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pathways to deep decarbonization *in France*

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Deep Decarbonization Pathways Project

The Deep Decarbonization Pathways Project (DDPP), an initiative of the Sustainable Development Solutions Network (SDSN) and the Institute for Sustainable Development and International Relations (IDDRI), aims to demonstrate how countries can transform their energy systems by 2050 in order to achieve a low-carbon economy and significantly reduce the global risk of catastrophic climate change. Built upon a rigorous accounting of national circumstances, the DDPP defines transparent pathways supporting the decarbonization of energy systems while respecting the specifics of national political economy and the fulfillment of domestic development priorities. The project currently comprises 16 Country Research Teams, composed of leading research institutions from countries representing about 70% of global GHG emissions and at very different stages of development. These 16 countries are: Australia, Brazil, Canada, China, France, Germany, India, Indonesia, Italy, Japan, Mexico, Russia, South Africa, South Korea, the United Kingdom, and the United States.

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The Institute for Sustainable Development and International Relations (IDDRI) is a non-profit policy research institute based in Paris. Its objective is to determine and share the keys for analyzing and understanding strategic issues linked to sustainable development from a global perspective. IDDRI helps stakeholders in deliberating on global governance of the major issues of common interest: action to attenuate climate change, to protect biodiversity, to enhance food security and to manage urbanization, and also takes part in efforts to reframe development pathways.

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Executive summary

In 2012, a National Debate on Energy Transition defined two main pillars for energy transition in France: the Factor Four (F4) – a 75% reduction in GHG emissions in 2050 (compared to 1990) – and reducing the share of nuclear power in the electricity mix (from 75% in 2015 to 50% in 2025), without further indication of the long-term role of nuclear energy. The National Debate Council of 2013 also identified two main structural features that would characterize France's energy-transition pathways:

- the level of energy demand reduction in 2050, compared to 2010, and
- the level of diversification of the energy supply.

This permitted delineating four scenarios, or pathways, which provide a rather complete mapping of France's possible energy futures.

The law on Energy Transition for Green Growth, adopted in July 2015 is grounded on the target of a 50% reduction of total final energy demand by 2050. It appears highly consistent with an *Efficiency* or *EFF*-type pathway (Table 1). The *EFF* pathway's crucial feature is indeed this very ambitious target of reducing demand. It supposes a 2% annual reduction in per-capita final energy consumption for France until 2050, the most ambitious rate among all decarbonization pathways analyzed in the Deep Decarbonization Pathways Project. This scenario entails:

- overcoming the energy-efficiency gap in all sectors, but particularly in the thermal retrofit of the entire stock of existing buildings,
- very ambitious changes in transport behavior, to stabilize individual mobility and goods transport,
- technology changes aimed at decarbonizing the entire car fleet, and
- a surge in the use of variable renewable energy (VRE), so that they account for up to 50% of power generation.

If this ambitious target of halving energy demand proved impossible to achieve, other pathways should be considered. Maintaining the emissions-abatement targets for 2050 would then entail a higher supply of decarbonized energy, which would reorient the strategy on the *Diversification* or *DIV* pathway. This, in turn, would raise another set of challenges: developing new nuclear plants consistent with Post-Fukushima safety standards at a competitive cost; making carbon capture and storage (CCS) technology available to industry; and the socio-technical possibility of producing very high amounts of bioenergy.

EFF and *DIV* pathways are then further analyzed (Section 2). A set of climate policy options, by sector, consistent with the peculiarities of both pathways, are then implemented. This is done within the computable general-equilibrium (CGE) model Imaclim-R France, to assess the economic impacts of each pathway.

The size of the carbon tax required to reach the F4 objective in each pathway amounts to 360 €/tCO_2 in *EFF* in 2050, and 280 €/tCO_2 in 2050 in *DIV*. A carbon tax would raise revenues amounting to €15bn (in *DIV*) or €20bn (in *EFF*) immediately after its introduction, and increasing until 2050 in spite of the gradual decline in emissions, to reach €30bn in both scenarios (i.e. 1% of GDP).

Aggregate cumulative investments are similar in both

Table 1 : Four future pathways for low-carbon energy transition in France

Diversification		Supply-side mix	
		Priority to one source of energy	
Final reduction in energy demand in 2050, compared with 2010	-20%	Diversity (DIV) 50% nuclear in electricity after 2025 40% renewables in electricity mix in 2050	Decarbonization (DEC) 75% nuclear in the electricity mix on the whole period 20% renewables in electricity mix in 2050
	-50%	Efficiency (EFF) Decrease to 25% nuclear in 2050 70% renewables in electricity mix in 2050	Sobriety (SOB) Phase-out of nuclear by 2050 90% renewables in electricity mix in 2050

scenarios but the *DIV* scenario would mainly rely on investments for decarbonized supply in the energy industry, whereas the *EFF* scenario places a larger share of the burden of investment decisions on end-users. In both cases, the drop in energy consumption, and the growth in non-fossil energy sources, would substantially improve France's energy trade balance from its current level of imports at 3% of GDP – an amount roughly equal to France's external trade deficit.

Household energy spending in the *EFF* scenario is halved in 2050 compared to 2010, despite the increase in investment for thermal retrofits, as a result of substantial energy savings in homes and changing mobility behavior patterns. In the *DIV* scenario, the household energy budget is reduced only by a quarter. The *EFF* scenario would drive annual economic growth 0.1% higher than *DIV* over the entire period, leading to a GDP 2.4% higher by 2050. This difference is mainly the result of the differences in household energy budgets and government consumption, which are transferred to other consumption, inducing more economic activity and more domestic production. Between 300,000 and 600,000 additional jobs would thus be created under the *EFF* scenario compared to the *DIV* scenario, mainly in the service sector, as a result of this "induced employment" phenomenon.

The report defines the scenarios, analyzes the obstacles to be overcome and the measures to be deployed and finally assesses the macro-economic impacts. Together, these factors clearly illustrate the magnitude of the uncertainties weighing on the energy transition. In section 3, a sequential two-stage analysis of the *EFF* and *DIV* pathways is conducted, taking into account the most uncertain dimension of each pathway, and the required adjustment of the strategy if:

- *EFF* fails to implement an ambitious energy savings program; or
- DIV finally cannot rely on the development of a new generation of nuclear power plants.

The analysis shows that the *EFF* strategy is apparently more robust, since it reduces the need for decarbonized energy, and leaves more room for maneuver if demand-reduction policies fail to perform as well as expected.

Furthermore, the analysis pleads in favor of setting up an institutional management system for low-carbon energy transition, comprising:

- imperatives, i.e. bringing together objectives which must be achieved regardless of which strategy is chosen (though insufficient in themselves to achieve the Factor Four target) ;
- short-term goals consistent with the long-term objective, but to be periodically reconsidered. The energy-transition management system should thus entail setting up a permanent monitoring system, the checking of progress annually, and providing feedback for dynamically managing the transition process. As part of this approach, the transition strategy would be regularly reviewed and adapted roughly every five years, in pursuit of adaptive short-term policies consistent with the long-term strategy.

Section 4 focuses on triggering the energy transition, in a macroeconomic context dominated by short-term imbalances. Energy transition policies can indeed lead to higher growth and a lower unemployment rate in the medium to long term. But even with very optimistic assumptions about the penetration of energy efficiency and low carbon options, the triggering of a low-carbon energy transition might be inhibited by the initial adjustment costs. These adjustment costs can be overcome only though a complex set of measures which encompass energy regulation measures on the demand and supply side, new patterns of development for urban and transportation infrastructures, a carbon tax, and a successful negotiation on recycling the revenues from this tax. Finally, the full deployment of the transition will require new financial devices to drastically decrease the risks to investors in low-carbon technologies and to redirect savings towards sustainable low-carbon projects.

A final conclusion is perhaps that a deep decarbonization pathway involves a profound modification of the social contract established at a time of cheap fossil fuels. Such a transition cannot be disconnected from the country's overall development strategy, and to succeed, will be conditional to France's ability to mobilize around reforms which, taken together, may define a new social contract.

1 The New French Energy Policy: From National Debate to the law on Energy Transition for Green Growth

1.1 A new framework for French long term energy policy

France's passage in 2015 of, the law on Energy Transition for Green Growth, represents the culmination of a process launched at the end of 2012 by the National Debate on Energy Transition. The debate over how to lower carbon emissions gradually identified the broad lines, and then the details, of what could be the 'French way' toward energy transition. The transition concept itself has a long history in France, with roots in projects designed to achieve more energy independence after the oil crises of the 1970s. The 1992 Rio UN Conference on Environment and Development and the Kyoto Protocol, ratified in 2005, led policymakers to a commitment to define new, lower-carbon energy policies aimed at reducing emissions by the energy sector.

Initial mentions began in 2003 of the need to reduce emissions by a "Factor of four" by 2050 – or F4. This F4 target was officially introduced in 2005, in the law that set France's energy policy guidelines, called in French the POPE law, for Programmation et Orientation de la Politique Energétique. Since then, F4 has been the focal point of France's energy policy.

1.1.1 The National Debate on Energy Transition in 2013

In 2013, when the Council of the National Debate on Energy Transition was convened, its Working Group on Pathways and Scenarios based its work on two main pillars: the F4 target for emissions in 2050, and reducing the share of nuclear power in the electricity mix. The first had already, albeit gradually, become a key plank of energy and climate policy in France. The latter, however, had only recently entered broad public discussion. Indeed, the discussion on diversifying the electricity mix, and reducing the share of nuclear power in electricity generation to 50% by 2025, dated only to the 2012 presidential election campaign. It is important to note that the 2025 objective has not been accompanied by an indication of what long-term role would be played by nuclear generation; all options remained open.

The process that was set up subsequently was rather unusual, breaking new ground in energy policymaking in France. The terms of the debate were not established from the outset by a political or administrative body, but were the result of a broad consultation among various groups of stakeholders including experts, business representatives, and civil society. Furthermore, the debate's aim was to define and discuss not one but several scenarios, or contrasting pathways. This began with the launching of a far-reaching inventory of different outlooks on France's long-term energy prospects, including scenarios produced by civil society (non-profits, NGOs, research centers, etc.). In all, 16 scenarios were selected, representing contrasting visions of the transition[1], but all displaying a sufficient level of internal coherence and relevance with respect to the two pillars, F4 emissions targets for 2050, and reducing the share of nuclear power in the electricity mix.

1 For example, preliminary analysis revealed huge differences, with electricity consumption varying between 280 and 840 TWh in 2050, compared with 450 TWh at present.

Table 2 : Four future pathways for low carbon energy transition in France

Diversification		Energy Supply-Side Mix	
		Priority to one source	
Final energy- demand reduction in 2050, compared to 2010	-20%	1. DIVERSITY (DIV) Strong reduction in consumption comes at a cost Share of nuclear power in the electricity mix stabilizes at 50% after 2025 40% share of renewables in the electricity mix in 2050	2. DECARBONIZATION (DEC) Strong reduction in consumption comes at a cost Nuclear power retains its 75% share in the electricity mix Renewables are limited at 20% in the electricity mix after 2020
	-50%	3. EFFICIENCY (EFF) Cut in consumption through use of best technologies Share of nuclear in the electricity mix decreases after 2025 to 25% in 2050 70% share of renewables in the electricity mix in 2050	4. SOBRIETY* (SOB) Major changes in consumer behavior Complete phase-out of nuclear power by 2050 Almost 90% share of renewables in electricity mix in 2050

* Energy sobriety is a neologism referring to "sobriété énergétique" in French. It means energy conservation or energy frugality.

The national debate process was designed as an exercise in deliberative democracy, but given the diversity of the 16 scenarios' starting points, they could not serve as the vehicle for direct input or discussions among the participants to the National Council of the Transition (environmental NGOs, other NGOs, employers, trade-unions, Parliament, local authorities and government). Instead, they needed to conduct analyses and discussions around a smaller number of visions. 'Families' of energy scenarios, were thus identified, grouping the 16 scenarios into four 'trajectories' or 'pathways.'

1.1.2 Four contrasting energy trajectories for France

These four possible energy futures were all compliant with the two-fold framing pillars or goals (F4 and 50% nuclear share in electricity mix in 2025, with one exception, discussed below), but very different in their structures and socio-economic implications[2]. Two essential indicators distinguish these pathways from one another (Table 2): the level of demand, as measured by the final energy-demand reduction by 2050 (either 50% or 20%); and the energy supply mix, as measured by the relative weight of nuclear power and renewable energy sources in the electricity generation mix.

The four pathways or trajectories delineate a very broad range, and provide a good mapping of France's possible energy futures. Setting aside the hypothesis that a major, game-changing, technological rupture could occur, it is hard to imagine a future outcome completely at odds with all four of these pathways. At one extreme, *Sobriety* (inspired by Negawatt[3]) is very close in its principles to the new German model of *Energiewende* (energy transition), with a nuclear phase-out. At the other extreme, *Decarbonization* (inspired by Negatep) corresponds to a continuation of the old French model, in which nuclear power predominates[4]. Between the two, *Efficiency* is very close to the scenarios elaborated by France's Environment and Energy Management Agency (Ademe)[5]. And *Diversity*

2 For more detailed information, see http://webissimo.developpement-durable.gouv.fr/IMG/pdf/tude_Trajectoires_DNTE_cle74f7d5.pdf

3 Association négaWatt, Manifeste négaWatt, Réussir la transition énergétique, Thierry Salomon, Marc Jedliczka, Yves Marignac, 2012

4 Sauvons le Climat, Diviser par quatre les rejets de CO_2 dus à l'énergie : le scénario Negatep.

5 ADEME, Contribution de l'ADEME à l'élaboration de visions énergétiques 2030 2050, Synthèse.

draws on one of the three scenarios produced by the National Alliance for the Coordination of Energy-Research[6], which adopts a deliberately balanced position between the various forms of leverage and sources of low-carbon energy.

1.1.3 Quantitative targets in the law on Energy Transition

This scenario analysis was a major input for the design of the law on Energy Transition and Green Growth. Indeed, although it does not explicitly refer to the pathways selected by the energy transition debate, it is clearly consistent with the *Efficiency* pathway, based on the Ademe scenario, which meets or is close to the law's quantitative targets. The law sets the following preliminary targets:

- Cut greenhouse gas emissions by 40% by 2030 and 75% by 2050, compared with 1990.
- Cut final energy consumption by 50% by 2050, compared with 2012.
- Cut fossil energy consumption by 30% by 2030 compared with 2012.
- Raise the share of renewables in overall consumption to 23% by 2020, and 32% by 2030, with sectoral targets of 38% for heating, 15% for fuel and 40% for electricity.
- Reduce the share of nuclear power in overall electricity generation to 50% by 2025.
- Set additional targets for 500,000 thermal rehabilitation projects per year, starting in 2017, 7 million loading docks for electric vehicles by 2030, and 1,500 bio-digesters over the next three years.

So the course has been set and the target scenario has been documented. However, this does not prove the social or technical feasibility of this scenario. A particularly high level of uncertainty, notably, surrounds the feasibility of halving energy consumption between now and 2050. This uncertainty suggests that managing the energy transition should involve a dynamic learning process, taking account of the results obtained and of the difficulties encountered in the deployment of the various policies. The F4 target will not be dropped, but the routes to achieving it will probably have to be adjusted over time. There is reason to think the likeliest pathway will result from some cross-breeding of the first-best *Efficiency* scenario with rival scenarios, in particular *Diversity (DIV)*. The *Diversity* pathway achieves the main targets differently: with less demand reduction, and more decarbonized supply. *DIV* seems to represent the likeliest alternative option, if energy demand reductions in the *EFF* scenario, do not reach a 2% annual reduction rate[7]. The DIV and EFF strategies are thus presented and discussed below.

1.2 The Diversity and Efficiency Scenarios: Their content and uncertainties

The various pathways to the energy transition, entailing the substantial de-carbonization of France's energy system by 2050, have been identified. They all involve overcoming challenges which will require suitable public policies. The different challenges to be overcome, which weigh on the likelihood of a successful transition, are the main causes of uncertainty. We begin by identifying the uncertainties weighing on a successful transition via the *Efficiency* (*EFF*) pathway. *EFF* seems to be most consistent with the law, and it

6 ANCRE, Scénarios de l'ANCRE pour la transition énergétique, Rapport 2013. http://www.allianceenergie.fr/page000100dc.asp?card=985

7 SOB could also be considered as an alternative to EFF scenario within the framework of a decision of nuclear phase out which is not currently under discussion. On the contrary, DEC is really contrasted to EFF scenario on both pillars of decarbonization: supply side mix and final energy demand reduction. DEC is also not consistent with the objective of reducing the nuclear share in the electricity mix in 2025.

is also the only pathway to tackle the most inertial sectors, opening a wider range of options. Yet, it also presents several main foreseeable challenges and potential difficulties.

Foremost among them is the ambitiousness of halving energy demand in 35 years. If it proved impossible to achieve the ambitious target of halving energy demand, maintaining the 2050 emissions-abatement targets would entail a greater supply of decarbonized energy. This, in turn, would necessitate keeping nuclear power output at a higher level, as in the *DIV* pathway, and raise another set of uncertainties.

1.2.1 *The Efficiency scenario: How far can demand be reduced?*

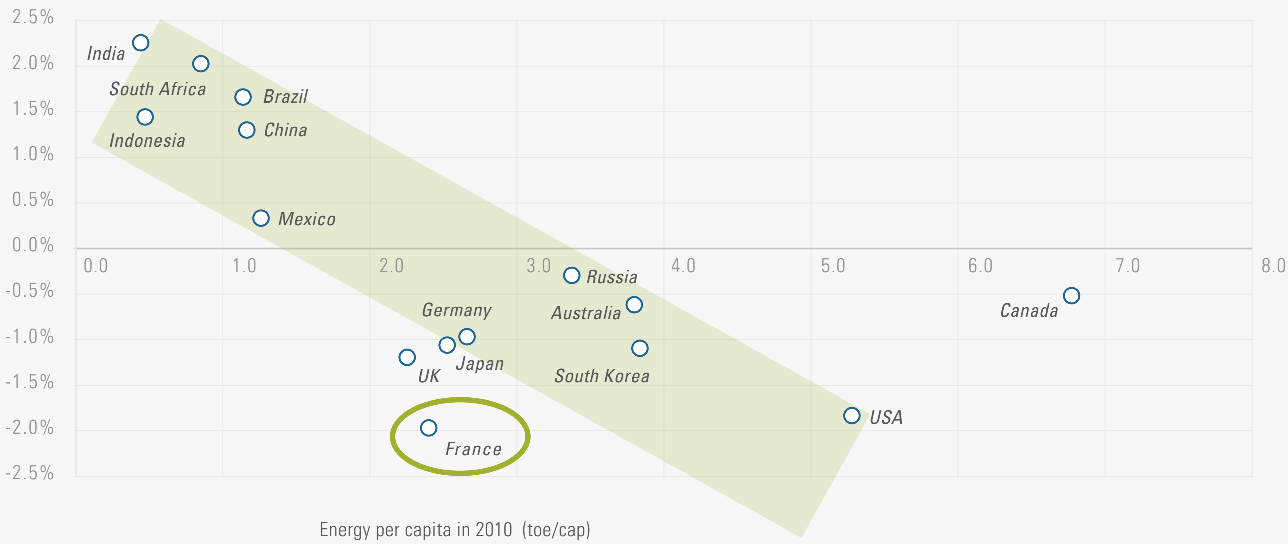
The very ambitious demand-reduction target in the *Efficiency* scenario is its crucial feature. It supposes a 2% annual reduction in per-capita final energy consumption in France until 2050, i.e. the most ambitious rate among all the decarbonization pathways analyzed by the Deep Decarbonization Pathways Project. This, while France already has a low level of energy consumption, making further improvements appear even more challenging (Figure 1).

Overcoming the energy-efficiency gap in the thermal retrofit of buildings

Among the key challenges the EFF scenario would raise on the demand side, one can note the need to carry out the deep thermal retrofitting of almost all existing buildings. The number of dwellings to be heavily rehabilitated each year would need to increase steeply, to reach 600,000 to 800,000 homes a year, compared to less than 150,000 light rehabilitations of dwellings a year today.

Experience shows that thermal retrofit of buildings is often justified when doing a standard economic calculation, yet thermal retrofitting is often difficult to trigger in real life. The reasons include substantial transaction costs, difficulties in accessing funding, and the short payback time – consequently, the high implicit discount rates – requested by building owners to retrofit. The 'landlord-tenant dilemma' is also a major issue: the landlord is supposed to commission the thermal retrofit, but he

Figure 1 : Energy-consumption reduction vs. initial level in Deep Decarbonization pathways



does not pay for energy consumption and thus has limited incentive to invest in the property's energy efficiency. All these factors contribute to the 'energy-efficiency gap', a familiar problem identified since the energy crises of the 1970s. While the investment cost of a deep retrofit will be recovered through annual savings over the lifetime of the building, owners usually require much shorter payback times, most often 3 to 5 years.

Various types of policies may be deployed to narrow the gap between collective and individual rationality: subsidies to reduce the cost of investment, such as tax credits; or increases in energy prices through environmental taxes. The subsidy option may be hampered by the constraints of public finance, while the tax option is certainly worth considering, but inevitably has an impact on household budgets, particularly for the least well-off. It should therefore be supplemented by structural policies designed to extend the timeframe of the decision (i.e. to lower the discount rate): the provision of suitable funding packages, which would reduce the uncertainties and various transaction costs each project entails.

