 2020; it is, paradoxically, also the key to reliable and economic integration of localized energy production, along with investments in smarter control of demand and decentralized supply. Effective transmission and distribution regulation, the development of regionally integrated approaches to planning and operation of grids and markets, and support from stakeholders are required.

4. Fuel shift in transport and buildings. The aggressive penetration of electric mobility, hydrogen fuel cells and 2nd generation biofuels for the transport sectors required after 2020 is contingent upon urgent action on progressively tightening emission standards, technology development programs and standards development for charging infrastructure. Likewise for buildings, the required large-scale roll-out of heat pumps and, to a lesser extent biomass/

biogas (potentially via district heating) means that these choices must be built into the design of energy efficiency programs in the next few years; roll-out could begin selectively in the near term in new construction to build up the commercial infrastructure required for wider application later on.

5. *Markets* – A massive and sustained mobilization of investment into commercial low-carbon technologies is needed, the vast majority of which will probably come from the private sector. Investors need greater certainty about future market conditions and the future competitive landscape. Current market design, i.e. energy markets based on marginal cost pricing, must be reviewed in light of the capital-intensity of these new technologies. Low-carbon investors need more clarity about the ultimate fate of high-carbon assets, to have sufficient confidence that their investments will be profitable under a sufficiently wide range of future market conditions.

If these priorities are addressed in the next few years, the public, investors and governments can move forward with a comprehensive infrastructure agenda that is consistent with the 2020 and 2050 objectives. This agenda should link to the specific investment agendas of governments, equipment manufacturers, TSOs and utilities.

THE CASE FOR AN ENERGY TRANSFORMATION

The energy transition towards a decarbonized economy has benefits that reach beyond climate change mitigation. This section describes the case for Europe in a broad sense. The study results are put in perspective by arguments both supportive and critical of the case.

RATIONALE FOR AN ENERGY TRANSFORMATION

The case for an energy transformation has been made several times over the past decades. The late 1970s and 1980s saw different levels of progress on biofuels (Brazil), nuclear, efficiency, renewables and cogeneration in response to energy security and environmental concerns. Interest in energy efficiency in particular was spurred by the oil embargo in 1973 and continued through the early 80s, but interest in efficiency waned once the price of oil returned to low levels in the mid 80s. In the 1990s, technology development in wind, solar and batteries as well as the introduction of electricity market liberalization drove the need for and potential of higher renewable targets. Over the past decade a combination of high growth in demand for energy, slowing growth in oil supply and growing concern about climate change have been driving the case for renewable energy and energy diversification. The current case for an energy transformation can be summarized as follows:

A. Lower energy costs per unit of output and more stable and predictable energy prices.

While unit electricity costs in the decarbonized pathways could be on average 10-15% higher than in the baseline (excluding carbon pricing), energy costs per unit of economic output come down by 20% to 30% compared to the baseline,

due to increased energy efficiency and a shift from oil and gas to decarbonized electricity in the buildings and transport sectors. Because the economy in the decarbonized pathways depends on low/zero fuel-cost sources (mostly renewable energy and nuclear), the marginal production costs are low and energy costs are more stable and predictable.

B. New economic growth and job creation through innovation.

The transition requires about € 7 trillion¹⁶ of investment over the next forty years in new energy efficiency measures, clean technology and new infrastructure. The new technology investments could create between 300,000 and 500,000 jobs. About 250,000 jobs could be at stake in the fossil fuel industry. Clean tech investments could provide a €25 billion annual export market over the first decade, depending on whether Europe can reach and maintain a leading position. The impact is likely to differ from region to region and for different sectors of the economy.

C. Increased security of energy supply and more economic stability.

Demand for fossil fuels could fall by over 60%, compared to an increase in fossil fuel demand in the baseline. In a future with higher competition for natural resources, Europe would become less reliant on energy imports. It is conceivable that other dependencies could arise in the event that some technology supply chains become more reliant on specific sources for critical materials.

D. More sustainable energy and fewer emissions.

Greenhouse gas emissions are reduced by 80% in the decarbonized pathways from 1990 versus only a 10% decrease in the baseline, even though the baseline includes significant energy efficiency measures. Depending on emission levels outside

16. This includes € 4.2 trillion that is also required in the baseline

Europe, some cost for climate change adaptation may be avoided. Other emissions, like NO_x, SO_x, black carbon, other particulates and noise will also decline significantly. In the decarbonized pathways, economic growth is more sustainable, as a shift away from fossil fuels is required in any case at some point in the future due to resource depletion.

