The great transformation: decarbonising Europe’s energy and transport systems

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Foreword

The euro-area crisis dominates the economic news. Yet, the world and Europe may face even more important challenges that will shape our lives and the lives of our children. World population is projected to increase to 9 billion or more by 2050. At the same time, current trends indicate an increase in living standards and a growing middle class around the world. These two mega-trends will have profound implications, and the way they are managed will be one of the key determinants of prosperity and peace in the decades or even centuries to come. A number of factors are important in this respect.

More people and more income will increase the global demand for energy. Choosing the right sources of this energy will be one of the determining factors of global temperature. The continued reliance on fossil-fuel energy sources is one of the main factors behind the risk of significant global temperature increases. The internationally agreed goal of limiting the temperature rise to less than two degrees Celsius above pre-industrial levels appears increasingly illusory. Currently, fossil energy sources dominate many economic areas. For instance, our transport infrastructure is largely based on fossil fuels, and is thereby one of the main contributor of the carbon dioxide emissions that are linked to global temperature. Thinking about a decarbonisation strategy is therefore a key challenge with a global dimension.

Economic growth in Europe will be affected by the costs of this transition from the current energy and transport system. A smooth transition towards a low-carbon energy and transport system could come at comparatively modest cost. Furthermore, identifying the most economically beneficial solutions early on and becoming a global technology leader and standard setter offers vast opportunities for exports and economic growth. Hence, our decarbonisation strategy may eventually have a greater impact on long-term European growth than the current economic crisis.

Bruegel is contributing to this debate with this report, which is based on research that received funding from the Fuel Cell and Hydrogen Joint Undertaking. The authors argue carefully that to make decarbonisation growth friendly, a consistent policy approach is needed. Policy intervention appears indispensable as the energy and transport system is so based around and locked-in into an incumbent technology. Overcoming this lock-in is crucial. The report makes three main proposals. First, the scope, geographical coverage and duration of carbon pricing should be extended. By setting a higher carbon price, incentives for developing and investing in new low-carbon technologies are created. Second, temporary consortia for new infrastructure to solve early-phase market failures could be put in place. This is discussed using the example of hydrogen vehicles. Lastly and importantly, an open and public transition model is needed so that second-best transport solutions do not get a head start that afterwards cannot be reversed.

The technological, economic and political challenge ahead is vast. But choosing the right decarbonisaton strategy offers huge economic, environmental and societal benefits. We should not overlook this debate because of the euro crisis.

Guntram Wolff, Deputy Director, Bruegel
Brussels, January 2012

Executive summary

Transition is necessary

The major challenge facing the energy and transport system is the reduction of its fossil fuel consumption and carbon footprint. This requires a shift in the way we produce and consume energy. Due to the limited carbon-reduction potential of incumbent technologies, new low-carbon technologies will have to enter the mainstream market. Some of those new technologies offer significant side-benefits such as reducing local pollutant and noise emissions. Furthermore, decarbonising the economy based on new technologies could induce growth.

Transition is a complex endeavour

The current energy system, in its complexity, has developed over centuries. The rapid diffusion of new technologies requires either that they have serious advantages over incumbent technologies, or that downstream changes are minimal. Presently, most low-carbon energy and transport technologies meet neither of these criteria: they are more expensive than the technologies they replace but offer little, if any, advantage, and they require substantial downstream changes to the incumbent energy or transport system in order to accommodate different primary inputs and different operating characteristics. Consequently, transition requires that stakeholders roll-out all parts of the new system synchronously.

Market failures impede transition

Markets alone will not encourage the development and deployment of un-competitive technologies, even if they are necessary for a low-carbon future. In order to encourage the development of these technologies, it is important to monetise the societal benefits they provide by putting prices on greenhouse gases, pollution, noise, and import dependency. In the absence of first-best solutions (for example a global long-term carbon price) policymakers should build on existing instruments in order to provide sufficient incentives for early investment into research and development, demonstration, and deployment of low-carbon technologies.

Innovation is essential to develop the required new technologies. Without effective policies to protect intellectual property or alleviate the private costs of innovation, there will be underinvestment in R&D. But even if competitive low-carbon technologies are available, path dependencies due to institutions, risk-aversion and network effects prevent a quick roll out. This poses a huge challenge to policymakers if they are to help new technologies supplant the incumbent system without favouring one of the alternatives.