Any scenario that, as *Efficiency* does, requires a substantial drop in energy demand, will need the capacity to gradually ramp up deep thermal retrofit programs for building stock. Yet doing so successfully will depend, to a large extent, on the government's ability to frame policies: articulating energy prices, providing suitable funding, lowering transaction costs, and supporting an adequate business structure to make the retrofitting operations happen at such large scale. Particular attention should also be paid to vocational training to enable the acquisition and dissemination of required skills.

Transport: changes in behavior and technology

The *Efficiency* scenario also sets ambitious targets for cutting energy demand in the transport sector. Doing so would involve changes in mobility practices, technology, and infrastructure. Regarding mobility behavior, the scenario assumes that the current plateau in individual mobility (kilometers per person and per annum) will continue, with mobility steadying by 2030, and ultimately dropping by 20% by 2050 as a consequence of the reorganization of urban systems to limit commuting and promote public transportation.

This scenario is also counting on major changes in automobile technology, including the almost-complete disappearance of conventional, petroleum-powered internal combustion engines. By 2050, the scenario assumes the fleet would consist mainly of electric, hybrid-electric, or natural-gas vehicles.

The adoption of electric vehicles has for several years been identified as a key factor of decarbonization for France. Various car manufacturers have developed electric vehicles and an electric-car sharing service has operated in Paris since 2012. Planning for the installation of electric car infrastructure and charging terminals is among the aims of the law on Energy Transition for Green Growth. However in 2014, sales of electric vehicles only accounted for a small market share, with 10,000 vehicles out of a total of 1.8 million autos registered. At 2015 oil prices, the economic fundamentals of electric vehicles are frail: with an initial extra investment cost of €8,000-10,000 over a conventional car and annual energy savings of about €1,000, by using electricity instead of gasoline, the payback period is at best 8 years. This is probably insufficient in view of the observed consumer behavior, and the corresponding implicit discount rates as seen in the energy-efficiency-gap discussion, above. France's recent introduction of a €6,000 incentive (rising to €10,000 in some cases) for electric vehicle purchasers cuts most of the initial extra cost and may help to stimulate sales, but it may also endangers public finances in case of rapid take-off of electrical vehicles. A substantial and lasting reduction in the payback period would thus require both technical advances and/or a steep rise in gasoline prices through the introduction of a carbon tax.

Constraints on scaling up Variable Renewable Energy

One of the characteristics of the *Efficiency* scenario is the importance given to the development of renewable energy sources, in particular variable renewable energy (VRE) sources – i.e. solar and wind. The increase in use of VRE, central to the *EFF* scenario, mirrors the diminishing share of nuclear power in the electricity mix that should drop to 50% by 2025 and to 25% in 2050. In this scenario, renewable energy sources account for 70% of electricity generation in 2050, of which 55% is derived from Variable Renewable Energy sources. Whereas overall electricity production would decrease slightly[8], installed capacities would almost double compared with 2010, due to the lower load factor of variable sources. Variable Renewable Energy sources would then represent installed capacity on a par with the current level for all generating technologies.

This development of the non-dispatchable sources raises a series of specific problems regarding grid development and management. Even at relatively low VRE market shares – less than 30% – the network incurs various system costs: first, for connecting new and more widely dispersed generating plants; second, to build up reserve capacity (as a backup, in the event of a sudden variation in the VRE generation regime); third, to re-optimize the power plant fleet and its management, to minimize ramping costs. All these changes to existing electricity systems must allow for the proper integration of next-generation resources into the infrastructure, so as to guarantee the stability of the network and minimize the risks of blackout.

Increasing the share of VRE in the power generation mix poses other types of problems. These grow out of the structural mismatch, at certain times of year, between the grid demands and the power supplied by VRE sources. At times, VRE produces a massive surplus. Research carried out in Germany suggests that, with current demand profiles, when VRE account for more than 40% of output, significant surplus production starts occurring[9]. Similar research in France confirms the threshold of 40% above which significant surplus production starts appearing[10]. Large unused production would of course hamper the cost-effectiveness of VRE.

Several types of solution are currently under consideration to remedy the mismatch of supply and demand, in systems where VRE accounts for over one-third of total generation. Matching supply and demand can be improved either through extensive regional supergrids, or smartgrids bringing more flexibility in demand and a better adjustment on local networks. Mass electricity storage is also an option. For the time being, storage would mainly rely on hydraulic pumping stations and secondarily batteries. Finally, power to gas options, i.e. converting surplus electricity into hydrogen or methane gas may also bring a solution. A new study performed for the ADEME, the French Agency for Energy Efficiency, indicates that a 100% renewable power supply, based on the regional complementarity of resources, might be manageable, under conditions of low and flexible demand and assuming favorable developments in mass energy storage[11].

8 The decrease occurs in spite of opposite forces on electricity demand: decrease thanks to efficiency but increase because of electrification of end-uses (electric vehicle particularly).

9 Wagner, A., 2014. Residual demand modeling and application to electricity pricing. The Energy Journal, 35(2),45–73.

10 D. Grand, C. Le Brun, R. Vidil, Transition énergétique et mix électrique : les énergies renouvelables peuvent-elles compenser une réduction du nucléaire ? Revue de l'Energie, 619, Mai-Juin 2014.

11 ADEME, 2015. Vers un mix électrique 100% renouvelable en 2050. Rapport final. 119 pages.

Solutions are many, but for different reasons – relating to technology, economics, or physical potential – none of them represents a comprehensive and risk-free answer. The development of VRE to levels above 40% of total electricity generation is consequently subject to serious uncertainties. It represents one of the most important challenges to be addressed in the energy transition.

1.2.2 An Alternative Scenario: Diversity, or the search for a larger decarbonized supply

The alternative scenarios must cope with other forms of uncertainty. The *Diversity* scenario (*DIV*) would involve a less drastic reduction in demand, compensated for by a greater supply of decarbonized energies. At stake here is securing a larger decarbonized energy supply, primarily from three very different sources: third-generation nuclear power plants, biomass energy, and urban heat networks.

Challenges for scenarios with a significant new nuclear contribution

France has a large fleet of nuclear power plants, but aging, with most of the capacity installed between 1980 and 2000. Assuming a 35-to-40-year service life, this would mean the oldest plants should be dismantled by 2015-2020. This fits in with some of the priorities of France's nuclear policy, which stipulates that decommissioning of the oldest plants should start by 2017. Assuming that the average service life of second-generation plants (built from 1980 to 2000) can be extended to 45 years, and that decommissioning makes allowance for each plant's characteristics, enabling the process to be smoothed out, then the 50% nuclear power threshold would be crossed by 2028. This would be three years later than the target set by the Law on Energy Transition. But from then onwards, the decommissioning of old capacity would continue, and new third-generation plants should have to begin going on line.

On the basis of the above assumption, and due to the long lead-time in the nuclear industry, the building of new reactors would need to start in the early-2020s, following on the first European Pressurized Reactor (EPR) to be built in France at Flamanville. Designing these future projects would have to start immediately. Were that to occur, the main questions relate to the form and siting of such plants, the requested technical and safety standards, and their final cost.

While there has been an increase of over 50% in the cost of nuclear power plants since the first industrial reactors, the analysis of the cost of the various types of second-generation reactors has shown that four main factors explain this phenomenon[12]:

- The increased size of nuclear plants, which in turn impacts the scale and duration of construction.
- Rising labor costs in the nuclear sector, outstripping average inflation.
- The absence of learning effects in the nuclear industry, although some gains were registered in the course of developing different types of second-generation plants.
- Higher nuclear safety standards, with higher costs correlated with more stringent safety requirements.

The building of Finland and France's first EPRs in the 2000s drew fresh attention to the pressing question of rising nuclear plant construction costs. Both projects have taken much longer than planned. The total cost of the Flamanville investment is estimated at €10.5 billion, equivalent to nearly €6,500 per MWe. This is twice the total cost, including interim interest, of France's last two second-generation reactors. There has been no decision yet on when construction will start in the United Kingdom. It looks as if only the two

12 Lévêque, F. (2014). The Economics and Uncertainties of Nuclear Power. Cambridge University Press.

EPRs being built in China are likely to meet their initial targets, partly thanks to different rules in managing this type of major project.
The increasing size and complexity, a factor in the second-generation reactors' steadily rising costs now appears to be impacting third-generation EPR reactors, too. These difficulties will have to be overcome. They also come in addition to the commonly raised issues of waste management and social acceptability.

The role of biomass in decarbonizing the energy sector

All the transition scenarios depend on a significantly higher contribution by biomass energy. Compared with current volumes, of about 10 Mtoe, the various scenarios project a threefold increase in biomass-generated inputs. However each scenario highlights a different energy carrier. Each option assumes that various obstacles can be overcome. For developing wood on a large scale, the main difficulty is achieving an adequate supply as forest land ownership is fragmented, hampering long-term exploitation of the resource. The main difficulty in developing of second and third-generation liquid biofuels is that it is conditioned on overcoming the technological obstacles holding back radical innovation in thermal or biological transformation processes. To achieve a quick uptake of the different bioenergy options, various technical, industrial, and professional nodes need to be deployed along the industry value chain.
Lastly, growth in the use of biomass raises the question of how much land would be required. Mainland France extends over 550,000 sq km; farmland takes up 110,000 sq km or 60% of arable land, and forest a further 150,000 sq km. Under the *Diversity* scenario, 20,000 sq km would be required for dedicated energy crops (switchgrass on farmland; short-rotation plantations harvesting on woodland). A further 31,000 sq km would be used to grow first-generation biofuel feedstock (starches, sugars, vegetables, for ethanol and esters), or to capitalize on agricultural by-products and wastes. Even under the least ambitious scenario, this would entail using almost 9% of the land area of mainland France to grow energy feedstock.

2 Two Alternative Strategies for Deep Decarbonization: A Detailed Analysis

In this section, we represent the *EFF* (*Efficiency*) and the *DIV* (*Diversity*) decarbonization strategies in each sector (Table 3) with the Imaclim-R France model. Imaclim-R France is a computable general equilibrium model that quantitatively represents the interrelated technical and economic impacts of different energy scenarios, as an aid to policy reform and design (see section 2.1). The model allows for the consistent analysis of how changes in technological systems and economic constraints (such as funding, evolution of prices or of the economic agents' behavior) impact various measures' effectiveness.

2.1 The Modeling Framework

Imaclim-R-France is[13] a dynamic computable general equilibrium (CGE) model belonging to the Imaclim family of models developed at

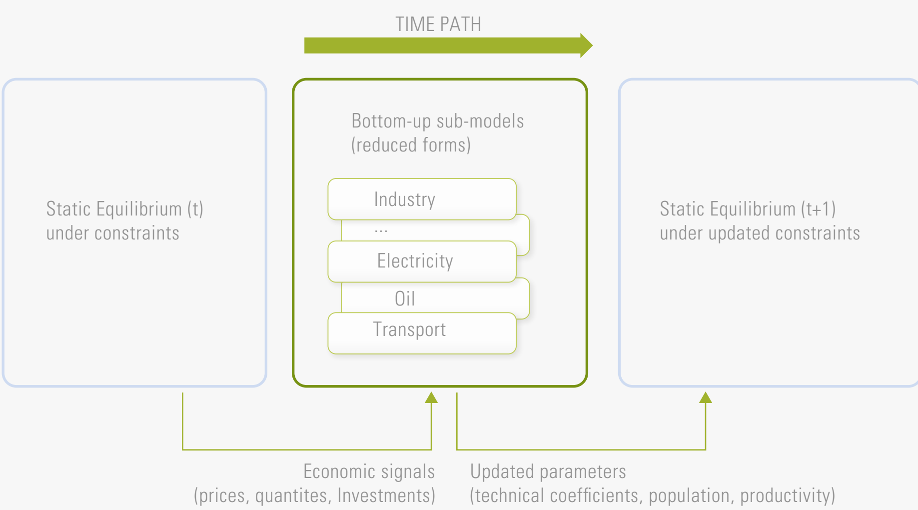
13 The economy is broken down into 13 sectors: energy (crude oil, refined oil, gas, coal, electricity), transport (road transport of goods, shipping by sea and inland waters, air transport, collective transport for passengers), construction, energy-intensive industry, agriculture and services.

Table 3: Description of main sectoral indicators of strategies in EFF and DIV

	Programs and strategies	
Sector	EFF	DIV
Residential – existing buildings	About 600,000 retrofits per year on average, and retrofitting of the entire stock of existing buildings between 2010 and 2050.	Average of 350,000 retrofits per year on average, retrofitting 55% of the stock of existing buildings between 2010 and 2050.
Service	23 M sqm retrofitted each year (100% of the stock between 2010 and 2050).	15 M sq m retrofitted each year (60% of the stock between 2010 and 2050).
Freight transport	Increase in quantity of t.km until 2030 and stabilization in 2050 at the level of 2010	Increase of the quantity of t.km in 2050 by 55%/2010, i.e. continuation of current trends in the evolution of tonnes.km.
Passenger transport	Stabilization of the quantity of pass.km in 2050/2010 (i.e. a 15% decrease of the per capita mobility).	Increase (following current trend) of the demand for individual mobility (+ 25%/2010 in 2050).

Source: From Carbone 4, 2014. Etude des 4 trajectoires du DNTE

Figure 2: The recursive and modular structure of the IMACLIM-R model



CIRED[14]. It is a hybrid model which represents, year by year from 2004 to 2050, simultaneous changes in technology systems and the economy (Figure 2). Imaclim-R uses a recursive architecture to represent both the long-term growth engine (demographic growth and labor productivity) and the various forms of short-term frictions affecting the technico-economic adjustments (imperfect expectations, incomplete use of production factors, inertia at various levels – equip-

14 Crassous, R., Hourcade, J.-C., Sassi, O., 2006. Endogenous structural change and climate targets : modeling experiments with Imaclim-R. Energy Journal. Special Issue on the Innovation Modeling Comparison Project.

Sassi, O., Crassous, R., Hourcade, J.-C., Gitz, V., Waisman, H., Guivarch, C., 2010. Imaclim-R : a modelling framework to simulate sustainable development pathways. International Journal of Global Environmental Issues. Special Issue on Models for Sustainable Development for Resolving Global Environmental Issues. 10(1/2): 5–24.

Waisman, H., Guivarch, C., Grazi, F. Hourcade, J.C., 2012. The Imaclim-R model : infrastructures, technical inertia and the costs of low carbon futures under imperfect foresight, Climatic Change, 114(1).

ment, technology, preferences, trade, or capital flows). Economic growth is thus described as a succession of static equilibriums, representing for each year the equilibrium of economic flows (production, consumption, international trade) under fixed technical parameters. The dynamic is represented by sector-specific models reflecting shifts in technology and stocks of production factors (capital, labor, natural resources), thus fueling changes in technical parameters between each static equilibrium.

At each date, the static equilibrium is constrained by the characteristics of installed equipment and technologies, as well as by the imperfect allocation of investments between sectors: for example, surplus production capacity in some sectors and under-capacity in others. In such a framework, the model can represent, among others, the effect of tension on prices and volume, unemployment due to insufficient flexibility in the labor market, distortions caused by economic signals (previously existing taxes) or agents' behaviors (as represented by behavioral routines).

The dynamics of the economy are governed by endogenous modelling of capital accumulation and technical change. Capital accumulation is represented through firms' investment, households' savings, and international capital flows. The cross-sector distribution of investments is governed by investors' expectations about sectors' profitability, under imperfect foresight and technical conditions as described in sector-specific reduced forms of technology-rich models. Imperfect foresight is a consequence of uncertainty about future relative prices, final demand and investments profitability, other non-energy prices (land and real estate) and non-economic determinants of public decisions in transportation and urban planning. At a given date, agents have limited information about the future, and shape their expectations on the basis of past and current trends (adaptive expectations). Under such semi-myopic foresight, installed capital resulting from past investment decisions may not be adapted to future economic settings. However, the capital stock cannot be replaced quickly due to inertias, which act as constraints on investors' adaptability to varying economic conditions (activity levels and prices).

Energy flows are represented in the model both in value and physical quantities, enabling the respective roles of each energy sector to be isolated, as well as their interaction with the rest of the economy. The model uses physical variables (number of motor vehicles, collective dwellings or individual houses, annual energy efficiency of technologies, etc.) allowing for the integration of sector-specific data related to how economic incentives impact final demand and technology systems. This also facilitates the dialogue with non-modelers.

The agents represented displayed specific patterns of behavior in the dynamic modules. In the residential sector, the model represents investments in thermal retrofitting and in new heating equipment. Dwelling owners decide to invest in a retrofitting action if the investment is profitable. In the model, the return on investment for retrofitting actions takes into account the investment cost for retrofitting according to the objective in energy consumption, resulting energy savings discounted over the equipment lifetime and barriers to energy efficiency in the form of intangible costs[15]. For the electricity sector, the model represents the development of additional capacities with a wide range of technology (coal and gas with or without CCS, nuclear, solar, wind, biomass,

15 Giraudet, L.-G., Guivarch, C., Quirion P., 2012. Exploring the potential for energy conservation in French households through hybrid modelling. Energy Economics. 34(2):426-445.

and hydro) and an hourly load profile[16]. Spatial mobility and modal-shares of transport are the result of a maximization of the utility function, subject to the dual constraint of income and time-budget[17] in order to capture the connections between final demand, infrastructures, and equipment availability[18]. Freight demand is obtained by aggregating demand for goods transport in each productive sector. In other sectors, autonomous technical progress is calibrated on ongoing trends. Variations in energy prices – potentially including a carbon tax – induce additional gains in energy efficiency and energy substitution, under the assumption of imperfect foresight regarding energy prices. The model thus shows the impact of climate policy instruments – carbon taxation, incentives for the thermal retrofit, energy efficiency regulation for equipment, or transport-infrastructure policies – on agents' decisions and behaviors. Incentive policies are directly integrated in investment costs and energy prices, while the energy-efficiency coefficients of the various generations of capital goods include the effects of regulation.

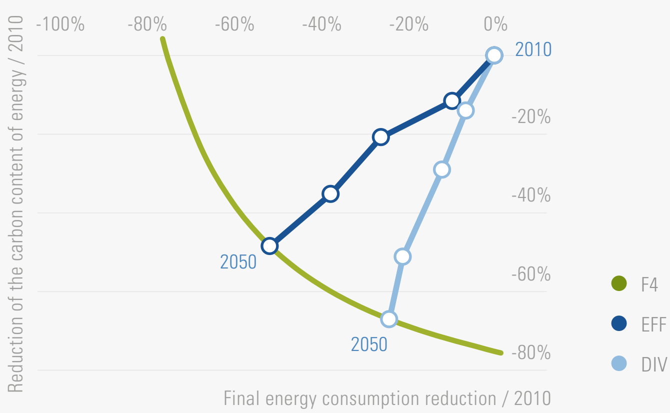
2.2 A Detailed Comparison of Alternative Pathways

The following sub-section describes sector-specific or transversal strategies, policies, and measures for either the *EFF* or *DIV* scenario. The selection of the particular policies and measures considered is based on an extensive review of the literature, focusing on sector-specific studies of policies that drive energy dynamics.

The pathways resulting from the *EFF* and *DIV* scenarios are shown in Figure 3. It plots the reduction of final energy consumption (x-axis) against the decarbonization of final energy 2010 (y-axis), both compared to 2010 levels. In this representation, all the pairs (final energy consumption; carbon content of energy) that achieve the F4 target are marked with the green line, representing the F4 isoquant. The points above the isoquant fail to achieve the F4 target, whereas those below exceed it.

In this graphical representation, the almost immediate divergence between the *EFF* and *DIV* strategies appears clearly, and leads to very different respective roles for the two parameters in reaching the F4 target. *EFF* yields a 50% reduction in demand, coupled with a 48% drop in the car-

Figure 3: DIV and EFF pathways, according to demand reduction and energy-decarbonization on 2010



NB: the dots on the pathways mark decades 2020, 2030, 2040 and 2050

16 Bibas, R., Mathy, S., 2011. Dynamiques d'investissement et de maîtrise de la courbe de charge dans le système électrique français, presented at La journée de la chaire modélisation prospective 2011 Prospective pour les enjeux Energie-Climat, October 11th, Jardin Tropical, CIRED, Paris, France.

17 Zahavi, Y., Talvitie, A., 1980. Regularities in Travel Time and Money Expenditures. Transportation Research Record. 750, pp. 13-19.