INSIGHTS THAT MAY CHANGE 'COMMON WISDOM'

This study has provided some facts around key challenges to the feasibility and affordability of an energy transition:

A CO₂ reduction of at least 80% by 2050 is technically possible. A combination of efficiency, near full decarbonization of the power sector and fuel shift in transport and buildings can realize 80% emission reduction compared to 1990. Near full decarbonization of the power sector can be achieved by various mixes of low carbon supply technologies, like renewable energy, CCS and nuclear.

An expanded European grid can effectively reduce intermittency challenges. Intermittency issues on a national scale are becoming significant (e.g., Danish power prices falling to below zero). Local solutions, like storage capacity investments are typically considered. These can alleviate intermittency issues, but often result in relatively high renewable energy curtailment, e.g., up to 15%. The cost of storage plus the loss of renewable power production could be material. A cost effective solution is to expand the inter-regional transmission grid across Europe. Fluctuations in demand and supply are canceled out to a large extent and back up capacity is available at larger scale. The grid investments required are around 10% of generation investments and reduce curtailment to 1 to 5%, making it an effective and economic solution.

A high renewable supply system is technically feasible. Higher levels of intermittency can be managed through a combination of significantly expanding the European transmission grid, building significant back up capacity plants, applying demand

response and potentially using energy sources from outside Europe (e.g., North Africa).

Roughly speaking, for every 7-8 MW of intermittent capacity (wind and solar PV), about one additional MW of back up capacity is required. Back up plants form an important part of the system balancing and are required especially at times in winter when the solar power is low, wind lulls occur and the demand for heat pumps is the highest. The load factor of the back up plants is expected to be below 5% for the 40%/60%/80% RES pathways and up to 8% in the 100% RES scenario.

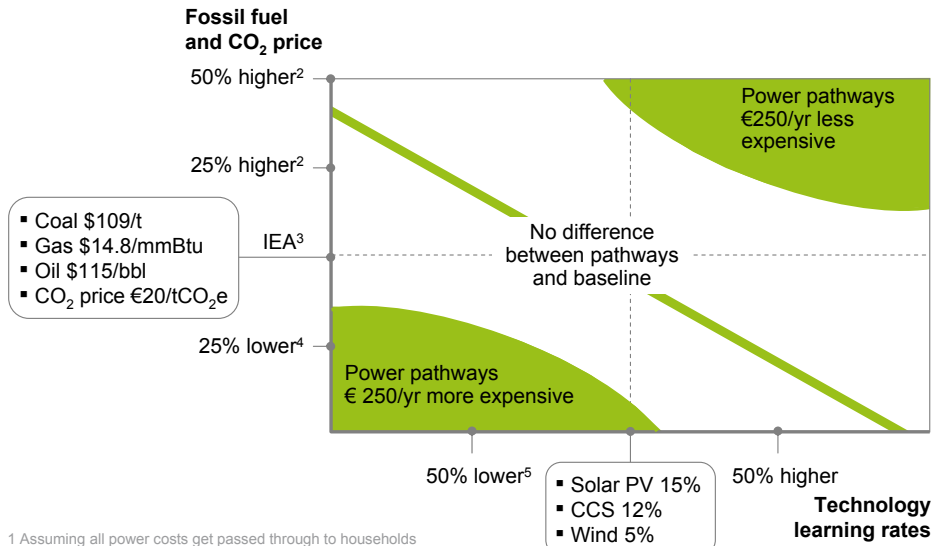
Technology breakthroughs are not required to decarbonize the power sector. All technologies assumed in the three main decarbonized pathways are commercially available at large scale, except CCS, which is in late stage development. Although technology breakthroughs can be expected, they are not required to decarbonize the power sector. Continuous cost reductions are required to make the decarbonized pathways economically competitive versus the baseline. Decarbonization in the transport sector requires mass application of electric vehicles, hydrogen fuel cell vehicles and/or biofuels. This requires a significant improvement in performance and cost. Similarly, decarbonization in buildings requires a breakthrough in the application of heat pumps.

Costs of electricity of the decarbonized pathways are comparable to the baseline and, even with pessimistic assumptions, the impact per household is below € 300 per household per year. Depending on the assumptions, electricity costs can be higher or lower in the decarbonized pathways. If assuming IEA fossil fuel prices and industry average views on technology learning rates, the cost of decarbonized energy is € 100 per year per household more expensive. When assuming an average CO₂ price of 20-30 € per tCO₂e over 40 years, the cost difference disappears. A significantly higher CO₂ price may be required to provide incentives for new investments. Volume 2 will address the policy implications. When assuming 25% higher fossil fuel prices, a CO₂ price of € 40 per tCO₂e and 50% higher technology learning rates, the average household is €250 per year better off,

EXHIBIT 1

The cost of the decarbonized pathways and the baseline are likely to differ less than € 250 per year per household

Cost impact of the decarbonized power pathways per year per household¹



1 Assuming all power costs get passed through to households
 2 CO₂ price assumed of € 40/tCO₂e
 3 IEA WEO 2009 '450 Scenario' assumptions for 2030, kept constant up to 2050
 4 No carbon price
 5 For all technologies. Learning rate is defined as capex improvement per doubling of cumulative installed capacity

vice versa. Superimposing 25% lower fuel prices, 50% lower learning rates plus €500 billion cost of change would result in a €300 higher annual cost per household than in the baseline (see Exhibit 1).