A key to success is domestic and international, and public and private cooperation. Leaving coordination entirely to the market might result in late deployment and fragmented networks and markets. Some technologies require a completely new underlying infrastructure. This infrastructure has a high cost that may not be fully recoverable by the initial providers, when the business is regulated *ex post* or late entrants face lower costs. To recoup their initial investment, providers might have an incentive to capture customers by implementing artificial barriers to prevent switching. This can lead to fragmented markets and slow adaptation of new technologies.

A similar problem is also faced by companies in other parts of the value chain. The costs of exploring, and building, new markets is high and may not be fully recoverable given that later entrants may reduce profit margins. Thus, early movers might not be willing to take risks. This is unfortunate because exploring new low-carbon technology business models has a high social value. It provides important information to consumers, competitors and politics about the viability of technologies.

Some low-carbon technologies might never be commercialised because better alternatives exist. However, continuing to fund these technologies might be essential in case the first-best alternative fails to deliver. In this case, having a back-stop technology on the shelf for quick deployment might save valuable time in the fight against climate change.

Finally, low-carbon technologies do not only offer environmental benefits. Deploying and exporting them might offer business opportunities. Under certain conditions it is even conceivable that economies as a whole might benefit from low-carbon technology industries that were built on early local deployment. This early deployment of still non-competitive low-carbon technologies will, however, often not happen without public support.

Thus, private investment into new technologies provides many positive spillovers for society. As markets do not compensate for these spillovers companies will be reluctant to make the necessary investments. Consequently, without public intervention, the transition will only happen slowly or may not take place at all.

Fuel cell electric vehicles will not be provided by the market alone

We use the example of fuel cell electric vehicles to demonstrate that certain low-carbon technologies only enter the market if at least some of the market failures previously described are resolved. This example was chosen because fuel cell electric vehicles promise to be a carbon-free transport alternative with significant range and no local pollutant and noise emissions, but their deployment is held back by the very high initial cost and the absence of the required dedicated infrastructure. Under the existing framework conditions, fuel cell electric vehicles will be virtually absent from the vehicle market in 2050 while incumbent technologies (gasoline, diesel) will still play a major role. We show that this changes when policies are implemented to account for the emission cost of conventional vehicles, support to R&D is provided and the infrastructure externality is overcome. With such a concerted approach, fuel cell electric vehicles might become an important transport technology by 2050, accounting for more than 10 percent of the market. Early cost reductions (such as through R&D) are essential to overcome the gap that prevents deployment. In the most optimistic scenario based on industry forecasts, fuel cell electric vehicles might capture more than 25 percent of the market according to our modelling.

Existing tools are insufficient

There is an extensive menu of current policies at regional, national and European levels that are intended to address the market failures. Fuel taxes, vehicle emission standards and R&D funding, for example, can be effective tools for tackling some of the barriers. However, the totality of current policies is insufficient to resolve the market failures that hamper the transition. There are insufficient funds for R&D, no global long-term carbon price, and deployment efforts are not coordinated. Most importantly, no solution for the infrastructure externality is being implemented, and support for technologies is not predictable.

Smart policy tools for transition

To enable the private sector to make the necessary investments for development and deployment of the technologies needed for the energy and transport system transition, a set of smart policies needs to be implemented.

First of all, the cost of carbon in different sectors needs to be aligned in order to stimulate efficient emission-mitigation behaviour. Thus, all forms of transport should be included in the European Union emissions trading system (ETS). A corresponding additional carbon component in the fuel price would ensure that consumers' daily modal choice decisions take the carbon cost into account and thus prevent lower fuel consumption incentivising increased vehicle use. Second, policymakers need to convince companies that carbon will continue to be sensibly priced beyond 2020. Thus, policy should financially commit their future budgets vis-à-vis companies that invest in low-carbon technologies to preserve the operability of the EU ETS beyond 2020. This could, for example, be achieved by letting public banks issue options on the carbon price. Significant exposure of public banks to the carbon price could serve as a tool to commit future policymakers to ensuring the reliability of the system over decades. Third, tightening average emission standards for certain appliances is an effective second-best solution for incentivising the provision of low-carbon appliances in the absence of a global and long-term carbon price.