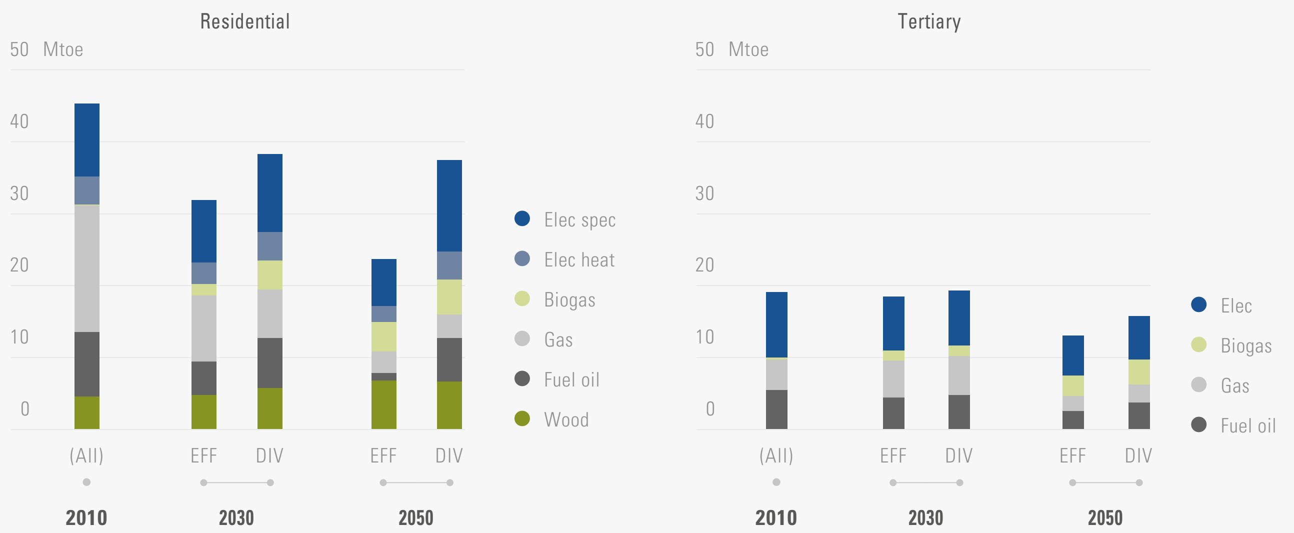
18 Waisman, H, Guivarch, C., Lecocq, F, 2012. The transportation sector and low-carbon growth pathways. Climate Policy. 13(1):107-130.

bon content of energy. *DIV,* by contrast, has lower demand-reduction (24%) and so would need to achieve greater energy-decarbonization (67%) to make for it. This level of decarbonization in *DIV* is particularly ambitious, given that it applies to final consumption that is around 40 Mtoe higher. Figure 4 shows, for the *EFF* and *DIV* scenarios, the changes in sectoral energy mixes for residential housing, tertiary sector, transport, industry, aggregate final demand, and electricity generation.
In the following, we examine in greater detail the sectoral measures considered in each scenario. Running a simulation of the *DIV* and *EFF* policies and measures using the Imaclim-R France model, we will consider the consequences for energy consumption, energy mix, and greenhouse-gas emissions (CO_2 from energy and industrial processes).

2.2.1 Introducing a Carbon Tax

Both the *EFF* and the *DIV* scenarios presuppose the introduction of a carbon tax, which is levied on all sectors, and assume that economic agents will accurately anticipate its future increase. Tax revenues are supposed to be refunded annually to households as a lump sum[19]. The carbon tax comes on top of specific policies and measures introduced in each scenario and its level is computed in order to comply with the Factor 4 objective (Figure 5).
In the *EFF* scenario, the carbon tax would reach €120 per ton of CO_2 in 2030 and €360 in 2050, compared with resp. €90 and €280 per ton of CO_2 in the *DIV* scenario[20]. During the first years, the carbon tax would increase

Figure 4a: EFF and DIV scenario. Final-energy consumption and energy mix



19 Other assumptions could have been made: either recycling carbon tax revenues through subsidies on energy efficiency or renewables, or more particularly through an alleviation of labor charges. This last option will be discussed in the last section concerning the macroeconomic features of energy transition.

20 These values are very close to recommendations in expert reports (Quinet 2009, 2013; Rocard 2009). The experts who drafted the Quinet report in 2009 (La valeur tutélaire du carbone, Rapport de la commission présidée par Alain Quinet. La documentation française, Rapport n°16, 424 pp) recommended a carbon tax set at a rate of €32/t CO_2 in 2010, rising to €56 in 2020, €100 in 2030 and between €200 and €350 in 2050. These values correspond to the implicit value of the constraints for reducing CO_2 emissions entailed by the targets for 2020 and 2050.

only slowly, in both scenarios, to avoid heavily penalizing households equipped with energy-intensive technology or organizations that cannot be changed overnight (e.g., long commuting distances due to residential choices). On the other hand, the aim is for households and economic sectors to anticipate the progressive nature of the tax, so they shift investment towards technology, equipment, and organizations with low energy consumption and greenhouse gas emissions. In particular, it is important to change people's decisions on

Figure 4b: EFF and DIV scenario. Final-energy consumption and energy mix

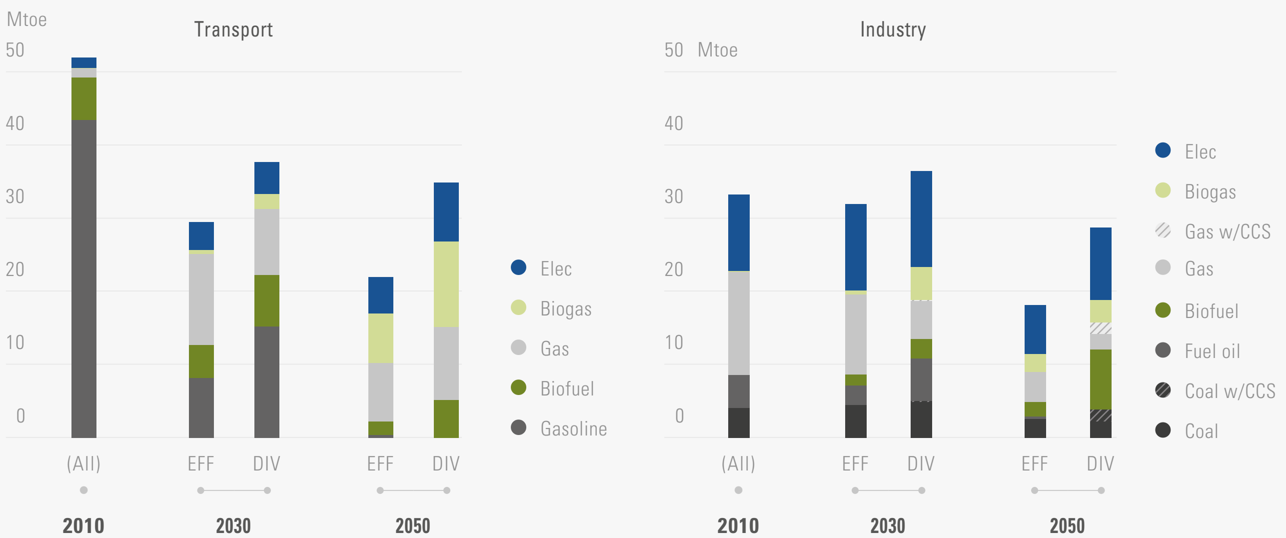


Figure 4c: EFF and DIV scenario. Final-energy consumption and energy mix

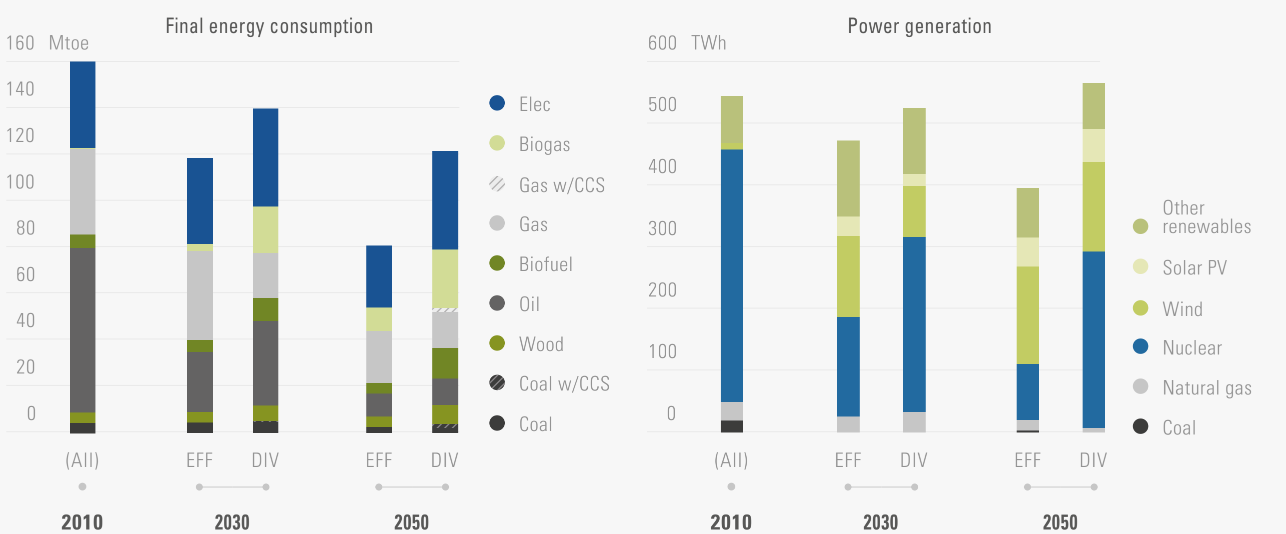
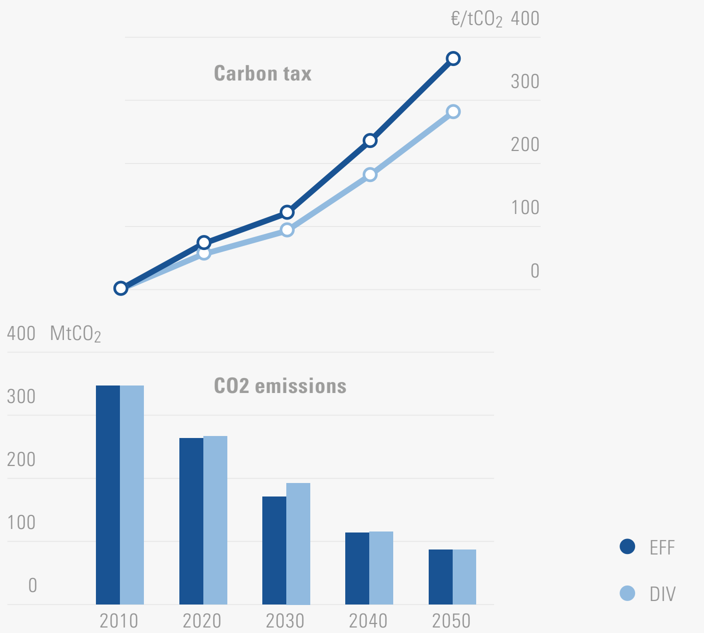


Figure 5: CO_2 emissions and carbon tax trajectory in EFF and DIV scenarios



where to dwell, to reduce in the power sector the distance travelled between home and work or to encourage choosing homes close to collective transport infrastructure.

2.2.2 The Thermal Retrofit Challenge in the Residential Sector

The residential and service sectors consumed in total 68 Mtoe, accounting for 43% of final-energy consumption in France in 2010, and 26% of energy-related CO_2 emissions. Between 1990 and 2010, their final-energy consumption increased by slightly more than 15%, although emissions were up only slightly (by 3%) because higher energy demand has been mainly driven by electricity. In 2015, building stock comprises about 30 million dwellings. Some 70% of the building stock that will exist in 2050 has already been built. About 300,000 dwellings are built a year, and only 30,000 are demolished.

Ambitious thermal regulations have been introduced for new buildings since the Grenelle de l'Environnement in 2007. Regulations were introduced requiring new buildings to comply with low-energy standards at 50 kWh/sqm/year, which represent a substantial cut in energy consumption compared with the previous thermal regulations. By 2020, the new positive-energy buildings should be producing more energy than they consume. There remains, however, uncertainty about new buildings' energy consumption because of the question of the degree of their compliance with thermal regulations. In the scenarios we describe, the positive-energy-building thermal regulation is supposed to be really effective after 2025.

But the main challenge in attempting to achieve the cuts in energy consumption projected for 2050 is to improve the energy performance of existing buildings. The existing building stock mainly consists of dwellings with low-grade energy labels. France's first thermal regulation was introduced in 1975 and 55% of the 2010 building stock are older than that. Average final-energy consumption in existing dwellings is 190 kWh per sqm, with thermal energy (heating and hot water) accounting for nearly 80% of energy consumption.

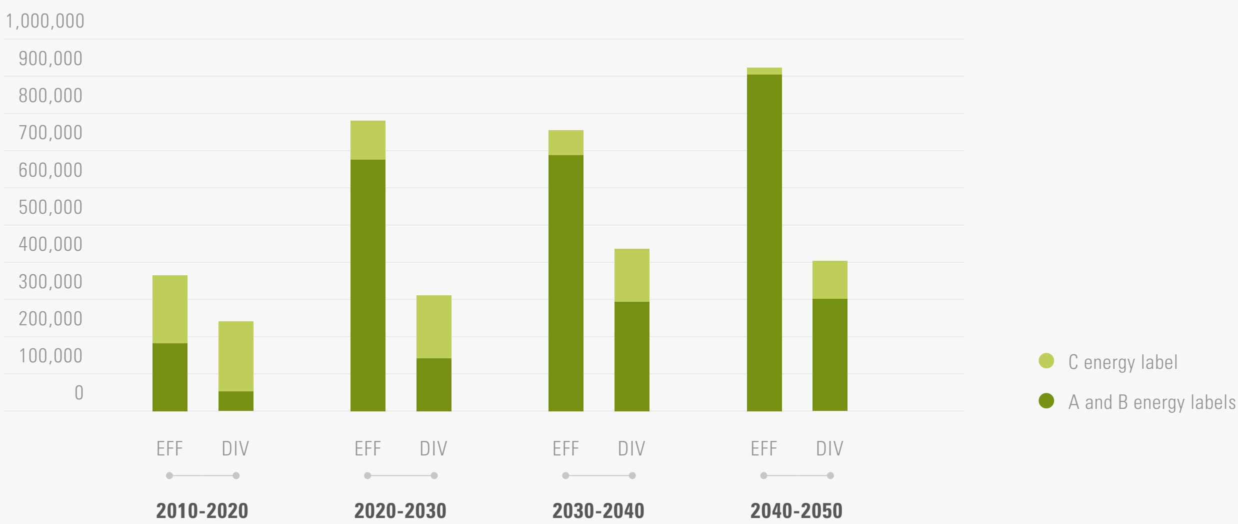
In the residential sector, the challenge for the *EFF* pathway is to push through an ambitious thermal-retrofit program to enhance the energy performance of the entire existing building stock. To achieve this, financial incentives would be introduced in the form of subsidies or tax credits for high-performance materials and equipment (boilers), coupled with interest-free 'eco-loans' for retrofit work, to bring dwellings into line with top-grade energy labels.

The sum of incentives represent an annual average addition of € 2.5 billion to the government budget. Schemes providing for financial engineering to contain the risks entailed thermal retrofit operations (failure to meet energy-efficiency targets once completed, cost overruns) would also be deployed. These financial mechanisms would include third-party funding schemes, energy-performance contracts, and guarantee funds for collective dwellings, among others. These mechanisms would be designed to limit the risk-aversion holding back such work. As such, they would reduce the implicit discount rate for property owners faced with the decision to retrofit or not.

These mechanisms – financial and non-financial – would increase the acceptability of retrofit for property owners, by bringing the private discount rate (which sometimes exceeds 20% per annum[21]) closer to the social discount rate (about 4% per annum). Some observers nevertheless argue that incentives alone will not be sufficient to bring about thermal retrofit of the entire building stock[22]. The scenario consequently assumes that compulsory retrofit measures would be enforced, in order to achieve an average of 570,000 high-grade A and B label[23] (with energy consumption below 90 kWh/sqm/year) thermal retrofits per annum (Figure 6).

In the *DIV* pathway, the same financial and non-financial incentives would be deployed as in the *EFF* pathway, but without the back-up of any compulsory measures, leading to a substantially lower number of annual thermal retrofits: around 350,000 each year in total, but with only 200,000 each year being high-grade retrofits.

Figure 6: Number of thermal retrofits per year by post-retrofit energy grade



21 The average discount rate for investments in energy efficiency was estimated to be equal to 20% by Train (1985). Train, K., 1985, "Discount rates in consumer's energy-related decisions: a review of the literature", Energy 10(12): 1243-1253

22 Giraudet, L.-G., C. Guivarch, P. Quirion, 2011, "Comparing and combining energy saving policies : will proposed residential sector policies meet French official targets ?", The Energy Journal, 32(SI1):213-242

23 France introduced energy labels for buildings in 2006, with a seven-tier ranking running from A for the best performance to G to the least satisfactory, with regard to a building's energy consumption. Energy labels A to G refer to the following level of energy consumption: A: <50 KWh/sqm/year; B: from 51 to 90 KWh/sqm/year, C: from 91 to 150 KWh/sqm/year, D: from 151 to 230 KWh/sqm/year, E from 231 to 330 KWh/sqm/year, F from 331 to 450 KWh/sqm/year and G >450 KWh/sqm/year.

The results for the *EFF* scenario also show high market penetration by dwellings with A or B energy labels, to account for 90% of stock by 2050 (Figure 7). In contrast, with the *DIV* scenario such dwellings would only account for 25% of stock, C-grade dwellings would represent 30% of the total, and lower grades would continue to exist, contrary to *EFF*.

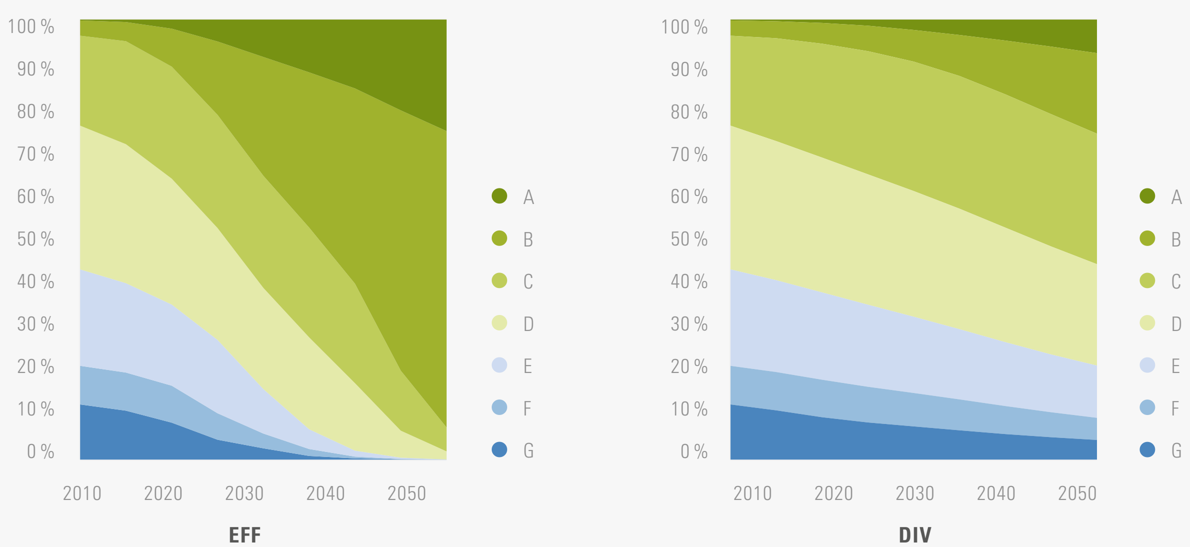
Furthermore, consumer behavior regarding electricity consumption is also a major concern because of its current steep upward trend, driven by the emergence of new devices and uses. Equipment per household is a concern, as is the level of use of the equipment. Both scenarios integrate comparable gains in energy efficiency, but the *EFF* scenario is more optimistic regarding shifts in patterns of consumer behavior (i.e. less equipment per household and lower level of utilization of the equipment). *EFF* thus yields a 28% reduction in overall specific-electricity consumption by 2050, compared with 2010, in contrast to a 45% increase in such consumption under the *DIV* scenario.

2.2.3 *Policies and Measures in the Service Sector*

The service sector represents one-third of building floor space, with 620 million sq m. It has an average energy consumption of 245 kWh per sq m (versus 190 kWh per sq m for residential property). This final energy consumption is largely due to specific end-uses of electrical equipment. Heating and sanitary hot water represent only 50% of energy use (compared with 80% in residential buildings)[24].

As it does with residential buildings, the *EFF* scenario provides for a much more ambitious

Figure 7: Evolution of energy labels in existing buildings in EFF and DIV scenarios



24 This average conceals large disparities in the consumption of service properties, due to very diverse end-uses: on average catering premises (hotels and restaurants) register unit consumption 2.7 times higher than educational buildings.

thermal-retrofit program than the *DIV* scenario. Under *EFF*, 21 billion sq m would be retrofitted, yielding a 55% gain in energy efficiency, compared to 15 billion sq m for the *DIV* scenario, with only a 45% gain in energy efficiency. *EFF* also considers specific efficiency measures for electric appliances, such as more ambitious regulation, than *DIV*.

2.2.4 Passenger Transport

Since 1990, per capita mobility has increased on average by 0.7% each year, reaching 985 billion passenger-kilometers in 2012. As a result, demand for passenger transport in France has been growing 1.2% annually, faster than the population (growing 0.5% a year). However since the 2000s, per capita mobility has flattened out at roughly 15,000 km per year.

The private car is still the preferred mode of transport thanks to its high level of convenience. It represents more than 80% of mobility for France as a whole. Since 1990, the impact of increasing personal transport (up 30%) on energy consumption has been partly compensated by a 15% gain in the energy efficiency of road transport achieved, despite the low rate of renewal of the fleet, thanks to the introduction of stringent norms for new vehicles. Average fleet emissions were 169 g CO_2 /km in 2010. European Union directives have set targets for reducing emissions to 130 gCO_2/km by 2015 and 95 gCO_2/km by 2020 for new sales.

The future trends for individual mobility will depend on a combination of several factors: regional development and the relative position of centers of employment and housing; relative expenditure on road and collective transport infrastructure; and changes in patterns of mobility such as car sharing, remote working or teleconferencing.