Both nuclear and fossil plants with CCS can be compatible with intermittent renewable energy sources. The combination of an expanded grid and increased back up plant capacity can balance a system that contains both some quantity of “baseload” generation as well as high levels of intermittent power. Load factors of nuclear and coal plus CCS remain high throughout the year, while curtailment of renewable energy remains below 3%.

Nuclear and/or coal-with-CCS plants are not essential to decarbonize power while safeguarding system reliability. A scenario with 100% renewable energy was evaluated. It includes

15% imports from North Africa and 5% from EGS, qualified as a breakthrough technology. It was evaluated in particular from the perspective of system reliability and was found to be capable of delivering the same level of reliability; the cost of electricity for this scenario contains higher levels of uncertainty and warrants additional study, but it does not appear to be dramatically more expensive than the main decarbonization pathways studied. In this pathway, storage and/or biogas are needed to keep emissions from OCGT plants at reasonable levels.

Delay by 10 years is not the better option if the 2050 target needs to be met. Although fundamental research will develop without large scale investments in renewable technologies, the cost improvements through scale effects are not realized if investments are delayed. Furthermore, the required investments prior to 2050 would have to be realized in 3 rather

18. Demand Response (DR) refers herein to a change up or down in a customer’s electricity demand in response to dispatch instructions or price signals communicated to customers’ premises; DR as used here does not reduce the energy delivered in a day, it time-shifts it within the day.

than 4 decades, increasing pressure on supply chains and funding, potentially leading to price increases due to shortages.

Distributed production does not take away the need for increased transmission. The analysis assumed up to 50% of solar PV is deployed on rooftops and the grid solutions reflect that assumption.

Storage facilities and electric vehicle-to-grid are not necessary but could improve the technical feasibility and economics. Storage beyond existing hydro and battery back delivery will reduce the need for grid and back up capacity.

ARGUMENTS THAT WOULD MAKE THE CASE MORE OR LESS ATTRACTIVE

There are a number of reasonable arguments that the case for transformation could be less attractive than portrayed in this report. Several of these warrant additional work to better understand the implications. This is particularly true for the effectiveness of new policy and the potential cost of implementation, the impact on distribution and gas infrastructure and the costs of change.

Similarly, there are a number of valid arguments why the case for transformation is more attractive than portrayed in this report. These may cancel out the challenges mentioned above to a greater

or lesser extent. Of particular importance would be the impact of successful breakthroughs in technology and the reduced exposure to economic recessions caused by sudden increases in oil and gas prices.

Arguments for a less attractive case	Potential impact
1. Ineffective or counter-productive <i>regulation</i> could drive (capital) costs up, e.g., when energy efficiency measures fail, common standards are not adopted or investments are delayed due to lack of incentives.	<i>High.</i> Regulation is complex. Executing the transition well is critical. Misguided regulation could have devastating effects on the current system. For example, reduced success in energy efficiency could cut GDP by €300 billion in 2050.
2. Incremental costs for <i>distribution</i> are not incorporated. Individual house connections may have sufficient capacity, but on a street / neighborhood level, capacity could be insufficient to cope with EVs, heat pumps and back delivery of decentral solar (although demand response ¹⁸ will reduce peak load significantly). Costs for DR not included.	<i>High.</i> Estimates of the total distribution investment costs are €200 to 300 billion. However, grid upgrades are also needed in the baseline, so the incremental cost in the pathways will be less. If none of the required investments were required in the baseline, the cost of electricity could increase by an additional €5 to €7 MWh (5%).
3. Lack of <i>public support</i> could drive costs up and delay implementation, e.g., requirement for more underground cables and permitting issues for on shore wind and CO ₂ storage.	<i>High.</i> Public opposition to, e.g., new overhead power lines, onshore wind farms, new nuclear plants and new CO ₂ storage facilities has been and continues to be a major impediment.
4. The <i>cost of change</i> and the risk of (partial) failure are not incorporated. Large write-offs are common in industries under transition, e.g., UMTS, investments in fiber networks.	<i>High.</i> The magnitude depends on the effectiveness of regulation and the pace allowed.
5. The assumed technology learning rates and cost reductions may not be achieved (e.g., 15% learning rate for solar PV).	<i>High.</i> A 50% reduction in learning rates across all technologies could increase the delta to the baseline by €10 per MWh.
6. <i>Implementation constraints could be more severe, e.g., Iberia/France interconnection, locations for wind onshore, solar, spatial requirements for heat pumps.</i>	<i>Medium.</i> Alternative are available, e.g., laying part of the Iberia-France link underground or undersea; shifting the generation to more wind and less solar.
7. <i>Incremental gas infrastructure</i> costs for backup plants are not incorporated (primarily pipelines and storage)	<i>Medium.</i> Depending on the pathway, with lower residential and power demand for gas the current gas infrastructure might suffice.
8. <i>Fossil fuel prices</i> may be lower than anticipated by IEA.	<i>Medium.</i> A 25% price reduction reduces the transition benefits by less than €5 per MWh.
9. <i>Increased demand</i> could raise costs. If GDP increases faster than energy costs, consumers may decide to use more energy, not less	<i>Low.</i> Demand for decarbonized electricity will only increase if the costs are low and it is priced attractively.
10. <i>Extreme weather conditions</i> result in more year-on-year volatility in natural resources (e.g., wind lulls during winter when demand is high, potentially combined with cloudy skies)	<i>Low.</i> <i>Extreme weather conditions are included in the base case. Providing for conditions beyond these would cater for more than 1/20 year events adding < €1-2 per MWh.</i>