To provide the refuelling stations for new fuels that existing markets will not deliver, we suggest the establishment of temporary infrastructure consortia for the different low-carbon fuels. Each consortium would plan and organise the deployment of its respective fuelling station infrastructure. For this purpose, each consortium would be given the exclusive right to sell local concessions for new fuel stations to interested retailers. Consequently, competition between different low-carbon fuels and different retailers would be ensured. Finally, each consortium might organise internal cross-subsidisation between different parts of the value chain (for example, fuel and vehicle producers might support infrastructure) and between different fuel stations (for example, fuel outlets in remote areas might obtain support from fuel outlets in densely populated areas), if it finds that this encourages quicker roll-out of their technology. To avoid abuse, all relevant stakeholders should participate in the consortia and their constitution should be cleared *ex ante* by competition authorities.

Furthermore, the public and private sectors should explore new ways of sharing risk. Governments might participate in the up-side of successful technologies by making grants reimbursable in successful cases. Meanwhile public financing or guarantees dedicated to business units with a high concentration of regulatory risks might incentivise investment for two reasons. First, the corresponding company would be less exposed to regulatory uncertainty and might find it easier to acquire private finance for its low-carbon projects. Second, public exposure to regulatory risk signals commitment to existing policies and reduces regulatory uncertainty in the private sector as a whole.

One major improvement to current deployment policies would be to use public procurement strategically for experimenting with alternative technologies. We suggest that publicly financed trials (for example, for municipal vehicle fleets) should be allowed to fail commercially in order to avoid the focus on low-risk technologies. For this purpose, compensation for failed trials should be offered at a federal level, provided that the individual trial is part of a coordinated experimental scheme.

Finally, the most important step for supporting new technologies is a transparent and predictable support policy for all competing technologies. A consistent policy should primarily comprise a set of horizontal policies to resolve existing market failures (eg carbon pricing). But in the absence of horizontal first-best solutions for some market failures, the public sector should return to technology-specific support instruments for R&D and deployment. In this context, technology choice is critical. In the presence of multiple new technologies that compete not only for a market but also for production inputs (such as capital, labour and raw materials), excessive support to one technology might slow down the development of others. Consequently, a well-thought-through and structured approach adapted to the complexity of the challenge is needed. For this purpose, government should adopt a choice mechanism that is dynamic and adaptable, able to digest new information and optimise support in a quick, reliable, and effective manner. Predictability and technology-neutrality can only be ensured when technology choice is based on metrics and priorities defined by politics. Stakeholders need to be incentivised to provide unbiased forecasts of the capabilities of their technology. These forecasts should be processed in an open multi-technology model to provide guidance for the targeting of support. A corresponding model should be built, maintained, extended and published by an independent public institution. This transparent mechanism would ensure that stakeholders can predict public technology decisions, and would thus find it easier to commit to the long-term and risky investments that are needed to make the low-carbon energy and transport system transition a reality.

1 Rationale for supporting the transition to a new energy and transport system

1.1 Benefits of a new energy and transport system

The current energy and transport system is unsustainable. In 2009, emissions of greenhouse gases (GHG) from the 27 EU countries in the road transport and energy sectors amounted to 4.8 tonnes per capita. This is more than double the level typically considered sustainable (two tonnes per capita per year)[1]. Consequently, the EU has set a 60 percent reduction target for GHG emissions for the transport sector[2] and an 80-100 percent reduction target for the energy sector by 2050 compared to 1990 levels.

Currently, the transport and energy sectors are responsible for the majority of EU oil and gas imports. Approximately 75 percent of final energy consumption of oil is due to transport, and about 29 percent of final energy consumption of gas is due to the electricity sector (Eurostat, 2009a and 2009b). In 2009, the EU had to import 83.5 percent of consumed petroleum products, and 64.2 percent of consumed gas[3,4]. The EU considers reducing/containing this dependence to be an important factor in securing European energy supplies. As domestic sources of fossil fuels are limited, only a reduction in the total consumption of fossil fuels can reduce Europe's import dependency. Consequently, the major challenge facing the energy and transport

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[1] 4.8 tonnes is a result of a calculation using data on page 80 of EEA (2011). In 2009, GHG emissions per capita, for the EU27, was 9.2 tonnes. According to the pie charts, transport share of GHG emissions was 20.2 percent and energy supply share of GHG emissions was 32.4 percent, implying that approximately 4.8 tonnes per capita of GHG emissions are due to the transport and energy sector.