The *EFF* scenario assumes that regional development and infrastructure spending will enable rail transport to grow significantly, alongside public transport in urban areas. There would nevertheless be no sudden shift in the relative positions of residential and business centers. Average commuting distances would not grow any longer; it is assumed that daily travel times would gradually flatten out. At the same time, incentives to encourage remote working, car-sharing, and a service economy (in particular car-clubs) would limit the distance travelled by private cars. These trends are made possible by the spread of digital technology.

As a result, growth in individual mobility using private cars would be significantly limited in *EFF*, yielding ground to an increase in the modal share of collective means of transport, for urban and long-distance journeys, and an increase in soft modes (walking and cycling) in cities. The modal share of air transport would fall due to the introduction of taxation on aviation fuel, reflecting its environmental impacts, coupled with an end to exemption from the tax on petroleum products and the roll-out of competitive long-distance collective transport systems.

Individual ownership of motor vehicles would also decline in *EFF,* due to rising fuel prices pushed up by a carbon tax. By 2050, sales of conventional vehicles would have been partly replaced by electric and hybrid vehicles and partly by natural gas vehicles, a fuel with a low carbon content with use of biogas. This technology mix delivers a choice of vehicles consistent with the diversity of transport demand (long versus short distance, urban versus rural). Correlated with the drop in individual mobility, and changes in the corresponding habits and the relation to private cars, this scenario foresees a significant drop in the number of new vehicles purchased every year.

The *DIV* scenario, by contrast, assumes that it will remain difficult to change travel behaviors.

Furthermore, with a carbon tax set at a lower level than in the *EFF* scenario, there is less incentive to change such behaviors. Transport demand would consequently continue to increase in line with current trends, with little change in modal share. The only significant form of leverage would be technical progress making car engines more efficient.

Figure 8a : Private car sales in EFF and DIV scenarios

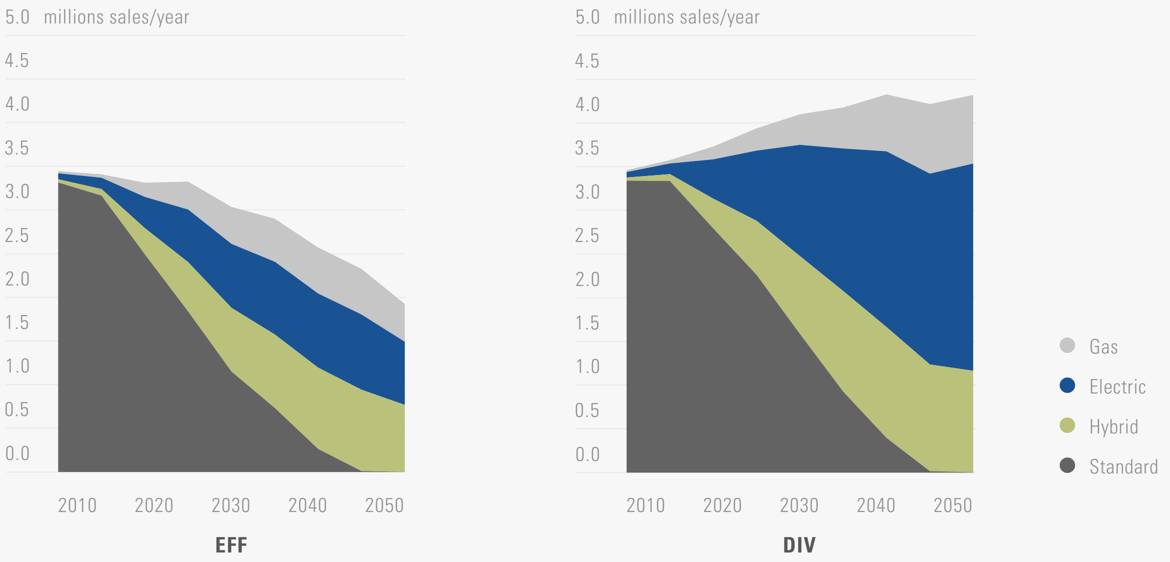
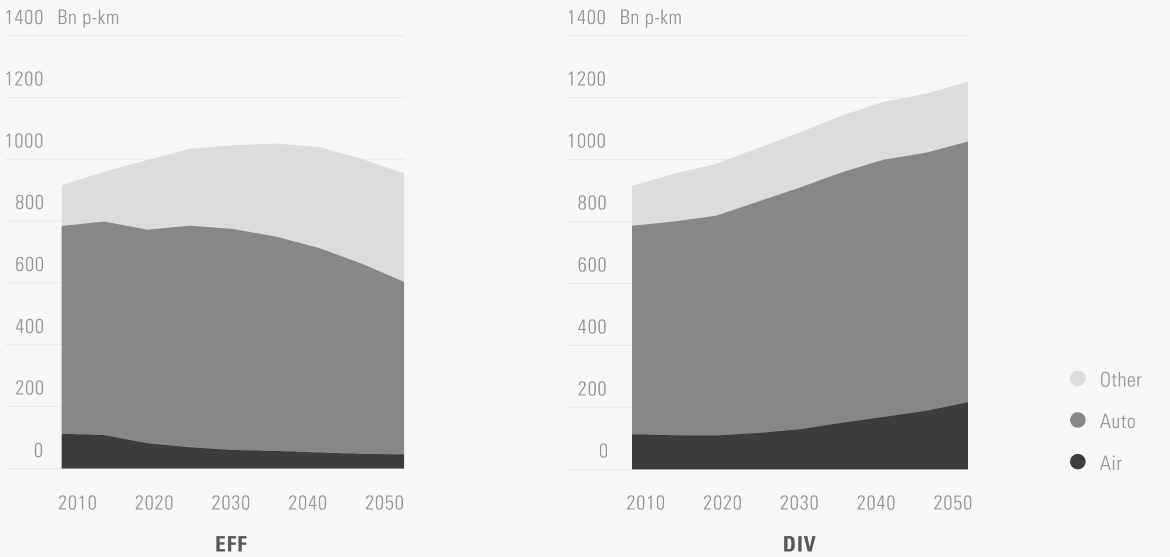


Figure 8b : Modal distribution for passenger mobility in EFF and DIV scenarios



2.2.5 Freight Transport

There is a strong correlation between GDP and demand for freight transport (see Figure 9), except during periods of crisis when the transport sector is disproportionately impacted.

The *EFF* scenario assumes gradual decoupling of freight ton-kilometers from economic growth, thanks to improvements in logistics, fewer empty runs, and ecodesign of products. A drop in distances travelled would also be possible by optimizing transport, thanks to better location of production and storage centers in relation to labor pools, and lower energy costs for moving personnel and materials. With a 1.5% rate of annual decoupling of freight transport and GDP growth, freight ton-kilometers would flatten out by 2030. As with passenger transport, the increasing availability of rail transport coupled with construction of multimodal platforms would increase the modal share of rail freight. Furthermore the *EFF* scenario supposes the energy efficiency of delivery vehicles would improve 20% by 2030.

Conversely the *DIV* scenario would not allow the uncoupling of freight transport and economic growth. Modal shift would be as slight as for passenger transport. In both scenarios, a switch to gas for road freight is also considered.

Figure 9 : Correlation between freight transport and economic growth in 2000-2010

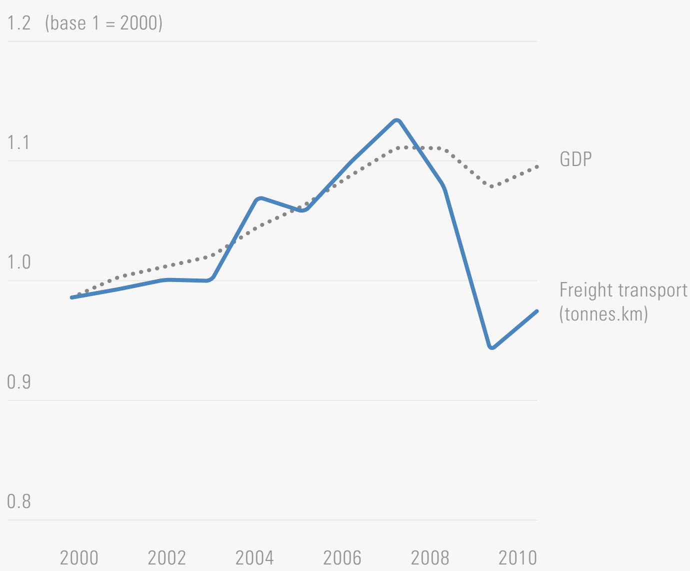
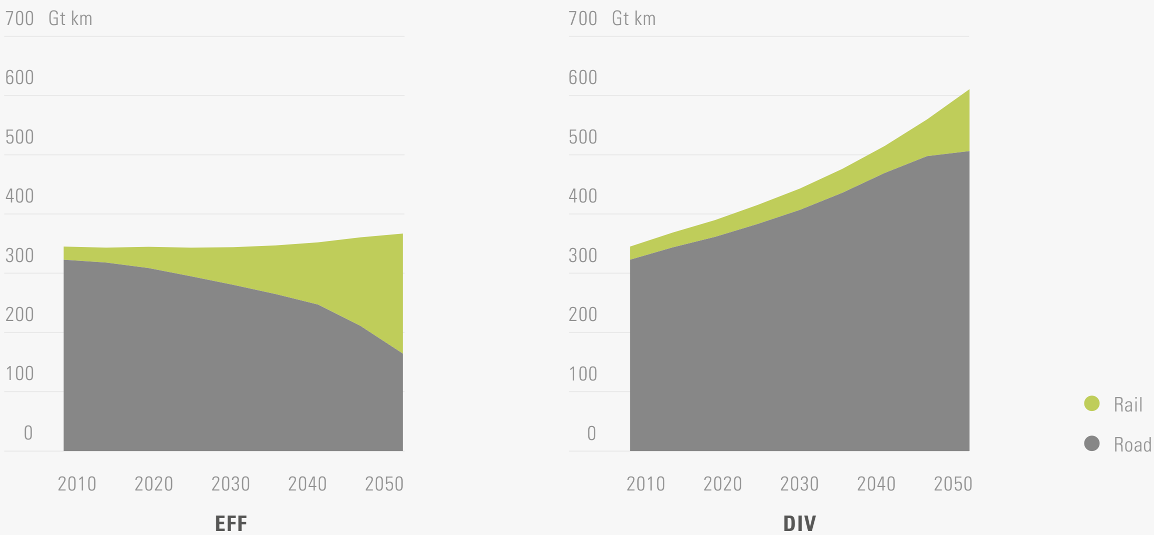


Figure 10 : Freight volumes in EFF and DIV scenarios



2.2.6 Policies and Measures in Energy-Intensive Industries

France's energy-intensive industries are regulated by the EU Emissions Trading System. Industrial emissions have decreased by 33% since 1990, while industrial output has increased by 25%. Half of this decrease in emissions has occurred in the past three years, due to the drop in industrial output. The main drivers for the significant decrease in emissions between 1990 and 2010 were the overall decarbonization of energy use in industry, and gains in energy efficiency. The increase in industrial added value has slowed, reflecting the fall in energy-intensive production in France (Table 4). In the 1970s, industry's contribution to GDP was above 30%. This share fell to about 25% in the 1990s, and is currently about 20%. We presume no major structural change in the scenarios: during the whole period, industry's contribution to GDP is seen remaining stable at 20% of GDP. An annual 0.3% to 0.5% improvement in energy efficiency is assumed[25]. This represents an energy efficiency improvement in both scenarios equal to 18% between 2015 and 2050, to which is added the impact of energy prices (including the carbon tax). Increasing energy prices drive greater energy-efficiency gains in industrial processes, more extensive recycling of raw materials, and the recovery of energy from waste. These latter trends are greater in *EFF* than in *DIV*, due to higher levels of carbon taxation in the former on the whole period. In total, in *EFF* industry's energy efficiency is improved by 48% between 2015 and 2050. In *DIV* it is improved by 36%.

The *DIV* scenario assumes that CCS technology will be available by 2025[26], coinciding with the point at which the price of carbon exceeds €100 per tCO_2. CCS capacity would then increase by 0.5 $MtCO_2$ per year. By 2050, about 10 $MtCO_2$ would be stored annually using CCS technology, covering around 20% of the gas and 40% of the coal consumed by industry.

Table 4: Evolution of production and of the CO_2 content of production between 1990 and 2010 for some energy-intensive industries in France

	Steel	Cement	Glass
Production (vol) 2010/1990	-17%	-27%	-4%
CO_2 content of production 2010/1990	-26%	-20%	-27%

2.2.7 Measures to Decarbonize the Energy Supply

Thanks to all the measures to reduce energy demand in the *EFF* scenario, final energy would fall 50% by 2050, compared with 2010, while it would fall only 24% in the *DIV* scenario. This means achieving the F4 target under the *DIV* requires decarbonizing an additional 40 Mtoe of energy compared to *EFF*. Therefore, in the *DIV* scenario, the decarbonization of the energy supply becomes the main challenge. Additional decarbonization potential in DIV is achieved by increasing the penetration of low-carbon electricity into end-uses, deep decarbonization of gas-fuels, and accelerating the diffusion of different carbon-free energy sources, bio-energies, and non-fossil heat sources.

Electricity

In the *EFF* scenario, electricity consumption would drop 29% between 2010 and 2050, despite the higher penetration rate of electricity. Electricity would be generated to a large extent by renewable energy sources, which would climb to 66% of electricity production. ERV would then account for 44% of output in

25 This assumption is in line with academic literature. Cf Webster, M., Paltsev, S., & Reilly, J. (2008). Autonomous efficiency improvement or income elasticity of energy demand: Does it matter?. Energy Economics, 30(6), 2785-2798.

26 The EFF pathway does not need to rely on the CCS technology.

2050, considered a manageable share provided that minimum-demand flexibility, short-term storage, and backup are all implemented. By 2050, nuclear power would represent a 27% share in the electricity mix.

In contrast, in the *DIV* scenario, electricity consumption would increase by 14%, driven by an aggressive increase in the electrification of end-uses, up 36%. To generate low-carbon electricity, nuclear power would retain a substantial level of production and would represent a 50% share of the energy mix. Second would be renewable energies at 44%. The share of renewables in electricity generation is smaller in *DIV* than in *EFF*, but due to higher total production, the electricity produced by renewables is higher in *DIV* than in *EFF* (260 TWh compared to 240 TWh in *EFF*). ERV would account for 33% of the total. Figure 12 shows the breakdown of electricity demand by sector, for each scenario.

Figure 11a: Energy mix for electricity generation

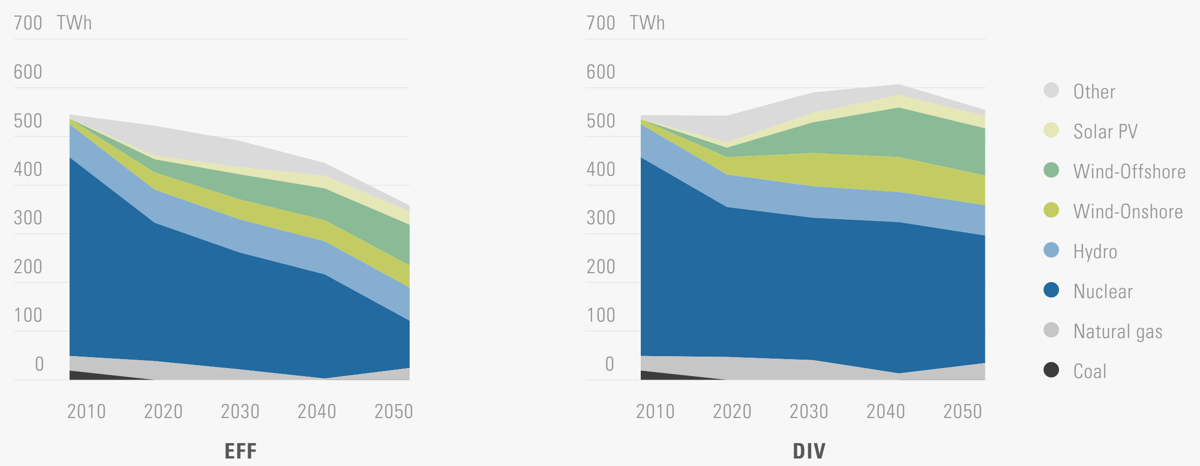


Figure 11b: Installed capacity for each scenario

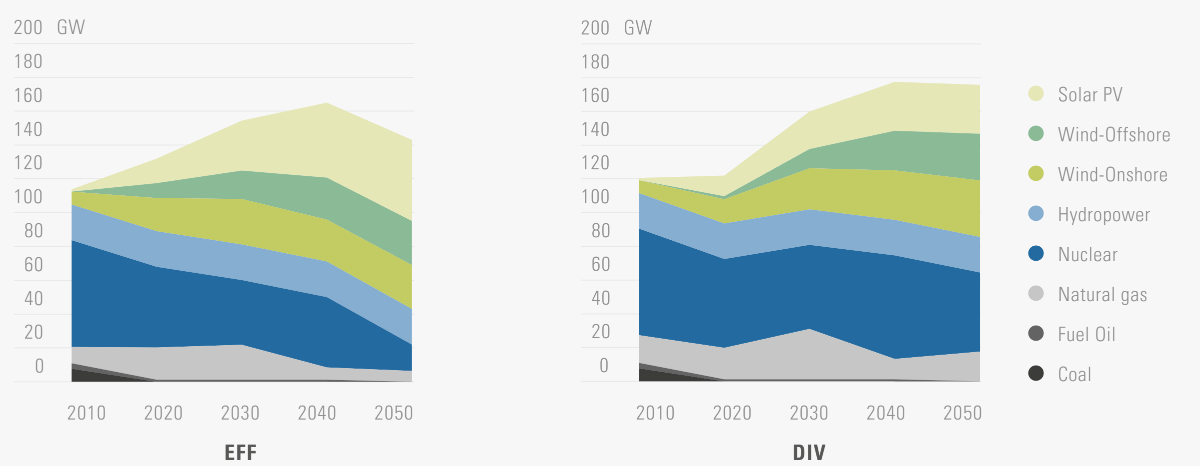
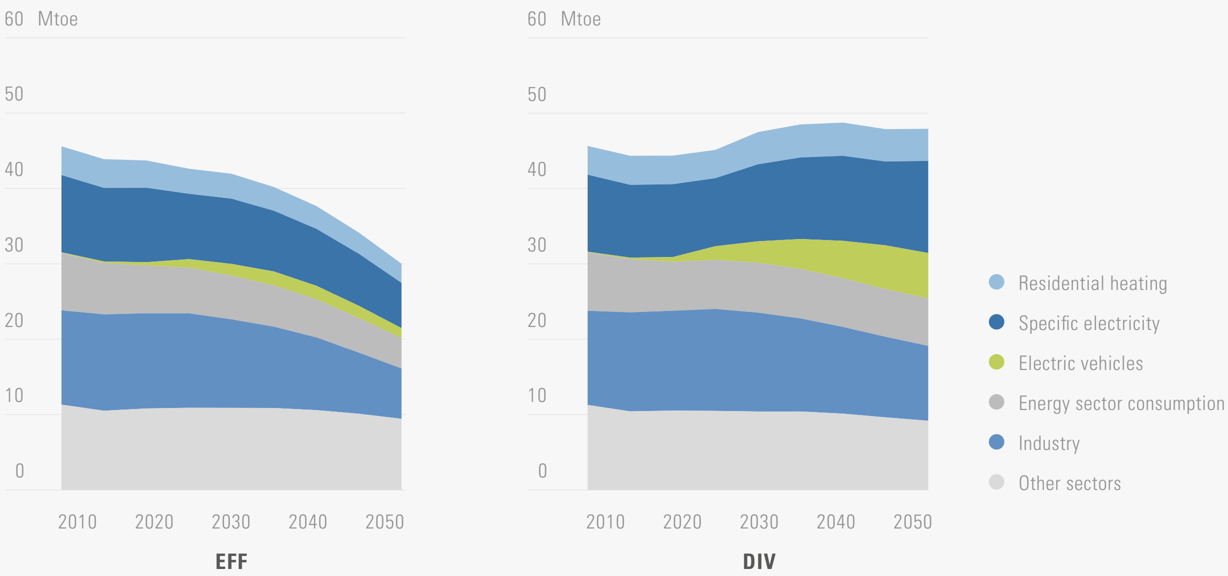


Figure 12: Breakdown of electricity demand by sector, for each scenario



Gas

The development of biogas opens the way for a decarbonized gas energy carrier. Biogas is produced by extracting methane from organic household wastes, livestock effluents, and agricultural residues. Even if biogas production is currently low (<0.5Mtoe), incentives for its development could drive a rapid increase. Biogas could partly supply road transportation and heat networks. It plays a large part in both the *EFF* and *DIV* pathways, contributing 10 Mtoe in *EFF* (about 33% of networked gas), and 25 Mtoe in *DIV* (more than 50% of the gas in the mains).

Liquid fuels

The *EFF* scenario foresees 5 Mtoe of second-generation biofuels in 2050, especially from lignocellulosic materials. This is not a major change compared to current level of biofuels. The *DIV* scenario relies on 13 Mtoe of second-generation biofuels in 2050. This level would have to rely on the potential for domestic production of these second-generation biofuels, which remains fairly uncertain, but is estimated at 7.5 Mtoe in France and 33 Mtoe in Europe on the medium term[27].

2.3 The Macro-Economic Impacts and Social Dimensions of the Energy Transition

2.3.1 Costs and Prices of Energy

The set of assumptions specific to each scenario leads to different impacts on the price of energy (see Figures 13 and 14).