Arguments for a more attractive case	Potential impact
1. <i>Innovation</i> and related energy price reductions could create additional spillover effects in other sectors (e.g., energy-intensive industries)	<i>High</i> . Past innovations have had significant impact on productivity levels and contributed up to 1% additional GDP growth.
2. <i>Technology learning rates</i> are too conservative, or a <i>breakthrough technology</i> could emerge within the next 40 years.	<i>High</i> . Except for hydro, nuclear and conventional geothermal, all low/zero carbon supply technologies are emergent. Promising new concepts are being tested at pilot scale.
3. The exposure to <i>oil and gas price spikes</i> is lower in the decarbonized pathways. The risk of an oil or gas price triggered recession is therefore lower.	<i>High</i> . Academic studies have shown a direct correlation between price spikes and the onset of recessions. The pathways are significantly more resilient, saving 0.5% of GDP at the outset of such a crisis (over €70 billion a year).
4. The <i>total car cost of electric vehicles</i> or fuel cell vehicles will converge to the total car cost of a combustion engine car. Currently, a € 5,000 car cost difference is assumed to remain until 2050.	<i>High</i> . If the production cost of conventional and electric cars converges, it would result in an improvement in the decarbonized case of up to € 500 billion over forty years.
5. The assumed <i>technology mix</i> for 2050 is not fully optimized and the actual 2050 system could be more efficient and less costly than modeled in this study. The CO ₂ abatement effect of CCS on co-fired biomass is not taken into account, which could be 5-10%	<i>Medium</i> . More detailed understanding of the regional and future costs will allow more optimal technology allocation.
6. The <i>cost of capital</i> could fall below 7% due to smart regulation, optimizing risk between investors and other stakeholders, enabling higher leverage and lower interest rates.	<i>Medium</i> . A reduction in the cost of capital from 7% to 5% improves the electricity cost by about € 5 per MWh.
7. Integration with <i>regions outside Europe</i> could lower the cost of the technology mix. Large potential for solar CSP from North Africa or geothermal power from Iceland or Turkey would provide firm dispatchable power. Russia could supply low cost biomass and biogas.	<i>Medium</i> . The potential contribution of North African solar CSP and Icelandic geothermal would reduce the need for balancing and back up capacity, but higher transmission requirements could reduce that benefit. There may be other potential benefits in developing these options.
8. Fossil <i>fuel prices</i> could be higher than anticipated by IEA in the baseline. The same fuel prices are used in the decarbonized pathways, yet a global <i>shift away from fossil fuels</i> could result in lower prices.	<i>Medium</i> . A 25% increase for fossil fuels would give a relative benefit of €5 per MWh.
9. <i>Load shifting capability</i> could be larger than currently assumed in the study.	<i>Low</i> . While reducing the need for transmission and backup further, the cost for these is only about 10% of total power investments.
10. <i>Storage</i> will become more cost effective than transmission and backup, reducing the need for transmission investments (e.g., EV batteries).	<i>Low</i> . The cost for transmission and backup is only about 10-15% of total power investments.



GREEN EUROPE

80% CO2 REDUCTION

SUSTAINABLE ENERGY

LONG TERM GDP GROWTH

SUSTAINABLE ENERGY

ECONOMIC GROWTH

LESS POLLUTION

INTEGRATED EU

DEMANDSIDE MANAGEMENT

CO2 REDUCTION

GREEN EU

ROADMAP 2050

A PRACTICAL GUIDE TO A PROSPEROUS, LOW-CARBON EUROPE