[2] COM (2011)144, available at http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:52011DC0144:EN:NOT

[3] Reducing the fuel consumption of a sector not only reduces import dependency but – in case it induces a significant reduction in fossil fuels consumption – lowers fossil fuel prices. This induces a shift in welfare from oil exporting to oil importing countries.

[4] The numbers refer to the Eurostat energy dependency figures.

system is the reduction of its fossil fuel consumption and carbon footprint.

With the current fuel mix[5], even the most ambitious improvements to incumbent technologies are likely to be insufficient for reaching the reduction targets set by the EU. For example, improvements to motor vehicle internal combustion engines and conventional power plants are limited by physical factors. Fuel consumption would converge to a technical minimum that is significantly above zero. Consequently, the deployment of new clean energy and transport technologies would be necessary to maintain the current service level at near zero emissions.

An additional motivation for carbon-free technologies is that they often offer significant side-benefits. For example, internal combustion engines are responsible for a significant portion of local pollutant[6] and noise emissions. For this reason, internal combustion engines are, in contrast to some of the proposed alternative technologies, also detrimental to public health. Thus, significant societal benefits, in terms of greenhouse gas mitigation, decreased fuel dependency, and reduced local emissions of pollutants and noise, can be expected as results of a transition towards a clean energy and transport sector.

Furthermore, various authors have argued that decarbonising the economy could induce growth (eg Huberty *et al*, 2011). Policy arguments for green growth span a wide range of economic, environmental and social concerns. A sampling of such arguments demonstrates their diversity:

1. **Keynesian demand stimulus** for short-term job creation via deficit-financed investment in energy efficiency and energy infrastructure: for example, Houser *et al* (2009, 2-5) finds that green stimulus in the US performed as well as or better than traditional stimulus, creating 20 percent more jobs than traditional infrastructure spending.

2. **Improved trade competitiveness** via reduced exposure to terms-of-trade pressures from fossil fuel imports, particularly petroleum and natural gas. Decreasing demand for fossil fuel imports reduces the world market price of fossil fuels. Thus, the terms-of-trade of energy importers improve, ie EU countries will have to export less in order to pay for foreign fuels. Thus, domestic consumption and consumer welfare can increase.

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[5] Many observers dismiss biofuels based on expected cost (Runge and Senauer, 2007; Ryan *et al*, 2006; Delgado and Santos, 2008)

[6] Eg Oxides of nitrogen (NO_X), volatile organic compounds (VOC), ozone, particles and Sulphur Oxides (SO_X).

3. **Increased innovation** in response to greater administrative constraints (also known as the 'Porter Hypothesis'): Porter and van der Linde (1995) argue that stringent regulation pays for itself by inducing private sector innovation. Additionally, WEF-BCG (2011) argues that companies that comply with stricter standards do better economically[7].

4. Publicly supported deployment creates markets for new technologies that might have a **higher than proportionate local value content**. Thus, new jobs might emerge (Wei *et al*, 2010).

5. Revenues from a 'polluter pays' scheme – such as emission allowance auction receipts or green taxes might be used to reduce distorting taxes on labour and capital. Under certain conditions a **'double dividend'** in terms of higher growth may arise (see Goulder, 1995).

6. Redirecting innovation and investments at an early stage to the **growing sector of clean technologies** might help some countries retain or even strengthen their international competitiveness, thereby boosting their economies and creating jobs. For example, Huberty and Zachmann (2011) argue that state-supported deployment can partly explain the success of the wind industry in Denmark and Germany.

Thus, the transition to a new energy and transport system promises significant societal benefits. As the next section demonstrates, a number of market failures impede such a transition. Thus, without public intervention the transition will only happen slowly or may completely fail to take place.