27 M. Giora, ADEME : Biocarburants de 1ère et 2ème génération : potentiels, bilans énergétiques, bilans environnementaux et analyse économique des filières

The massive investment required to develop renewable energies in *EFF*, or to introduce new generating capacity for replacing the aging fleet of nuclear power plants in *DIV* leads to a substantial increase in electricity-generating costs in both scenarios (Figure 13).The price of electricity[28] is higher in *DIV* after 2040 as, due to the higher demand, a new wave of third-generation nuclear plants has to be built. In both scenarios, the price of gas and liquid fuels is the combined output of the evolution of world energy prices[29], the projected carbon tax (higher in *EFF* than in *DIV*), and the penetration of biogas or biofuels, which push prices higher because of their production costs. This latter effect explains why gas prices are higher in *DIV*, where the penetration of biogas is larger (Figure 14). The higher price of liquid fuels in *EFF* compared to *DIV* is due to the impact of the carbon tax, which has a more significant effect on fuel prices than the cost of biofuel production.

Figure 13: Electricity-price trends in EFF and DIV compared to 2010

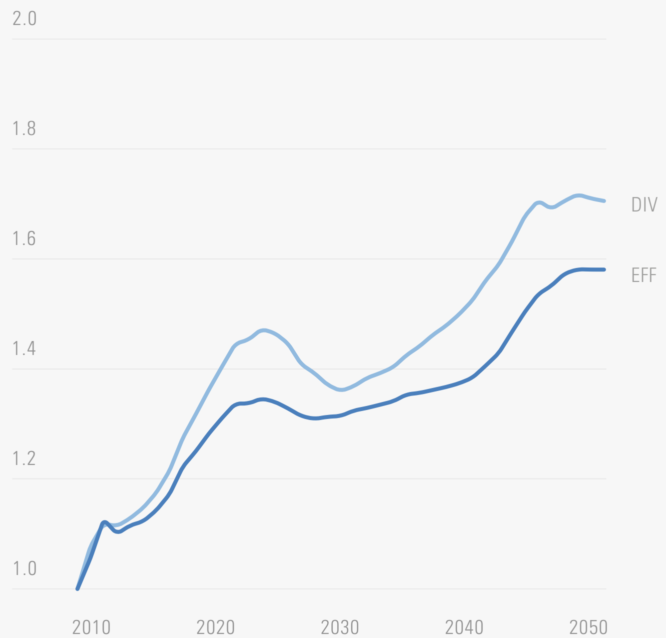
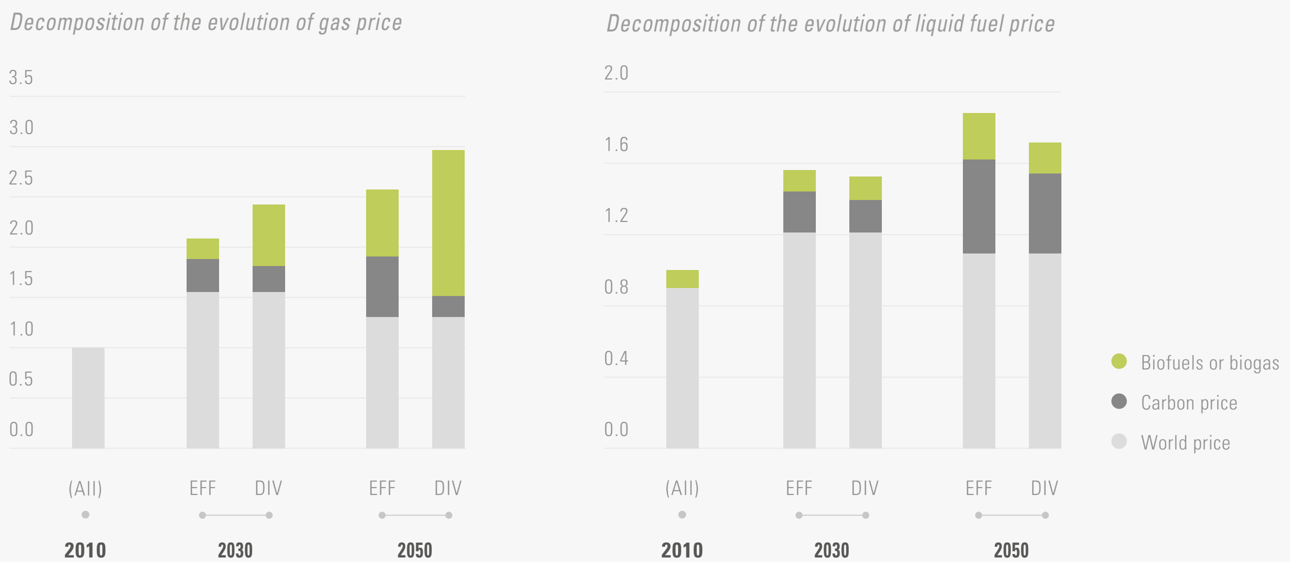


Figure 14: Decomposition of gas and liquid fuel price in EFF and DIV



28 The price of electricity is the sum of the complete cost of production, grid costs and taxes.

29 Energy import prices are taken from the IEA 450 ppm scenario.

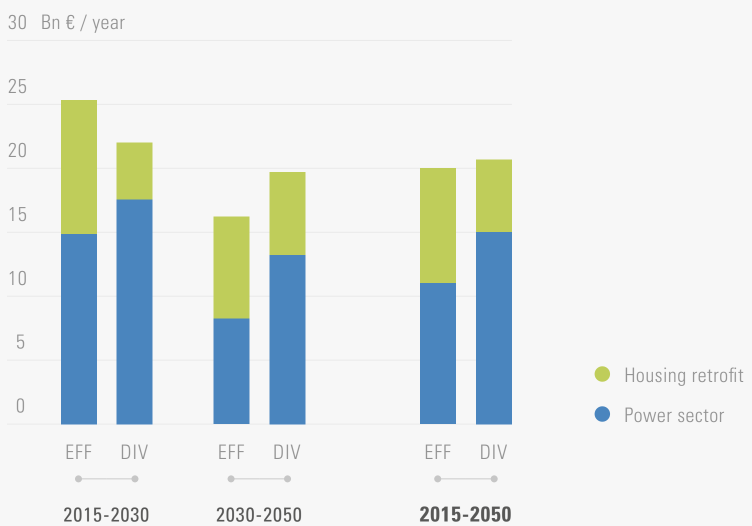
2.3.2 *Investment by Sector*

Aggregate cumulative investments are similar in both scenarios. However the structure of investments, and their time profiles across sectors such as electricity and residential buildings, are very different.

The *DIV* scenario would lead to high electrification of end-uses and a roughly 20% higher electricity demand by 2050 than *EFF*, entailing on average a 30% higher annual investment in power generation capacities: €15bn in *DIV* as against €11bn in *EFF*. On the other hand, as part of the effort to substantially reduce demand for final energy in *EFF*, the ambitious thermal retrofit of housing stock would require high investments in housing over the whole period: €9bn, on average each year, significantly higher than in *DIV* (€5.6bn, on average each year).

In total, the *EFF* strategy would lead to higher aggregate investments until 2030 because of the high level of investment in energy efficiency, while the *DIV* strategy would lead to higher supply-side investment between 2030 and 2050.

Figure 15: Average annual investment by sector in new electricity generating capacity and thermal retrofit of housing



2015 Overall, *DIV* would rely more on investments in decarbonizing supply in the energy industry, whereas the *EFF* pathway places more of the burden of investment decisions on end-users.

2.3.3 *Household Energy Expenditure*

The burden of energy services in a household budget (Figure 16) depends on how much is spent on energy consumption, and on the cost of different equipment for consuming or reducing consumption. For residential uses, this includes electricity expenditure; heating, sanitary hot water, and other end-uses, and also investments made in thermal retrofit. With regard to mobility, energy-services expenses include spending on fuel, investment in vehicles, or purchases of fares for collective transport and other forms of transportation.

The *EFF* scenario allows a large cut in household energy spending – it would be roughly halved in 2050, in spite of expenses of thermal retrofits. That it does so is the result of substantial energy savings in homes, and changing patterns of mobility behavior. Both trends are less pronounced in the *DIV* scenario, where household energy budgets are seen falling only by one-quarter. These different results must be interpreted in context, while emphasizing the positive aspects of energy conservation or, conversely, the corresponding loss of welfare or amenities.

2.3.4 *Trade balance*

The drop in energy consumption and the growth in non-fossil energy sources would substantially improve France's energy trade balance from its current level. Currently energy imports amount to 3% of GDP, roughly equal to France's trade deficit. In both the *EFF* and *DIV* scenarios, the energy bill would achieve balance out by 2050. Over the period, *EFF* would entail a slightly larger reduction in spending than *DIV*, which, also relying on carbon capture and storage, allows the use of more imported fossil energies. The balance of trade in non-energy goods would also improve, partly due to competitiveness gains arising out of energy savings[30]. The right-hand graphic shows the trend for the overall trade balance, highlighting the positive contribution of lower energy imports due to climate policies.

Figure 16: Share of energy services in household budget

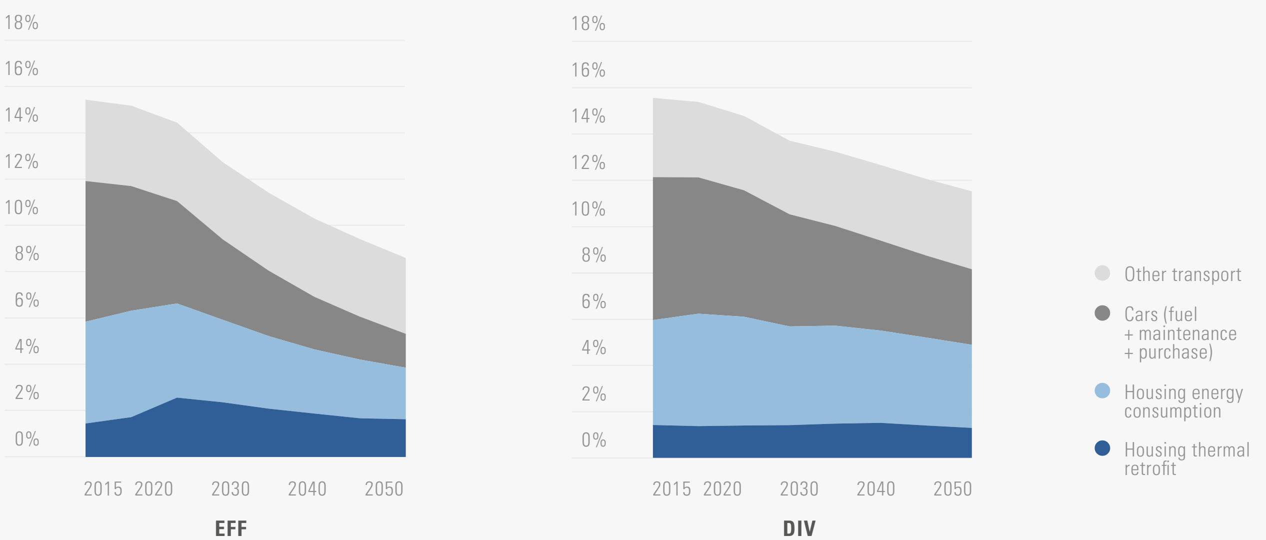
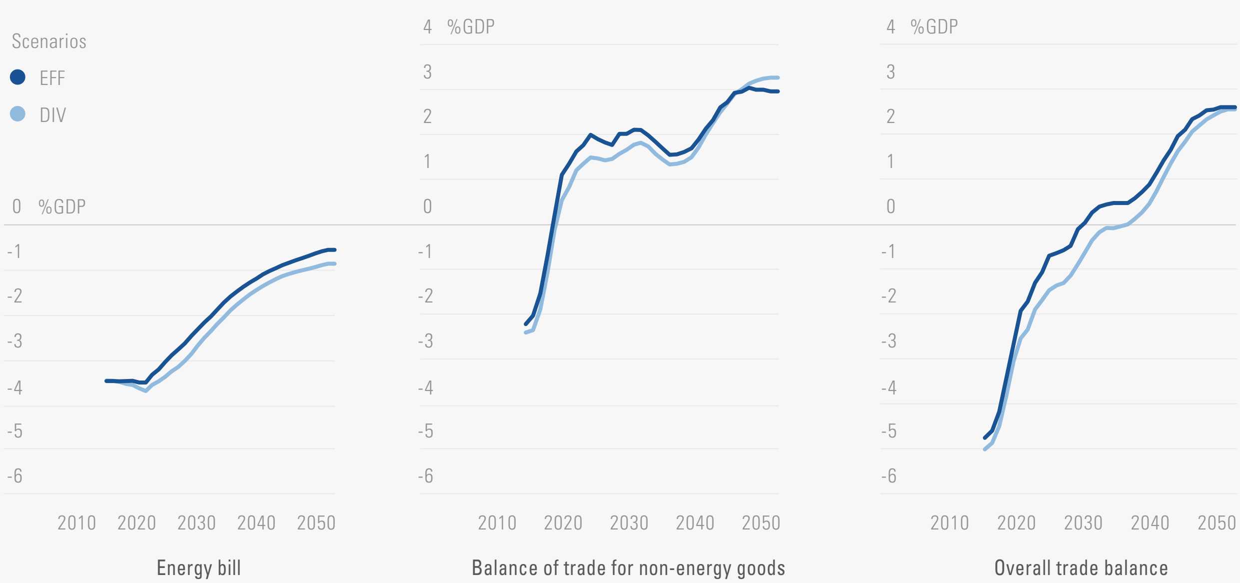


Figure 17: Variation in France's energy bill; balance of trade for non-energy goods; overall trade balance in relation to GDP in EFF and DIV scenarios



30 International prices for each sector in Imaclim-R France are taken from a 2°C global scenario computed with Imaclim-R.

2.3.5 Carbon Tax

In both scenarios a carbon tax would drive about half the cuts in emissions in 2050, with the remaining coming as a result of other policies, deployed in line with the assumptions specific to each scenario. Immediately after it is introduced, it would raise about €15bn in revenues (*DIV*) or €20bn (*EFF*). Thanks to the increase in the rate, carbon tax revenues would increase until 2050, despite the gradual decline in emissions, to €30bn in both the *EFF* and *DIV* scenarios, equal to about 1% of GDP. Several options for recycling tax revenue are possible: an annual, lump-sum refund to every households, or focusing on energy poverty; lower social security charges on labor; support for renewables and energy efficiency. This issue will be addressed in the last section.

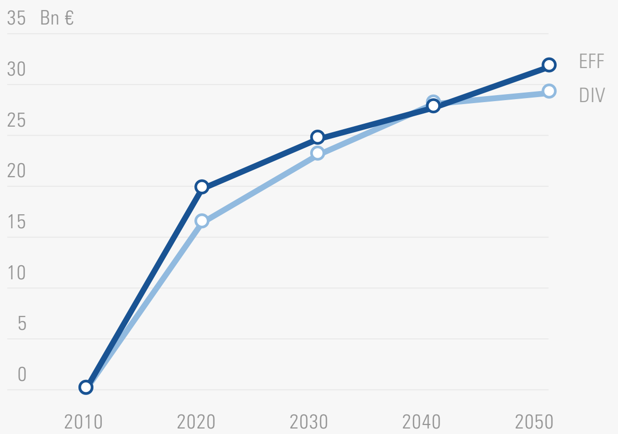
Table 5: Average annual GDP growth rate in 2015-30, 2030-50 and 2015-50

	2015-30	2030-50	2015-50
EFF	1.28%	1.55%	1.43%
DIV	1.23%	1.40%	1.33%

Table 6: Sectoral employment difference between EFF and DIV (EFF-DIV; positive numbers mean more employment in EFF) – thousands of jobs

	2030	2050
Energy	0	-20
Industry	-100	-350
Agriculture	-200	-230
Transportation	70	30
Services	830	860
Total	600	290

Figure 18: Carbon tax revenue in the EFF and DIV scenarios



2.3.6 Impact on Economic Growth and Jobs

Each scenario involves investments in energy-efficiency and low-carbon technology, and incentives and presumptions about the behavior of consumers and other economic agents. The combined effects of these, in ways specific to each scenario, in the end would have very similar impacts on economic growth. The *EFF* scenario would drive slightly higher annual economic growth over the entire period, 0.1% higher than *DIV* (Table 5). This would mean that by 2050, GDP under the *EFF* scenario would be 2.4% higher than under *DIV*. This difference is accounted for mainly by decreased household energy budgets and decreased governmental consumption, which are transferred to other forms of consumption that induce more economic activities and production in France.
While the difference between the two scenarios' impacts on growth is slight, there are specific consequences in terms of employment in individual sectors in each scenario. *EFF* enables more jobs to be created over the reference period than *DIV* (Table 6). On average, between 300,000 and 600,000 additional jobs would be created under *EFF* compared to *DIV*, in the building retrofit sector for direct employment and in the service sector for induced employment. The induced employment effect comes as household's energy budgets decrease, and the transfer of spending takes the form of other kinds of consumption. In *DIV*, more jobs are created in the energy sector, in agriculture and in industry.

3 Decarbonization and Green Growth: Towards a dynamic management of the energy transition

3.1 Robust Strategies, Resilient Systems, and Policy Informed by a Learning Process

The work of characterizing the different pathways, the obstacles to be overcome, measures to be deployed, and finally the measures' macro-economic impacts, reveals the scale of the uncertainties weighing on the energy transition. In such a situation, the policies deployed must be flexible. They must be designed to give priority to components that will make the policies more robust and resilient. This emphasis on robust strategies means giving preference to policies and measures – concerning the achievement of energy efficiency, the performance of renewable technologies, and the dynamics of the nuclear industry – that will hold up under a wide range of environments, domestically and at the international level. In different way, resilient strategy means developing energy macrosystems that will stay up and running, or recover quickly, in the event of crises, accidents, or acute instability. So a distinction needs to be made between robustness and resilience: finding robust solutions hinges on strategies that are suitable in different environments, whereas solutions which enhance resilience connect with the intrinsic capability of technology systems to respond to unexpected events or accidents.

Uncertainty can be managed in such a way as to encourage robust strategies and resilient systems by distinguishing three categories of actions: (1) Policies and measures common to all pathways, at least during the initial launch phase; (2) Policies constrained by severe inertia and delays in response or deployment, and where those delays or inertias must be taken into account in the timing of decisions; and lastly (3) Policies which preserve future freedom of choice, yielding high option-value.

3.1.1 Policies to be Deployed in All Cases

All the pathways to energy transition in France involve rolling out policies to enhance energy efficiency and decarbonize supply. Above all, it is worth noting that during the initial stage leading up to 2030, such policies must be deployed with the same intensity in most scenarios. They are thus very probably robust options.

Whatever the scenario, deep thermal retrofitting must make swift progress, starting now. The aim is to upgrade more than 200,000 dwellings a year by 2020; then in *EFF* more than 500,000 dwellings a year by 2030. So in all cases, a major scaling-up effort will be required over the next 15 years, through creating incentives and funding packages, organizing the industry, and training the workforce. Uncertainty is very high at present, but by 2020 or 2025 it will obviously be possible to carry out a preliminary assessment of the policies deployed and to decide whether to keep them, speed them up, or on the contrary, reframe them in line with better adjusted targets. But between then and now, it will be necessary to sustain efforts at the highest possible level.

Similarly, the electrification of transport – including private cars – is common ground shared by the various pathways, with the notable exception of *Sobriety*, which does not advocate electrification as a vector of decarbonization. In all the other cases, electric and hybrid vehicles must account for 10% to 20% of a total fleet of about 35m vehicles by 2030. This, depending on specific cases, would entail average annual sales of 250,000 to 500,000 electric vehicles over the next 15 years. Such swift development of the electric-vehicle fleet would obviously need to go hand-in-hand with substantial investment in private and public charging infrastructure.

On the supply side, all scenarios posit the fast growth of variable renewable energy (VRE) installed capacity. By 2030, there would be from 40 GWe to 60 GWe of wind capacity and 30 GWe to 50 GWe of photovoltaic solar panels. This would represent an annual average of more than 600 new masts with an average rating of 5 MWe and 20,000 new 1000-square-metre PV farms up to 2030.

So it should be apparent that the energy-transition scenarios assume – each with its specific features and exceptions – common constants, which coalesce into robust goals for the medium term (2030): exceeding 500,000 deep thermal retrofits a year; lifting annual electric-vehicle sales to over 500,000 by 2030; installing several hundred high-power wind machines a year and a couple of ten thousand PV farms. These items are sufficiently significant to constitute strategic goals for energy transition policies over the coming years. They also represent variables which must be tracked and monitored, to ensure that the course steered by the energy system lines up with what the energy transition requires.

3.1.2 Policies with Strong Time Constraints; The Option Value Problem

For the energy-efficiency and renewable-energy operations cited above, the roll-out time is only one or two years, starting from the decision to invest. This being so, the main difficulty relates to ramping-up with sufficient speed and volume. It is necessary to trigger a large number of investment decisions by a very large number of diverse players.

The other options posited by transition scenarios – supply-side options for large generating facilities, and the development of networks and storage infrastructures – pose a very different problem. Such investments are often very large and indivisible, with long construction and payback times. They are also in many respects irreversible.

The obstacles that must be overcome to trigger such investments are very different in nature from those holding back smaller investments in unit terms. For large-scale operators, the access to capital is much easier and the timeframe is longer – so their discount rate is lower – but the risk involved in major investments is very large in a global energy context of liberalization and market restructuring. Investment calculations should consequently take into account an 'option value' which encourages the extended use of existing facilities and/or systems, thus broadening the scope of possible outcomes – rather than lock-ins. It is nevertheless difficult to identify the circumstances in which taking into account uncertainties will favor a standstill, or to the contrary, stimulate investments that create future flexibility.