1.2 Market failures that impede an optimal transition

The current energy system, in its complexity, has developed over centuries. Though it suffers from an extreme degree of inertia, the energy system has undergone a series of transformations over time: from wood to coal, coal to oil, and to electrification. In each of these cases, the new energy source proved cheaper or more versatile than the one it supplanted or complemented. However, inertia in the energy system, due to path dependencies and market failures, such as network externalities, led to very slow transitions. Despite the notable advantages of each successive fuel, transitions took time: perhaps 200 years for coal and 75 for both oil and electricity. Inertia in previous transitions has been due to extant market failures.

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[7] However, some economists have argued that these findings are due to the so called 'environmental Kuznets curve', which postulates that, after a certain threshold, pollution intensity decreases with increasing economic activity.

Therefore, rapid diffusion of new technologies requires them to have either serious advantages over incumbent technologies or minimal downstream changes to work. Presently, ‘green’ energy and transport technologies meet neither of these criteria: they generate more expensive but, at best, indistinguishable services compared to the technologies they replace, and they require substantial downstream changes to the incumbent energy or transport system in order to accommodate different primary inputs and different operating characteristics. Thus, the inertia witnessed in prior transformations may provide only a conservative estimate for the scale of the green energy and transport transition challenge. The deployment of new energy and transport technologies will be hampered by their higher cost and technical shortcomings (eg range for battery cars, temperature sensitivity for fuel cell cars, volatility of the electricity produced by wind turbines). Markets alone will not encourage the development and deployment of uncompetitive technologies, even if they are necessary for a low-carbon future. In order to encourage the development of these technologies, it is important to monetise the societal benefits they provide by putting prices on greenhouse-gases, pollution, noise, and import dependency. But even after monetising the societal benefits, there are extant market failures which may hinder the development of new energy technologies or the transition to low-carbon fuels and technologies.

In this section, we will discuss market imperfections responsible for underinvestment in new energy and transport technologies, and how they have been dealt with in other cases.

1.2.1 Climate externality

Cumulative greenhouse-gas emissions cause global warming, implying potentially huge economic costs to society[8]. Thus, each source of greenhouse-gas emissions has a societal cost (a so called ‘negative externality’). To introduce the correct incentives for greenhouse-gas mitigation, various schemes have been proposed. The spectrum ranges from administrative measures, such as the prohibition of certain polluting technologies or emission restrictions, to the implementation of a ‘polluter pays’ principle via carbon taxes or tradable emission allowances.

Ideally, the introduction of a long-term carbon price reflecting the true cost of emissions, via taxes or tradable allowances, would be the first-best solution for reducing emissions at the lowest cost. It would ensure that emissions are reduced in

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[8] Stern (2006).

those sectors where abatement is most easily achieved. However, the first-best is not possible because (1) The optimal level of emission abatement – ie the level at which the cost of an additional abatement effort exceeds the benefit of the induced climate change mitigation – is unknown; (2) in the absence of an international agreement, a local carbon price has only a limited effect on overall abatement. The reason is that greenhouse-gas-emitting companies or sectors might move to countries without a carbon price (carbon leakage) or that, due to reduced demand for fossil fuels in the countries with a strict carbon price, fuel prices will decrease and result in higher fuel demand elsewhere (indirect leakage); (3) finally, there are numerous political constraints. Transport and energy costs are important factors for regional competitiveness, so policymakers are very cautious in implementing legislation which directly implies raising costs.

Unstable and inadequate carbon prices have developed in the EU. Other countries (eg Australia, China) are also considering implementing incomplete carbon trading schemes. In the presence of only a local and short-term carbon price, there would be under-investment in new energy and transport technologies. Companies face smaller than optimal current and future markets for clean technology, and, as a result, do not invest in technologies that might incur a high cost per ton of carbon abated in a small market in the short term. However, learning and economies-of-scale savings may result in a much lower long-term carbon abatement cost. The main benefit of limited deployment of the new technologies is not so much the direct reduction in greenhouse gases, pollution, noise, and fuel imports; rather it is the induced cost savings due to learning-by-doing, learning-about-costs, and learning-through-R&D. This learning makes later and larger deployments cheaper and thus reduces the cost of achieving benefits at a large scale. Furthermore, cost reductions resulting from learning might make the technologies competitive even in environments with less ambitious carbon mitigation policies (eg developing and emerging countries). Therefore, in the absence of a long-term global carbon price, it is sensible to provide incentives for R&D and deployment of these technologies, so as to approach the socially optimal investment level. In the EU, for example, significant support for renewable energy technologies and energy efficiency is partly justified as compensating the imperfections of the carbon market.