3.1.3 Designing Energy Transition Policies Informed by a Learning Process

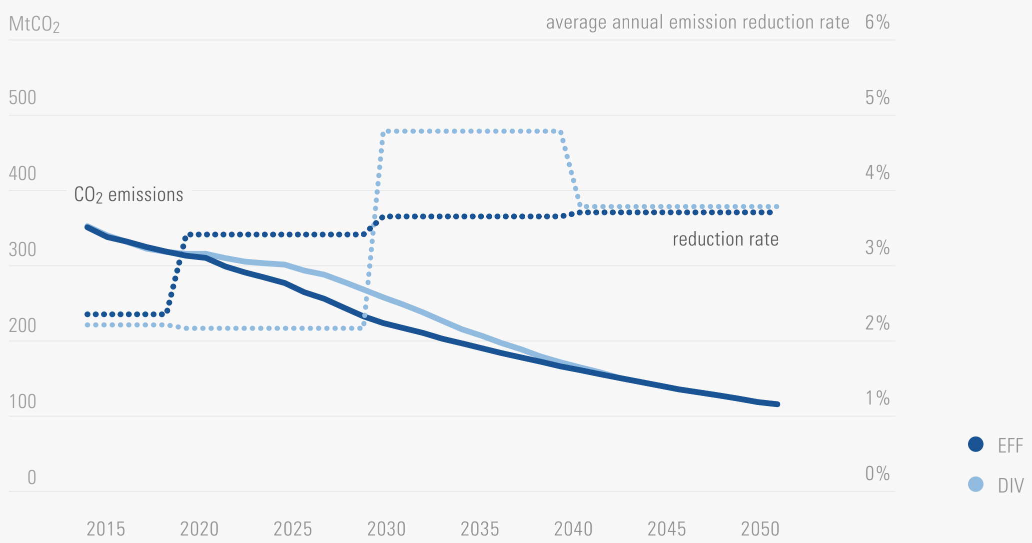
It is possible to grasp the various dimensions of climate and energy policies through approaches based on sequential decision-making, in which the implementation of policies is seen as an ongoing learning process. With this kind of perspective, policies must be reviewed and re-appraised at regular intervals. Ged Davis (*World Economic Forum and World Energy Council*) goes so far as to recommends a 'Rule of Seven' to describe the necessary process for revisiting any plan or scenario: dividing the timeframe of a piece of work by seven[31]. So a policy spanning 20 years would need to be reviewed every three years, a 35-year policy (e.g. 2015-2050) once every five years, and so on. This, indeed, provides a basis for the dynamic management of transitions.

3.2 Path Dependency and Irreversibility in a Sequential Approach: A Two-Stage Analysis of Decarbonization Pathways to 2030 and 2050

Although *EFF* and *DIV* reach very similar emission reductions by 2050, there is a contrast in the time profile for each pathway's emissions abatement because of the constraints and inertia that affect the deployment of their respective strategies. Notably, *EFF* is characterized by a rather steady average annual rate of emissions abatement, whereas *DIV* features strong variation. In the short-to-medium term (up to 2030), the *DIV* strategy would induce a moderate rate of abatement, but in the longer term (between 2030 and 2040), it would require an average annual rate of CO_2 emissions abatement close to 5%/yr. How much of a challenge is posed by such a high reduction rate? It is still higher than the highest annual rate of emission reduction ever achieved as part of planned action, about 3%/yr between 1979 and 1989, when France fully deployed its nuclear energy program.

An *EFF* pathway, in which the priority is achieving ambitious reductions in final-energy consumption would require rapid, continuous efforts to take up, across the board, the most efficient energy technologies available in all sectors. In case of the failure to achieve these goals, de-

Figure 19: CO_2 emission pathways and annual CO_2 emission reduction rate by decades in EFF and DIV



31 In an interview conducted by GBN Knowledge in 2004, Ged Davis explained its "rule of seven": "*If you take the time horizon of a piece of work and divide by seven, that probably gives you some idea of how long these scenarios will remain credible and be used. In Shell, for example, 20-year scenarios are renewed every three years; nobody is terribly interested in the 20-year scenarios you did three years ago. So it's not a hard and fast rule, but the important point is that we're not talking about scenarios being used for the full time horizon, but about a seventh of the time horizon. Their value, over time, diminishes very quickly. They become historical relics.*"

carbonization may stall, due to lower-than-expected access to the technical and economic potential that had been identified to reduce energy demand. For example, energy-efficiency investments in buildings, designed to close the energy-efficiency gap, may be severely restricted by the failure to overcome risk aversion, to change patterns of behavior, or to develop new skills at a very large scale as rapidly as necessary. Conversely a *DIV* pathway, which relies on a larger decarbonized energy supply, will require higher supply-side investments to achieve the take-up of low-carbon technologies. In this case, it may prove difficult to deploy technologies which are either currently not available or not as-yet mature, such as CCS or third generation nuclear power, or which may raise land-use conflicts due the intensive use of bioenergy.

Under these conditions, dynamic management of the decarbonization pathways will require continuous monitoring of whether key objectives are actually being achieved, coupled with ongoing adjustment of the decarbonization strategy itself. Otherwise, the initial development of the pathway could lead to energy demand that is too high, or which is locked into an insufficiently decarbonized energy supply. Economic analysis, risk assessment, and the identification of social preferences should inform policy decisions so that any subsequent changes are well anticipated and in that way do not cost too much.

3.2.1 DIV: A strategy dependent on the availability of non-mature technologies

The weakness of the *DIV* strategy resides in its reliance for decarbonizing energy on technologies that are not yet fully mature – such as third-generation nuclear power and CCS technology. This weakness is exacerbated for EPR by long lead times (it takes five to ten years to build a nuclear power plant) and so it is essential, as a consequence, to accurately anticipate the available options as time passes.

Assuming a 40-year service life for existing nuclear power Plants (NPPs), the first plants, which were commissioned in 1979 and are still operating, would need to be shut down before 2020. The question of extending the service life of NPPs clearly impacts the volume and nature of the investments required to carry through the energy transition. At one extreme would be the decommissioning of all plants after 40 years' operation. At the other would be extending the service life of all existing plants by 20 years. Depending on which option is taken, the need for new nuclear capacity to realize the *DIV* strategy varies a great deal (Table 7).

If a 40-year service life is enforced for all existing plants, it will be necessary to commission 35 EPR NPPs over the whole period, each rated at 1,650MW, including 20 units before 2030. It is unlikely that it would be possible to roll out EPR

Table 7: Number of EPR plants built each year to fulfil the DIV strategy, depending on the assumption on the service life of existing NPPs. Construction of new EPR plants under the DIV scenario described in part 2

		2020-24	2025-29	2030-34	2035-39	2040-50	Total
Service life of existing NPPs	40 years	3	17	11	1	3	35
	60 years	0	0	0	1	20	21
DIV		1	7	6	2	7	23
DIV_EPR		1	3	0	0	0	4

technology at this rate initially, given the current difficulties with the building of France's first plant. Furthermore, the risk that construction times could last as long as eight to 10 years could delay large-scale deployment of these plants till after 2030. So the option of a *DIV* strategy seems fairly unrealistic, unless the service life of at least some existing NPPs is extended. Going to the opposite extreme, if it was decided to extend the service life of all the existing plants by 20 years, it would only be necessary to commission the first EPR plant in 2040, with 20 NPPs to be built from 2040 to 2050.

The real outcome would no doubt be somewhere in between these two extremes, probably differing between plants, since some reactors display more severe wear than others. This approach was used in the *DIV* scenario described in Section 2 (see third row in Table 7): the oldest plants in the existing nuclear fleet would be shut down after operating for 40 years. The service life of the more recent plants would be extended by 20 years.

To determine how robust the *DIV* strategy is, we shall assume in the variant that follows that it takes the course described in Section 2 up to 2030, but that EPR construction proves much more difficult and costly than planned (*DIV_EPR* scenario). As a result only four NPPs[32] would be built before 2030, instead of eight (Table 7). Additionally, it would not be possible to extend the service life of a larger number of existing plants, because the oldest ones would already have been decommissioned and their more recent counterparts would all have been upgraded, in line with the initial *DIV* scenario.

Altogether, this in turn creates a shortfall in nuclear capacity compared with the initial *DIV* strategy. In a situation of this sort, by 2050 there would be an 18 Mtoe shortfall in the decarbonized supply needed to achieve the F4 target, between *DIV* and *DIV_EPR*. The difficulty of decarbonizing an additional 18 Mtoe in the 20 years between 2030 and 2050 would force the initial *DIV* strategy to look for additional forms of reduced energy consumption. The pathway obtained in this case, with Imaclim-R France, shows that by 2030 (*DIV_EPR* in Figure 20), only 20% of France's energy supply would have been decarbonized compared with 2010, whereas 30% should have been achieved. The decarbonization shortfall would only be very slightly compensated by further reductions in energy demand.

If the *DIV* strategy without third-generation NPPs is pursued until 2050, the drop in energy demand would remain limited, at 28%, and energy decarbonization would only reach 37%, instead of the initial target of 67%. So it would fall far short of the Factor Four (F4) target. We then posit that efforts to reduce demand would shift to potentials that can be rapidly mobilized during the 2030-2050 period, in line with the profile of the *EFF* scenario. We assume:

- Starting from 2030, compulsory retrofitting would enable about 600,000 deep retrofits to be completed per year on residential property, with a further 21m sq m on business property;
- Deployment of renewable energies generating electricity (mainly wind and solar) would speed up, so that RES would account for about 70% of the mix by 2050, with VRE accounting for 50% of output;
- To meet these goals, the carbon tax would increase steeply from 2030 onwards, catching up with the level of the carbon tax in the *EFF* scenario.

32 The choice of four is justified as follows. If only 1 or 2 EPRs could be built before 2030, earlier adjustments of the strategy would have occurred and the gap in low-carbon energy supply would have been better anticipated, but mechanisms would remain the same. Nevertheless, another option could have been to consider that 8 EPR could be built but at a much higher cost than expected and with a large delay. In such a case, the gap in low-carbon energy supply would have been smaller, but the decision not to build additional capacity in EPR after 2030 would have been the same.

Figure 20a: Description of the DIV_alter pathway compared to EFF and DIV

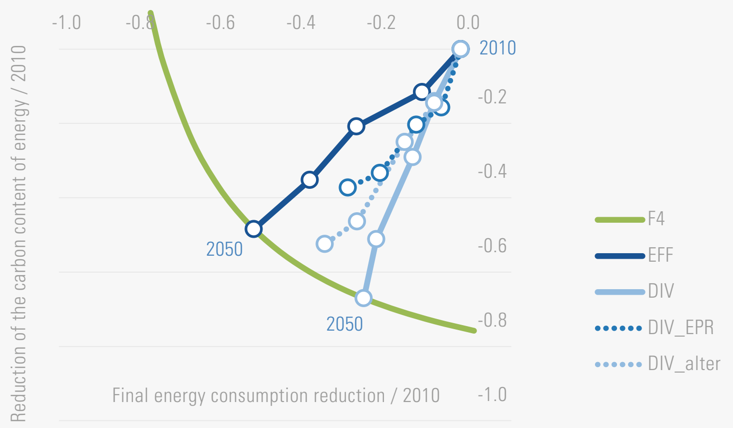
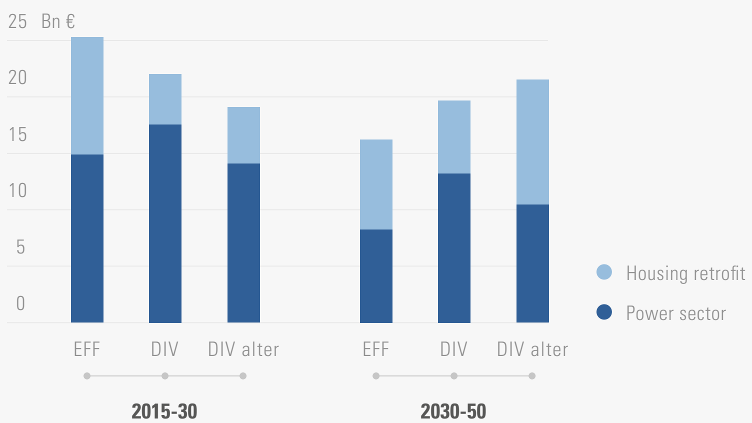


Figure 20b: Sectoral investments



In what follows, we shall refer to this scenario as *DIV*_alter. Under *DIV*_alter conditions, the additional cuts in energy consumption obtained through further measures would come closer to, but not actually achieve the Factor Four target. Emissions abatement would thus be limited to 68%.

This departure from the original *DIV* strategy leads to a shift in investments, with respect to time and sector. The fall in investments in the electricity sector observed before 2030 is compensated by a surge in spending on improving the energy efficiency of residential property. Annual investment 2015-50 remains almost identical to the original *DIV* strategy.

DIV_alter results in a slight drop in economic growth over the whole period compared with the original *DIV* strategy, notably due to the higher price of energy in general, and of electricity in particular. The carbon tax rate is higher than in *DIV* (360 €/ton compared to 280 €/tCO_2 in 2050). Furthermore, due to the constraints on deployment of new EPR plants, gas power plants would be built before 2030 and would be subject to a carbon tax during the whole period, with some of them remaining in operation even in 2050. The impact of higher energy prices,

Figure 20c: New capacities in the power sector

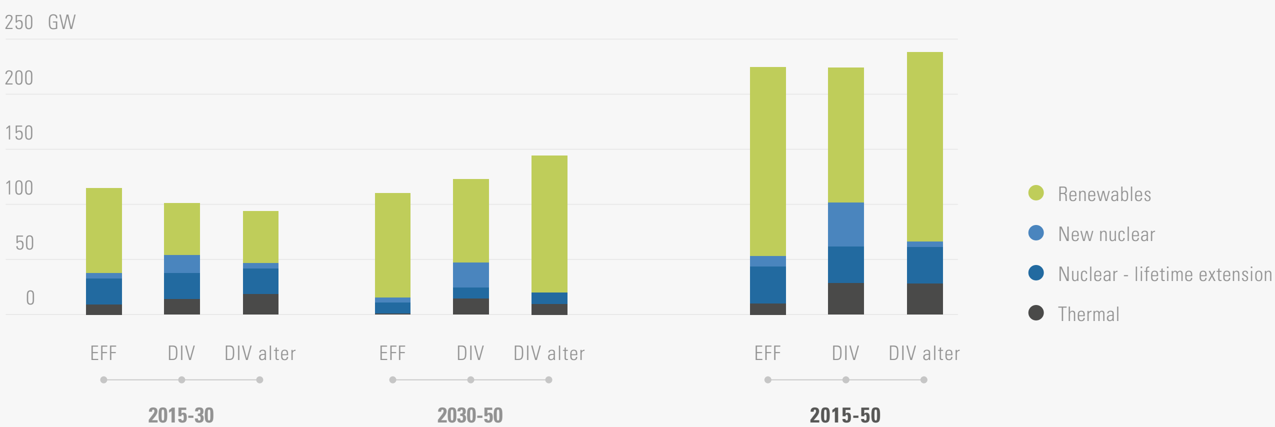


Table 8: Average annual GDP growth rate in DIV and DIV_alter

	2015-30	2030-50	2015-50
DIV	1.23%	1.40%	1.33%
DIV_alter	1.18%	1.37%	1.30%

not entirely compensated by energy savings, is noticeable as it affects: (i) household budgets, with the share of household spending on energy services increasing slightly compared with a *DIV* pathway over the whole period (12% in 2050 compared to 11.5% in *DIV*); (ii) the balance of trade, which deteriorates slightly compared with a *DIV* pathway.

3.2.2 *EFF: Betting on a change of lifestyle*

In this section we develop a similar exercise for the *EFF* trajectory, with the initial setting described in Section 2. The aim is to halve energy demand, through sectoral programs combining a nationwide thermal retrofit program for residential and business property, and rolling out the development of a substantial alternative transport infrastructure and services in the place of private cars.

Many obstacles may hinder the projected cuts in energy demand. In the residential sector, completing 600,000 retrofit jobs per year is conditional on overcoming a variety of transaction costs and setting up a sufficient number of professional training courses in the next few years to ensure sufficient professional capabilities. The effectiveness of energy savings and the attainment of the top-grade energy label after retrofitting may be compromised unless adequate controls and energy-performance contracts are introduced, as well. As things stand, the rules on decision-making in collective dwellings in co-ownership, or the behavior of households regarding the decision to retrofit, also represent severe constraints. In the following we shall assume that these obstacles will not be overcome in the coming years, despite the good intentions of policymakers committed to achieving major cuts in energy consumption in the building sector.

We shall consequently draw a distinction between two periods: 2010-2030 and 2030-2050. In the first period, the strategy adopted would be the one projected by the *EFF* scenario, but efforts to reduce energy consumption in residential and business property prove partly ineffective. The number of retrofits, but also the level of energy performance attained, fall short of expectations. In the same way, the growth of specific electricity demand fails to slacken as forecast. The pathway we shall call *EFF_dem* (*EFF* with less demand reduction) obtained with the Imaclim-R France model, shows that by 2030, energy demand would only fall by 20% on 2010, instead of the projected 26%. This equates to 10 Mtoe in 2030. If the original *EFF* strategy were pursued as initially planned into the second period, up to 2050, but with the same limited effectiveness in reducing energy consumption in buildings, the cut in energy demand would only reach 40% and not the 50% initially targeted. Total final energy consumption would be 16 Mtoe higher in 2050 than in EFF. The decrease of the carbon content of energy would reach only 37%, not the 48% initially targeted. The F4 target would not be met. The electricity sector would register the poorest achievement in terms of energy decarbonization because with demand exceeding initial forecasts it would be necessary to build gas power plants, in addition to deploying large-scale renewable electricity sources.

Figure 21a: Description of the EFF_alter pathway compared to EFF and DIV

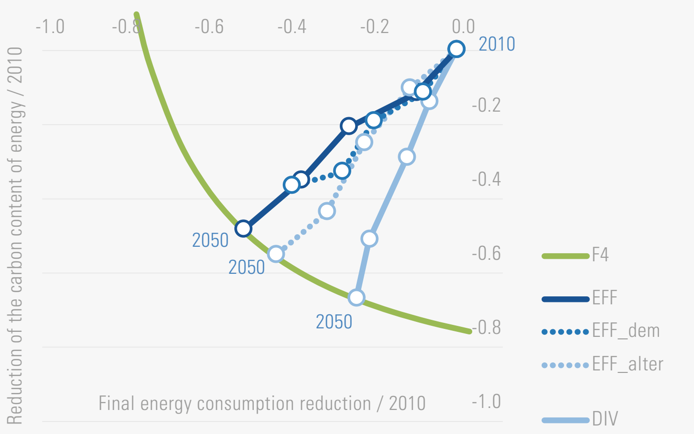
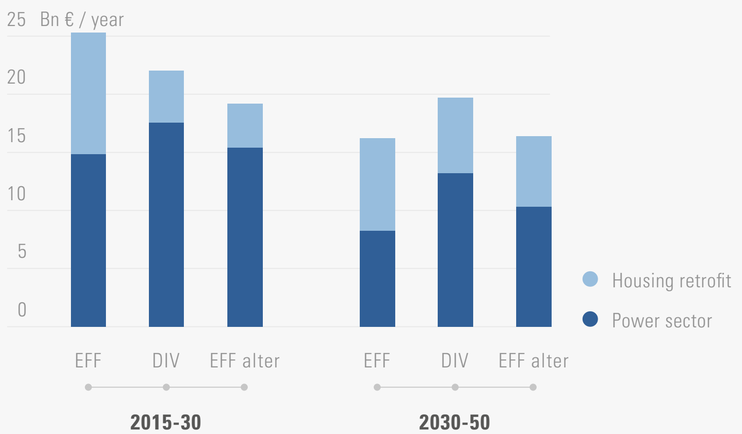


Figure 21b: Sectoral investments



Starting from this basis, the Factor Four strategy, in a scenario we call *EFF_alter* would step up the decarbonization of supply, along the lines of what is projected by the *DIV* strategy. So *EFF_alter* would entail:

- Deploying third-generation NPPs, amounting to an additional 8 GW capacity (five reactors), built in 2030-2050, over and above the initial strategy;
- Greater use of biogas than in *EFF*, entailing the production of 20 Mtoe by 2050, i.e.10 Mtoe more than initially planned (but still below the 25 Mtoe projected by *DIV* for 2050).

With these changes, the Factor Four target would be achieved in 2050 at a limited macroeconomic cost, because the annual growth rate would only dip by 0.01% over the entire period, leading to GDP in 2050 only 0.2% lower than in the original EFF strategy.