The flipside of having multiple instruments to incentivise emission reductions is that it inevitably leads to different prices for carbon in different sectors. According to Fankhauser *et al* (2010), combining taxes, subsidies, or standards with cap-and-trade instruments can undermine the carbon price and increase mitigation costs. That is, the absence of a single carbon price signal to coordinate abatement decisions in all sectors is causing economic inefficiencies. Consequently, there is over-abatement in some sectors (replacing classic lightbulbs in some applications implies huge cost per ton of carbon abated) and under-abatement in most other sectors (most new-builds of coal fired power plants would not happen at a sufficiently high and stable carbon price).

Conclusion: Climate change is a pressing issue which poses huge negative externalities. There is currently no effective policy tool for internalising the long-term international costs of climate change.

Recommendation: Policy should continue to strive for a global long-term carbon price. Moreover, policy should complement existing instruments with incentives for early investment into R&D, demonstration and deployment of clean technologies. Clean technologies are essential to achieving timely carbon mitigation.

1.2.2 Innovation externality

Innovation, especially as it pertains to specialised technologies, comes at a cost – the cost of R&D. Although acquired knowledge may offset the cost of innovation for the investing firm, this knowledge may be non-rival and non-excludable. This means that other firms may acquire the ability to imitate these innovations and lower their own production costs, without having incurred the cost of R&D. Additionally, even if they do not have the ability to imitate the specific innovation, they may gain some beneficial knowledge spillovers from the innovator. Therefore, R&D investments confer a positive externality to outside firms. This results in a situation where individual firms under-invest in R&D because they do not fully internalise the social benefits of R&D investments or because they anticipate costless benefits to be gained from the investments of others.

This effect is present in all sectors. In order to facilitate the internalisation of this externality, several policy instruments are available: protecting intellectual property rights (eg through patents or trade secrets), government funding for R&D and subsidies for private R&D.

Patents are a tool for removing the non-excludable aspect of innovations. Making innovations excludable would prevent firms that did not participate in R&D from reaping the benefits of the resulting technology at zero cost. In addition, excludability has the added benefit of reducing incentives to secrecy over technological knowledge which may benefit society. However, patents are an imperfect tool. A strong patent system increases incentives to innovate but decreases competition. As per Schumpeter's theory of creative destruction, market power is a driving force of innovation as innovation is a mechanism for destroying the market share of competitors. Therefore, in practice, patents are characterised by two dimensions: lifespan, and breadth. These two dimensions influence the degree of effectiveness of patents in encouraging innovation. In addition, enforcement effectiveness and enforcement speed are issues which affect the impact of patents on innovation. Therefore, patent effectiveness also relies on effective institutions, and trust in the institutions of individual countries. The energy and transport system transition is an international effort and will rely on institutional strength in multiple countries. Thus, strong international patent protection might increase the number of green innovations. However, strong international patent protection also allows innovators to demand higher prices for their more exclusive rights. This might decrease the rate of market uptake. Another weakness of patents in internalising the innovation externality is that they often cannot be applied to process knowledge (eg Ford's assembly line), which in many cases can only be protected via secrecy. Thus, patents alone cannot ensure an optimal level of innovation activity.

Another avenue of internalisation has to do with relieving the imbalance between costs to innovators and the social benefits of the innovations. This can be done via government-funded R&D or via government subsidies for private R&D. As the positive spillovers from energy and transportation technology innovations are essentially a public good, it may make sense for governments to contribute to the cost of producing them. Implementation is, however, key, as public R&D money risks simply replacing private R&D money without increasing the overall innovation level[9]. Governments may sponsor R&D wholly or via public-private partnerships. In such partnerships, it is often the case that intellectual property resulting from collaboration is shared via patents or contractual stipulations.

Consortiums of members from government, industry, and academia may provide a way to direct R&D toward industry-applicable solutions. Consortiums, although they produce more general intellectual property, may be an important avenue for coordinating efforts and may partially internalise the non-excludable nature of innovation. Furthermore, academic research which is wholly publically funded runs the risk of not being adopted or adoptable by industry. Consortiums are a way to share intellectual property rights and the costs of producing intellectual property (see Box 1). However, the R&D collaboration between competitors in the product market risks entailing anti-competitive effects[10].