These results of course still depend on the assumption that EPR technology will be available at a moderate cost by 2030. This would restrict the need to invest in other decarbonized energy. It would also substantially contain rising electricity prices in the *EFF_alter* scenario, compared with *EFF*. However, the lower reduction in residential energy consumption would entail a significant increase in household energy budgets

Figure 21c: New capacities in the power sector

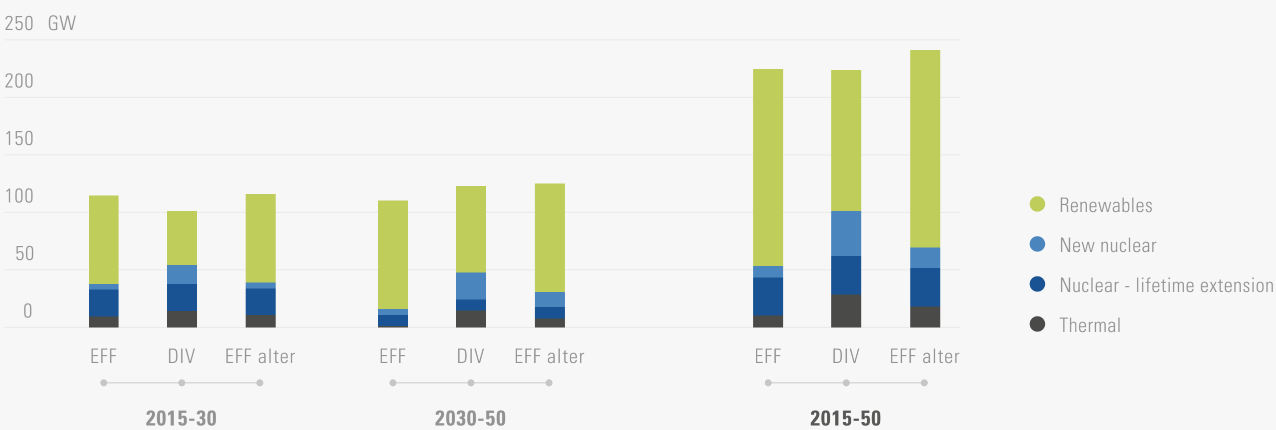


Table 9: Average annual GDP growth rate in EFF and EFF_alter

	2015-50	2015-30	2030-50
EFF	1.28%	1.55%	1.43%
EFF_alter	1.27%	1.54%	1.42%

compared with a pure *EFF* strategy (in 2050 it represents 9.3%, compared to 8.6% in the *EFF* pathway). Such spending would nevertheless be lower than in the *DIV* scenario.

3.3 Building Robust Energy-Transition Strategies and Dynamic Management

We may draw four main conclusions from the preceding analysis:

- The *EFF* strategy seems more robust since action focuses primarily on demand-reduction, which in turn reduces the need for decarbonized energy, but may leave room for maneuver if demand-reduction policies fail to perform as well as expected.
- It seems that it would be easier to achieve the Factor Four target by adjusting an *EFF* strategy, should this prove necessary.
- In case of partial failure, the economic cost of adjusting the *EFF* strategy appears to be lower than for adjusting a *DIV* strategy.

Progress in deploying the strategy will need to be checked at regular intervals, in order to anticipate any need for adjustment. Our analysis shows that a 15-to-20 year time step is much too long. Irreversibility could be avoided by adopting a dynamic approach to transition management, spanning much shorter periods of time; five years seems a good compromise.

Furthermore, this analysis pleads in favor of setting up an institutional management system for low-carbon energy transition, comprising:

- Imperatives, i.e. bringing together objectives which must be achieved regardless of which strategy is chosen (though insufficient in themselves to achieve the Factor Four target) (Table 10);
- Short-term goals and milestones consistent with the long-term objective.

The energy-transition management system should thus entail setting up a permanent monitoring system, checking progress annually, and providing feedback for dynamically managing the transition process. As part of this approach, transition strategy would be regularly reviewed and adapted roughly every five years, in pursuit of short-term goals consistent with the long-term objective (cf. Annex).

Table 10: Examples of imperative objectives on the way to energy transition

Sector	Indicator	Goal
Residential	Number of deep retrofits	350,000 retrofits per year
Business	Floor space upgraded per year	15m sq m per year
Passenger transport	Share of low-carbon vehicles in annual sales	20% in 2020 60% in 2030 100% in 2050
Industry	Energy efficiency	30% gain in 2050 on 2010
Power sector	Wind + solar	55TWh in 2020 100TWh in 2030
Biogas		6 Mtoe in 2030 10Mtoe in 2050
Biofuels		at least 5 Mtoe over the whole period

4 Triggering a Transition To a Deep Decarbonization Pathway in an Adverse Context: Macroeconomic insights

The previous sections explored the content of a low-carbon energy transition in France. A major remaining issue is how to trigger this transition in a context of short-term tensions with large debts, risks of recession, high unemployment, stagnating or declining household purchasing power and public budget limitations.

We now provide some elements of a response on how to trigger the low-carbon transition - the 'launching phase' of action. We do not cover the range of policy scenarios examined so far. Rather, using previous work with the IMACLIM-R France model (Hourcade and Bibas 2013)[33], we consider a reference scenario (*REF*), and for the analysis, a transition scenario, similar to the *EFF* trajectory analyzed in previous sections[34]. This scenario is based on a set of presumably Acceptable Policies and Measures (*EFF_apm)*. We analyze then the effects of various measures that would accompany the transition: economic policies, structural policies and behavioral changes beyond the energy sector. We look at the measures' social and economic outcomes over both the short and long runs. More detailed results are given in the Annex in table 12.

Both scenarios project a gradual economic recovery from the current crisis at a rate of 1.5% per year. The model derives energy demand from income levels, changes in consumption, and efficiency gains accrued in the transformation between primary energy, final, and useful energy. The energy supply is also endogenous, with the exception of the share of nuclear power for electricity supply; in REF, we assume that this falls to 50% of electricity production in 2025 but then rises again to reach 70% in 2050, in a context of gas price increases.

We first demonstrate why, despite the potentials for negative costs, the *EFF_apm* scenario results in lower employment and lower growth over the short term compared with REF due to the inertia in technical and social systems. We then analyze what policy mix is capable of turning these losses into gains, and transforming climate action into a lever for a green growth recovery. Unsurprisingly, the policy mix encompasses well-designed tax reforms and financial tools. Less intuitively, we will show that it must incorporate early public policy (financial) support for long-term structural changes, beyond the energy sector.

4.1 An "Acceptable" Policies and Measures (APM) Scenario

This Policies and Measures *EFF_apm* scenario comprises all the policies and measures deemed "acceptable" according to the ENCI-LowCarb stakeholder consultation. The Policies and Measures retained include regulatory policies (e.g., thermal regulation of new buildings), financial support for thermal retrofitting, and targeted fiscal tools[35] (a heavy truck environmental tax, a kerosene tax for air transport). These policies have a net negative discounted cost. This doesn't mean they are 'effortless' but they require specif-

33 With modelling work performed by Ruben Bibas from CIRED.

34 The low-carbon scenario retains, on the demand-side, the parameters of the ENCI-LowCarb scenarios from the European project "Engaging civil society in low carbon scenarios." The ways it differs from the EFF scenario discussed in previous sections are from a macroeconomic standpoint of a second order.

35 They are different from the general carbon tax envisaged in the previous sections.

ic expenses over the short term and they result in immediate costs for private and public actors expenditure to bring equipment up to standards, fiscal cost of public incentives, tax impacts[36].

This *EFF_apm* scenario cuts down GHGs emissions by a Factor Three. A strong decline of emissions between 2020 and 2040 is followed by a plateau, which marks the resistance to lower emissions by the transport sector. The lower energy demand leads to a nuclear capacity divided by three, and avoids the rise of nuclear after 2025, which is needed in *REF*. However, nuclear power still represents 50% of the electricity mix in 2050.

The economic outcome of this scenario over the period is stronger real GDP growth (an average annual growth rate of 1.15%, against 1.06% in *REF*) and employment gains (over 300,000 additional jobs), together with a 40% reduction in energy imports. These results are the logical outcome of the 'net negative discounted cost' options which act, in macroeconomic terms, as 'manna from heaven.'

But a look at the temporal profile of these effects reveals a more mixed outcome. In the first five years, *EFF_apm* leads to a decline in growth and employment. It is very slight at the aggregate level, but because the losses are not evenly distributed across society, the decline should be viewed as an indicator of significant burden for some social groups (low income, people in old houses or car dependent because they live in rural areas or suburbs) or industrial subgroups (steel, non-ferrous, cement, petrochemical). These burdens can undermine acceptance of the energy transition, and exacerbate the doubts of policy-makers about green-growth climate policies. Adjustment costs are thus important. They arise as a result of two intertwined mechanisms: (i) there is a delay between private and public spending (investments on the thermal retrofitting of buildings, tax credit to support these investments, taxes on fuel) and the positive effects of these expenditures, even if these benefits spread rapidly and (ii) household demand for non-energy goods diminishes because of increased spending on thermal retrofitting.

4.2 The P&M Scenario Plus a Carbon Tax: Still a 'triggering' phase problem?

In this scenario, we take the *EFF_apm* scenario and apply the economist's recommendation, a carbon tax, and check whether this improves the economic balance during the low-carbon energy transition. We thus complement the previous measures by adding a carbon tax equivalent to the path proposed by the Quinet report in 2009 (100€/tCO_2 in 2030, extended to 300€/tCO_2 in 2050). This Policies and Measures plus Tax (*EFF_pmt1*) scenario yields GHG emissions reductions closer to the F4 trajectory: -68.5% in 2050. The reason is that explicit carbon pricing accelerates the penetration of demand-side measures, and speeds up the phase-out of fossil fuels from the energy mix.

If the tax revenues are recycled through an annual, lump-sum refund to households, economic performance is lower than in *EFF_apm* scenario (an average growth rate of 1.09% against 1.15% over the period). Even worse, the growth rates during the first five years are negatively affected: 0.69% growth rate for *EFF_pmt1*, versus 0.73% for *EFF_apm* and 0.77% for REF.

The mechanism at work can be summarized as follows:

36 We exclude those measures that involve too complex mutations of the society (e.g., telecommuting, decoupling of production and transportation, dematerialization of the production content). These changes would have to be supported by specific sectoral policies which will not be adopted for purely climate-centric objectives and because they are only consistent with profound changes in individual and collective preferences and lifestyles. Fundamentally, they do not correspond to the same type of costs and benefits as other measures like stimulating the thermal retrofit of buildings.

- in a multisectoral model, the carbon tax spreads to the whole economy and drives production costs up;
- the international competitiveness of "made in France" products is affected;
- households' purchasing power is lowered by the rise of prices in the 'shopping basket' for non-energy goods.

Note that the GDP loss compared to REF by the end of period (-2%) does not automatically affect employment because the decline in labor costs for a given net salary promotes labor-intensive sectors and technologies.

In principle, the best way to limit the spread of higher energy costs through the economy is to lower payroll taxes (both employer and employee taxes). This prevents a rise in production costs of non-energy goods (and its adverse competitiveness effects), but households still suffer from lower purchasing power due to their higher energy bills. Thus we simulated a revenue-recycling scheme (in *EFF_pmt2)* where tax revenues are in part returned to households through a 'green check', and in part are used as a substitute for lower payroll taxes. In this scheme, part of the tax implicitly falls on non-wage revenues and energy imports.

EFF_pmt2 seems to overcome the barriers of the triggering phase. Its positive effect is important in the short term (0.81% growth rate compared to 0.73% in the *EFF_apm* scenario and 0.77% in *REF*). The main reason is that narrowing the difference between labor costs and net wages makes French industry more competitive (energy-intensive industries excluded), without the adverse effect that lower wages would have on domestic final demand. Over the medium and long term, this effect vanishes, and the difference becomes insignificant. Higher employment level improves workers' negotiating power. A larger share of the payroll tax cuts is transformed into higher net wages, mitigating the effect of higher energy costs. The overall balance is positive in 2050, with an unemployment rate 10% lower, while energy imports are 50% lower than in *REF*. One of the main obstacles to deploying this scenario is political in nature. Theoretical literature establishes that the double-dividend effect is not systematic. In fact, one central parameter is the share of payroll tax reduction (employer and employee contributions) that is transferred into higher net salaries. This indeed commands the delicate balance between the rise in production costs and purchasing power. This is one fundamental reason why this type of scenario requires *"the implementation of appropriate governance with a perspective covering multiple years [...] to institutionalize the need for governance, assess its impact, and assess the use of these revenues."* *(Rocard Commission, 2009*[37])

A well-conducted carbon tax should thus be part of global fiscal reform (like in Sweden in the early 1990s) and, in the context of French Social Security system, should be connected to overall social negotiations. The scenario's uncertainty, though, is its political feasibility. Its major weakness is that it demands quickly raising carbon taxes (100€ in 2030) which will affect a diverse set of interests, including in low-income populations (car-dependent workers in suburbs, farmers in mountain areas, fishers, truck drivers...). These vested interests can be mobilized to reinforce the opposition of energy-intensive industries. A 0.04 percentage point higher growth rate might not be sufficient to discourage this opposition; even with compensating transfer for these groups, the immediate impact may fuel strong antagonisms. The art of economic policy is to arrange the measures so as to ensure that their positive effects outweigh the negative ones, so the tran-

37 This advice, formulated by Michel Rocard in its report on a carbon tax was not followed, which contributed to the failure of the proposal, cf. Rapport de la conférence des experts et de la table ronde sur la contribution Climat et Énergie, 28 Juillet 2009, Documentation Française, Paris, 83 pages.

sition is politically acceptable. This demands enriching the policy packages analyzed so far, and fine-tuning the temporal layout of a diverse set of measures.

4.3 The P&M Scenario Plus a Carbon Tax, Financial Device, and Infrastructures Policies: A question of timing

There are two ways of lowering the carbon price: either by acting upon the time profile of the GHGs abatement required over the period, or by triggering the same level of investment in low carbon techniques but with lower carbon taxes. The dynamics of mobility needs, and of the share of these needs covered by road transportation, are critical for the time profile of emissions. The higher the gasoline-dependent mobility in the long run, the faster carbon prices have to increase. This is the case in the previous simulation (*EFF_pmt2)*, which capture the rebound effect of mobility needs after new technology improves the performance of engines, or after more conventional infrastructures are developed. Even high carbon prices over the short run fail to alter these trends. Even after most of the decarbonization is achieved in other sectors, very high carbon prices are needed to continue curbing carbon emissions in transport.

This has a strong implication for carbon prices, which, because of the transport sector problem, tend to be increased at a pace beyond political acceptability. This means that mobility trends cannot be altered through carbon price policies alone. They require specific evolutions (e.g., telecommuting, decoupling of production and transportation, dematerialization of production content), as well as a combination of infrastructure choices, regulation of real estate markets[38], and behavioral changes – which will not take place purely for climate-centric reasons. The energy transition thus becomes a component of an overall policy aimed at anticipating the adverse consequences of urban sprawl, and of the excessive spatial scattering of productive activities. We thus introduce in the Policies and Measures plus Tax plus Infrastructures (*EFF_pti*) scenario a shift of investments in urban and transportation infrastructures in favor of rail and water transportation, and also of soft modes (cycling, walking).

The second parameter is the sensitivity to risk of investment decisions. The carbon price signals are blurred by the volatility of energy prices, and the uncertainties that surround final demand levels and the performance of technologies. Investment risk sensitivity is particularly important for low carbon technologies since almost all entail high upfront costs. This is why we incorporated into this last variant the development of a large scale 'carbon finance' scheme, with a government guarantee to back low-carbon investments. This carbon finance[39] aims at reducing the investment risk for low-carbon investors (building owners, car buyers, wind-power plant developers, or industry managers). It is based upon a public guarantee covering, at a predetermined notional value carbon, carbon certificates representing a share carbon emissions reduction expected from a type of project in given coun-

38 An econometric analysis over the past 50 years show that, in France, the influence of the real estate prices is as important as the fuel prices on the dynamics of fuel demand for transportation activities (L. Lampin, F. Nadaud, F. Grazi, JC Hourcade, *Long-term fuel demand: Not only a matter of fuel price*, Energy Policy, vol 62, 2013, pp 780 – 787).

39 An example of such a scheme has been presented in Hourcade JC. Perrissin Fabert B., Rozenberg J., 2012. Venturing into uncharted financial waters : an essay on climate-friendly finance, International environmental agreements-Politics law and economics, 12(2), p 165-186, DOI:10.1007/s10784-012-9169. It has been taken up for Europe in Aglietta M., Espagne E., Perissin-Fabert E.: A proposal to finance low carbon investments in Europe. France Strategy, February 2015. http://www.strategie.gouv.fr/sites/strategie.gouv.fr/files/atoms/files/bat_notes_danalyse_n24_anglais_le_12_mars_17_h_45.pdf

tries. This allows for lowering the upfront costs of low carbon investments since the loans can be reimbursed in carbon certificates instead of in cash. In the modeling exercise we translated this mechanism through a lower discount rate for low carbon projects (4% instead of 8%).

Thanks to this new policy package (structural policies altering mobility trends and carbon finance), the F4 objective is reached with higher growth rates over the time period. The gain is significant over the long run (1.23% growth between 2010 and 2050, against 1.15% in the *EFF_apm* scenario and 1.06% in the REF scenario). But the most important outcome to trigger action is that the economic growth rate is 0.87% during the first five years, against 0.73% and 0.77% in the *EFF_apm* and *REF* scenarios, respectively.

What makes the difference here is strengthening of economic agents' anticipations so they are prepared for higher energy costs later while being confronted to significantly lower carbon prices in the short term (10€/tCO_2 instead of 33€/tCO_2). This can occur through both the credibility effect of the financial tools, and by avoiding the lock-in in oil-dependent transportation. The needed low carbon investments are carried out over the short term, to reach 100 G€ in 2050, even without very high carbon prices.

In terms of political economy, the *EFF_pti* scenario is more apt to overcome the political barriers to triggering a low carbon transition. The opposition from vested interest is less exacerbated; economic agents benefiting from more low carbon technologies and less dependent on conventional internal combustion thanks to urban and land-use policies will be in position to accept high carbon prices over the medium and long run. Moreover, a 0.15 percentage point higher growth over the short term generates means of compensating transfers for the residual adverse effects of carbon taxes on the most impacted categories of population and industries.

Conclusion

In 2012, the National Debate on Energy Transition defined two main pillars for low-carbon energy transition in France: the Factor Four (F4) – a 75% reduction in GHG emissions in 2050 (compared to 1990) – and reducing the share of nuclear power in the electricity mix from 75% in 2015 to 50% in 2025, without further indication of the long-term role of nuclear energy. The National Debate Council of 2013 also identified two main structural features that would characterize France's energy-transition pathways:

(i) reducing energy demand in 2050, compared to 2010 (-20% or -50%), and

(ii) the level of diversification of the energy supply.

This permitted delineating four scenarios, or pathways, which provide a rather complete mapping of France's possible energy futures. The law on Energy Transition for Green Growth, adopted in July 2015 is grounded on the target of a 50% reduction of total final energy demand by 2050. It appears highly consistent with one of the four pathways combining 50% energy demand reduction in 2050 and a diversification of the energy mix driven by the a strong deployment of renewable energy sources.

This report has considered these key features and studied the feasibility conditions of two different decarbonization pathways: one focusing on energy efficiency to obtain a strong reduction in energy demand (this pathway is highly consistent with objectives of the law on Energy Transition for Green Growth) and the other one considering potential limits to energy demand reduction and thus implying a higher level of decarbonized energy supply. Each strategy involves major challenges, which, in the first case, connect to the 'energy efficiency gap' issue and, in the second one, to the physical, technological and economic barriers to the deployment of massive decarbonized supply.

We have then analyzed the consequences of the uncertainties pertaining to the dynamic management of the energy transition. This entails that in the context of very high uncertainties on the environmental and political outcome, energy strategies have to be robust and ensure the resilience of the energy system. The main conclusion from this analysis is that the progress in deploying a specific strategy will need to be monitored and verified at regular intervals, in order to anticipate any need for adjustment. When one embarks on a long journey one has to identify the final destination but also has to leave room for adjusting the route and the pace of the vehicle, from time to time. Our analysis shows that a time step of 15-to-20 years to define all the ways and means of the energy transition is much too long. Irreversibility should be avoided by adopting a dynamic approach to transition management, considering shorter time steps. Furthermore, our analysis advocates the implementation of an institutional management system for low-carbon energy transition, based on imperative and robust options, and defining short-term goals and milestones consistent with the long-term objective.

But energy transition policies should also be embedded in a broader national development strategy. Even with long term benefits and very optimistic assumptions about the penetration of energy efficiency and low-carbon options, France's low-carbon transition might be hindered by short term adjustment costs. These adjustment costs can be overcome only though a complex set of measures encompassing energy regulation measures on the demand and supply sides, a shift in the urban and transportation infrastructures, a carbon tax, and successful negotiations on recycling the revenues from this tax. It also requires financial tools to drastically decrease the investment risks to spur investment in low-carbon options and to redirect savings which today go to real estates and liquid assets. The major conclusion is perhaps that DDP implies profound changes in the pervasive, implicit social contract that was established at a time of cheap fossil fuels. Such profound changes cannot be achieved through energy policies alone, disconnected from the country's overall development strategy. Ultimately, energy transition depends on the country's ability to mobilize around a set of reforms which, altogether, may resonate as a new sustainable social contract.

Annex

Table 11: Example of indicators for dynamic management of energy transition

	Monitoring year t	Five-year goal consistent with selected strategy
Overall indicators		
GHG emissions ($MtCO_2$)		
Final energy consumption (Mtoe)		
Electricity demand (Mtoe)		
Electrification rate (%)		
Share of RES in electricity production		
Share of nuclear power in electricity production		
Share of RES in heat production		
Share of RES in fuel consumption		
Residential		
Number of deep retrofits per year		
Specific electricity consumption (Mtoe)		
CO_2 emissions ($MtCO_2$)		
Business		
Number of sq m of deep retrofits per year		
Specific electricity consumption (Mtoe)		
CO_2 emissions ($MtCO_2$)		
Passenger transport		
Individual mobility (passenger km)		
Number of vehicles on the road		
Number of low-carbon vehicles on the road		
Modal share of collective transport (%)		
Final energy consumption (Mtoe)		
CO_2 emissions ($MtCO_2$)		
Freight transport		
Demand (tonnes km)		
Share of road freight (%)		
Share of rail freight (%)		
Share of inland-waterway freight (%)		
Final energy consumption (Mtoe)		
CO_2 emissions ($MtCO_2$)		
Industry		
Added value (euros)		
Energy efficiency (tCO_2/€m)		
CCS contribution ($MtCO_2$)		
Final energy consumption (Mtoe)		
CO_2 emissions ($MtCO_2$)		

Table 12 : Average GDP growth rates and policy packages

Scenario name	Description of the policy package	2010-15	2010-20	2020-30	2030-40	2040-50	2010-50
REF	Reference	0,77	0,83	1,09	1,47	0,85	1,06
EFF_apm	P&M	0,73	0,9	1,32	1,46	0,9	1,15
EFF_pmt1	P&M + Tax + recycling through annual lump-sum refund to households	0,69	0,86	1,32	1,32	0,87	1,09
EFF_pmt2	P&M +Tax + recycling through annual lump-sum refund to households and through lower payroll taxes	0,81	0,96	1,37	1,34	0,88	1,14

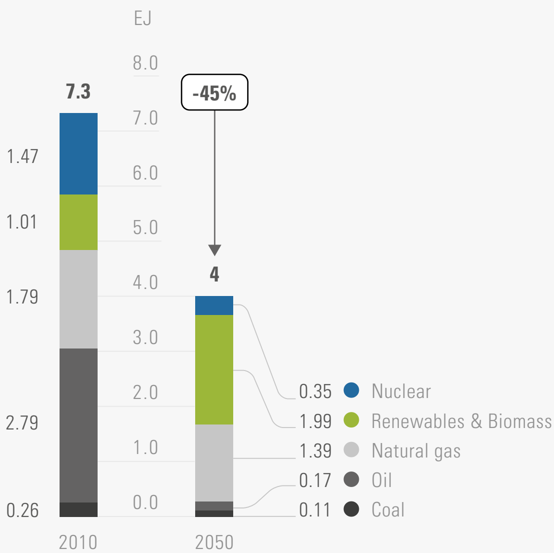
Standardized DDPP graphics for France scenarios

FR – Efficacity

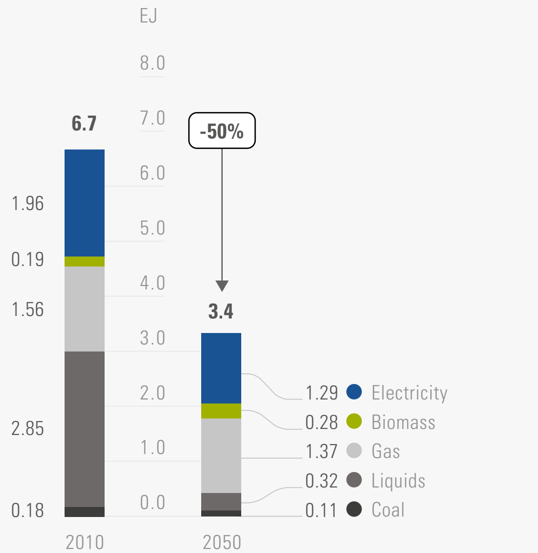
FR – Diversity

FR – Efficiency

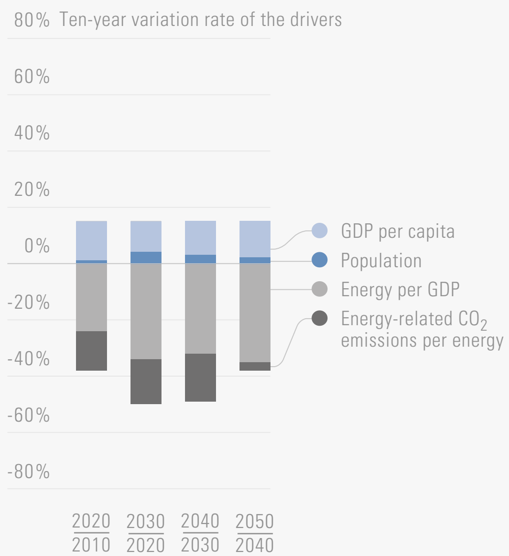
Energy Pathways, Primary Energy by source



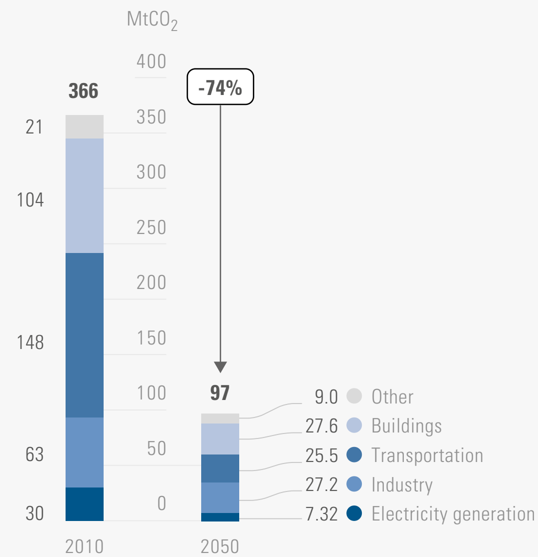
Energy Pathways, Final Energy by source



Energy-related CO_2 Emissions Drivers, 2010 to 2050

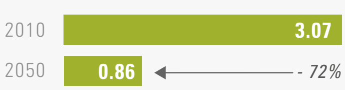


Energy-related CO_2 Emissions Pathway, by Sector



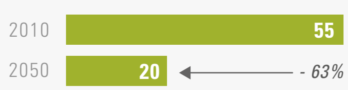
The Pillars of Decarbonization

Energy efficiency



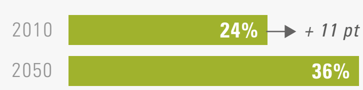
Energy Intensity of GDP, MJ/$

Decarbonization of electricity



Electricity Emissions Intensity, gCO_2/kWh

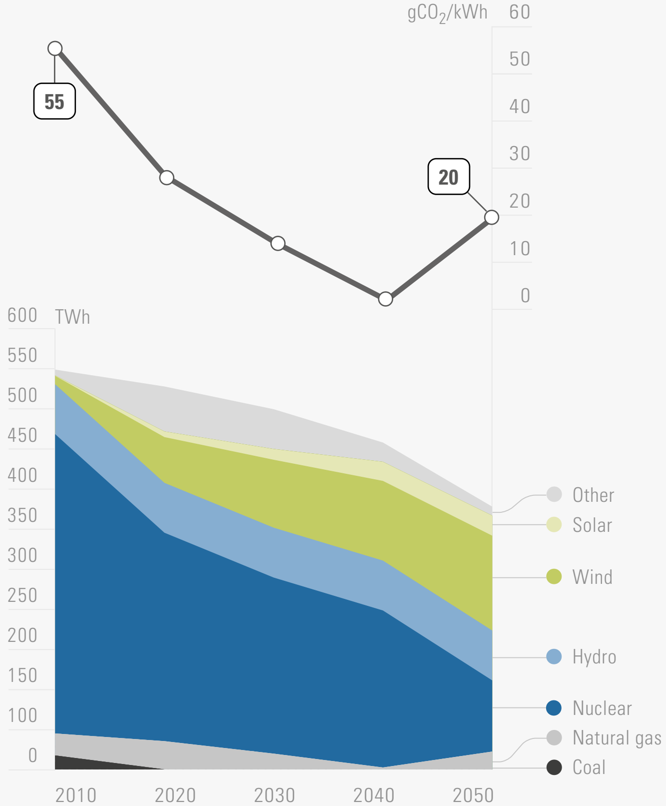
Electrification of end-uses



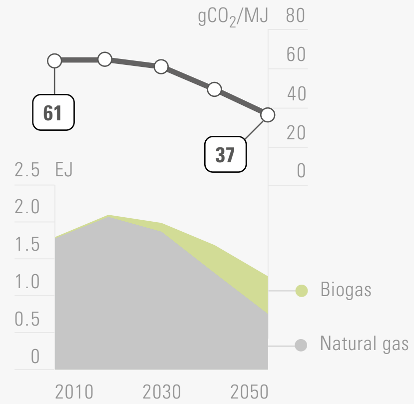
Share of electricity in total final energy, %

Carbon intensity

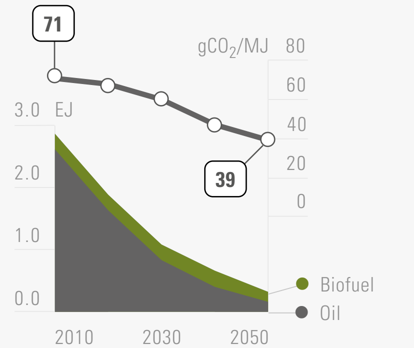
Energy Supply Pathways, by Resource



Electricity

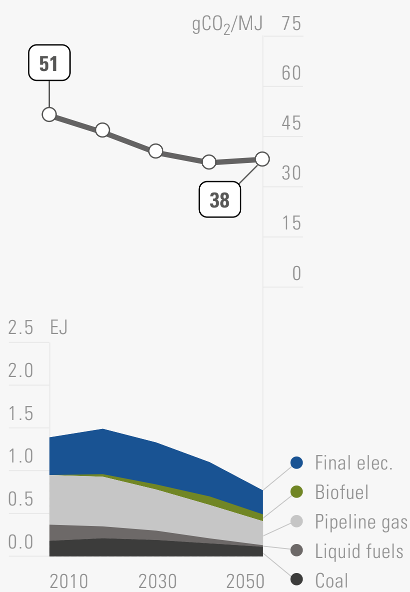


Pipeline gas

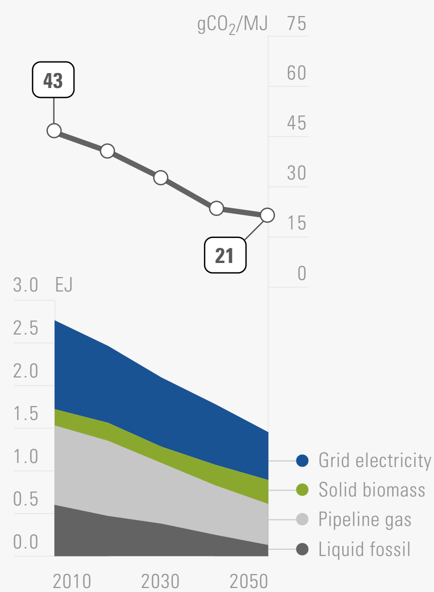


Liquid Fuels

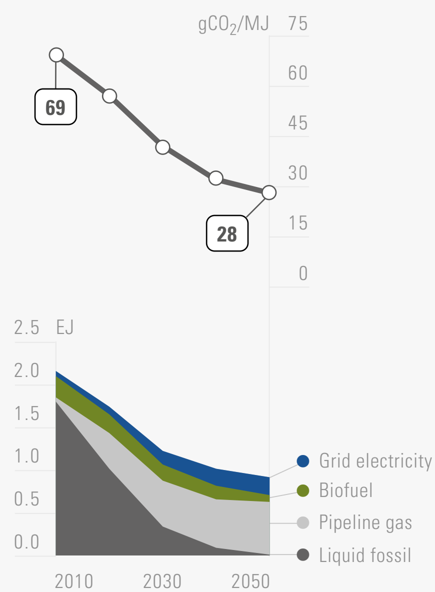
Energy Use Pathways for Each Sector, by Fuel, 2010 – 2050



Industry



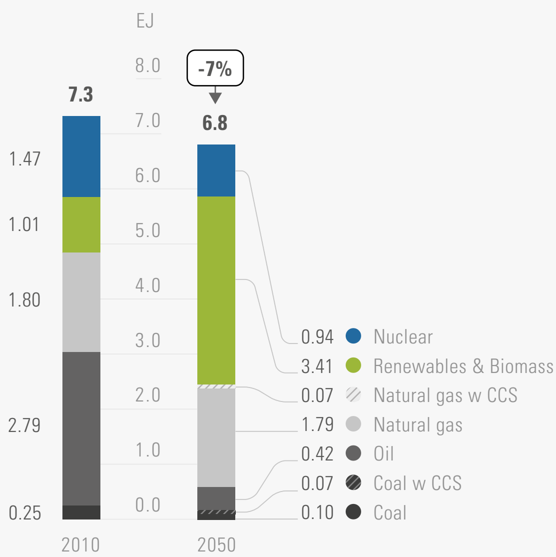
Buildings



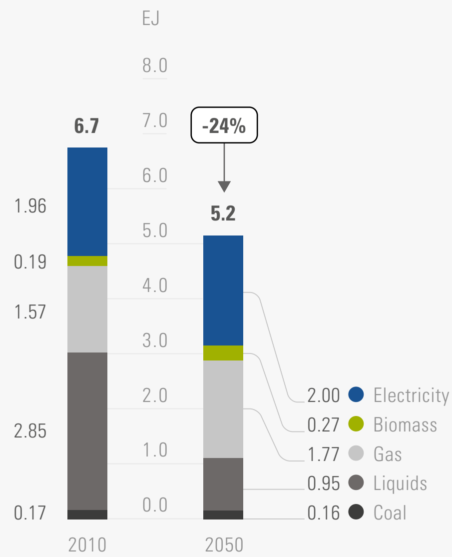
Transportation

FR – Diversity

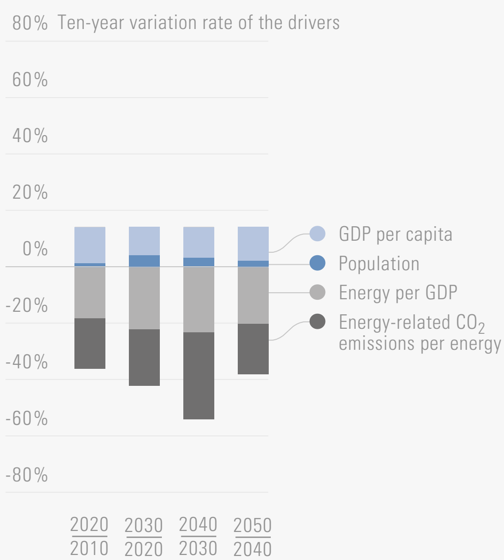
Energy Pathways, Primary Energy by source



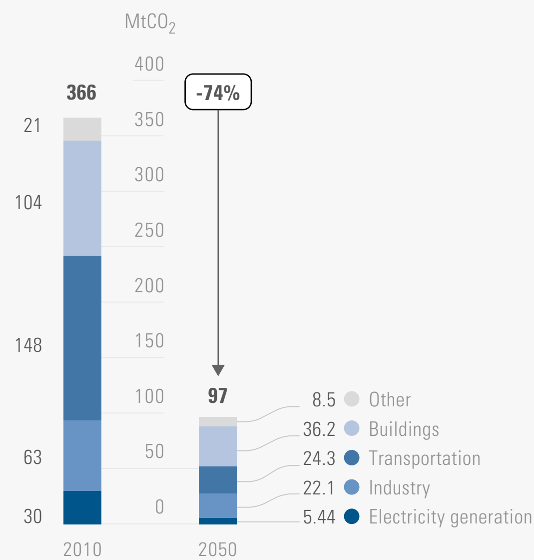
Energy Pathways, Final Energy by source



Energy-related CO_2 Emissions Drivers, 2010 to 2050

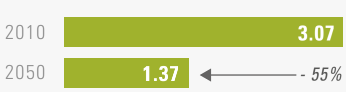


Energy-related CO_2 Emissions Pathway, by Sector



The Pillars of Decarbonization

Energy efficiency

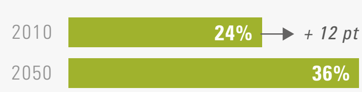


Energy Intensity of GDP, MJ/$

Decarbonization of electricity

Electricity Emissions Intensity, gCO_2/kWh

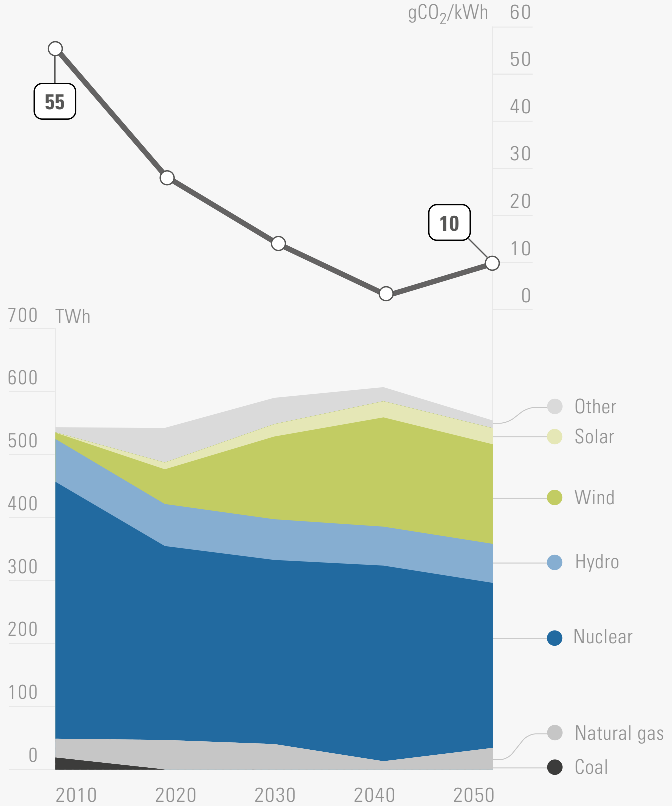
Electrification of end-uses



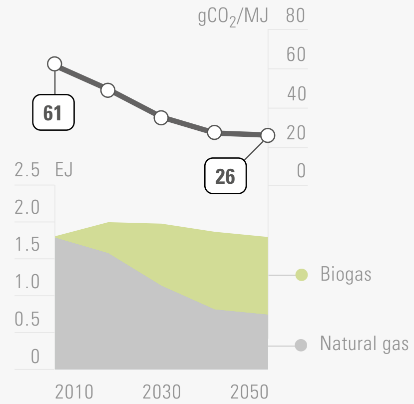
Share of electricity in total final energy, %

Carbon intensity

Energy Supply Pathways, by Resource



Electricity



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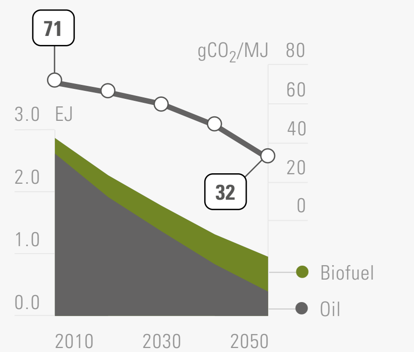

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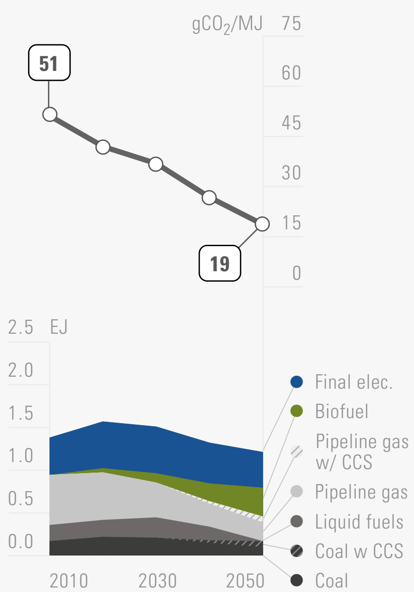
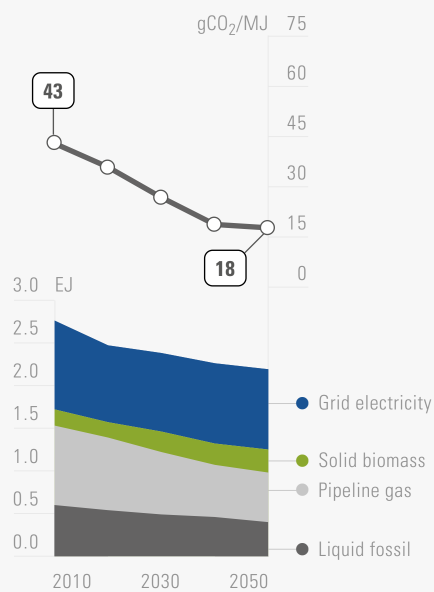
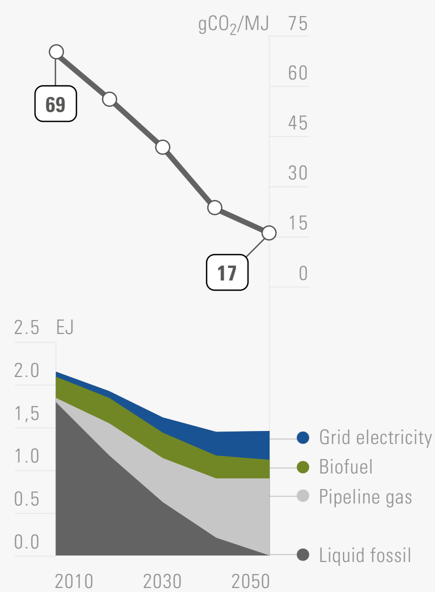


Industry



Buildings



Transportation