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9. David *et al* (2000) argue that the literature on whether public R&D is a complement or substitute for private R&D has been inconclusive.
10. See for example Goeree and Helland (2009).

BOX 1: R&D CONSORTIA

The VLSI (Very Large Scale Integrated circuit) project was designed to help Japan catch up with semiconductor technology. The project was conducted between 1975 and 1985 with a budget of €1.25 billion, of which 22 percent was financed by the government. It developed state-of-the-art semiconductor manufacturing technology. All the major Japanese semiconductor producers participated in this project, and Japanese semiconductor companies gained world leadership in this period. Beyond this anecdotal evidence, it was found that consortia have the effect of stimulating innovative activity in the selected firms. However, this comes at a cost. Among other components, these costs include the effects of reduced competition, administrative burdens on the research personnel of participating firms, and cost of government subsidies.

Take-home message: R&D cooperation between competing companies might stimulate innovation but can have high long-term cost.

Source: Sakakibara (1997).

Conclusion: Innovation carries with it a positive externality. Without proper policies to protect intellectual property or alleviate the private costs of innovative activities, there may be underinvestment in R&D.

Recommendation: Government policy should augment investment in R&D for areas where intellectual property protection is not enough. Consortiums may be useful in encouraging industry-oriented innovation and may alleviate some of the issues created by non-excludability.

1.2.3 Path dependencies

The transition from one energy system to another may be subject to path-dependence on, or lock-in effects from, existing systems. Path-dependence or lock-in, in the market failure sense, is the inability of the market to switch technologies despite the knowledge that the incumbent technology[11] is inferior or undesirable relative to an alternative (Liebowitz and Margolis, 1995). This is often due to the switching costs being higher than the benefit for some pivotal actors in the system.

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[11] Path-dependence based on insufficient knowledge at the beginning is not *ex-ante* inefficient but can be *ex-post* inefficient.

The market failure can occur for a number of reasons: lock-in due to uncertain payoff functions; lock-in due to learning-by-doing; institutional lock-in; and lock-in due to network effects.

Lock-in due to uncertain payoff functions

Often, when a new technology is introduced, its future payoffs are uncertain, ie even the distribution of payoffs is unknown. Cowan (1991) develops a model of lock-in referring to technologies of unknown merit as 'tortoises and hares'. He demonstrates that the reduction of uncertainty stemming from the adoption process may lead to lock-in. One illustrative example of lock-in due to learning-about-payoffs is the example of the two-armed bandit slot machine. Each arm of the slot machine has a different distribution of payoffs. However, over time, the player may converge on one arm if it is used more. As the player learns more about the payoff distribution of one arm (the one which is used more), he refrains from investing money to obtain knowledge on the payoff distribution of the other arm. Similarly, this analogy can be applied to technologies of unknown merit. Costly learning about *a priori* uncertain payoff functions can create a lock-in effect.

Lock-in due to learning-by-doing

Learning-by-doing can lead to technology lock-in. A more frequently-used technology tends to move along its learning curve faster, and may thus cause a cost-related snowball effect where adopters continue along the path even with the knowledge that the technology is inferior or undesirable. Thus, an inferior but more-developed technology may become locked-in. This lock-in is exacerbated over time. Acemoglu *et al* (2009) show that even research tends to 'build on the shoulders of giants', the giants being incumbent technologies.

Institutional lock-in

A potentially less obvious form of lock-in is institutional and policy lock-in. The automotive industry is an example of an industry for which institutional lock-in exists. Both formal and informal private institutions have developed alongside the internal combustion engine technological system. Knowledge-based institutions, such as technical schools, developed to train labour for servicing a growing auto network. Higher-learning disciplinary departments like highway or automobile engineering are intrinsically linked with the automobile industry. Industry approaches may become locked-in as a 'curriculum' for long periods. In addition, unions, industry associations, and media (eg *Motor World*, *Motor Age*) have emerged. The existence of specialised labour for this technology creates a sort of lock-in.

Public institutional lock-in may also occur. Subsidies or government institutions can have long-term impacts and persist for long periods of time. Williamson (1998) found that formal institutions change over decades while informal institutions, such as culture or norms, change over centuries. In the case of the automobile industry, a large network of institutions, including the American Automobile Association, the American Road Builders Association, and National Automobile Chamber of Commerce, formed alongside the technology; the 'highway lobby' is still seen as one of the most powerful interest groups (Unruh, 2000). The existence of government institutions specific to a technology might lead to policy biases as the obsolescence of a technology would mean the obsolescence of that institution. Public support of certain standards or technologies may exacerbate lock-in. This was the case for light-water nuclear reactor adoption (see Box 2 for details). The policies adopted by the US were biased toward one technology (Walker, 2000), and this also contributed to the choice of that technology in Europe, due to US aid (Cowan, 1990). Another example is the case of German coal subsidies which have persisted long after German coal became much more expensive than imported coal. Path dependencies exist due to the skill-set of the workforce in the Ruhr Valley of Germany, coupled with existing subsidies.

In general, institutional lock-in has the potential to create non-market forces that enhance technological lock-in. Institutional policy can override the neo-classical market forces of competition by removing uncertainty about the direction of technological development. Firms might then favour a certain technology not in response to market forces but to institutional ones. Care should be taken to develop policies and institutions which are not prone to lock-in and which are flexible to changing environments – ie not technology-specific. The fact that technology lock-in occurs naturally due to imperfect information and learning curves provides a case for government intervention. In the initial stages of a technology, when its merit is as yet unknown, government support should not be biased toward support for a single technology. Switching support at a later time is less effective and more costly due to learning costs (if no investment or learning was done in the interim), and potential network effects from the adopted technology. Thus, prior to the creation of subsidies and other institutions, governments should carefully consider their necessity and determine the ease of shifting from the respective subsidies and institutions in the future. This premeditation on the part of government would help in avoiding institutional lock-in.

BOX 2: NUCLEAR REACTORS

The widespread adoption of light-water reactors for nuclear power generation may be seen as a case of technological lock-in. Initially, there were three competing reactor technologies: light water, heavy water and gas graphite. Light water has captured most of the market, despite doubts about its technological superiority. For example, occupational radiation is 10 times lower for gas graphite reactors. Heavy-water reactors in Canada have been estimated to generate power at about 75 percent of the cost of light-water reactors of the same size (Cowan 1990). However, by 1975, there were only two distinct reactor types in the marketplace, and the majority of reactors planned or built were light water. The United States had originally developed light-water reactors for military uses and thus was much-advanced along that learning curve, compared to the other reactor types, when demand for civilian nuclear power emerged. Although countries such as Britain and France were developing their own gas graphite technologies, European countries, via the Euratom High Commission, signed an accord with the US. US support for light-water reactors was likely strengthened by the new orders from Europe, and the US provided financial aid and technical assistant to Europe. The US-Euratom accord even affected fuel prices, as prices for enriched uranium were subsidised. Graphite reactors did not need enriched uranium, but this advantage was dampened by the lowered prices of enriched uranium. Although there was debate throughout the 1970s, development of nuclear technologies was expensive and both gas graphite and heavy water presented technical problems. The UK eventually adopted light water as it had been thoroughly developed outside the UK.

Take-home message: Government support might tip the balance towards one technology. This might speed up the selection process but it may not be efficient in the long-term, especially when the merit of technologies is unclear at the beginning and government choice is driven by secondary objectives.

Source: Cowan (1990).

Lock-in due to network effects

Network effects are present when switching between products is costly and the value of a product increases with the number of users of the product (eg telephones) or the presence of complementary products (eg software for a specific hardware). In energy and transport systems, we are faced with the second type of network effect. Complex value chains focused on the incumbent technology (in transport: car manufacturers, fuel producers, fuel distribution, and consumers) create a classical lock-in effect. This problem is exacerbated when switching costs are high. Switching costs are a function of: the investment cost of the components, the minimum (efficient) network size, and the level of uncertainty about the new system. Thus, highly capital-intensive systems, with significant scale economies and a large number of alternatives will be the most difficult to replace. Consequently, bringing a new technology to market in such a system requires that it is either largely compatible with the incumbent system (eg through hybridisation or the use of adaptors), to benefit from incumbent network effects, or that it manages to effectively deploy its own system.

Conclusion: When governments, firms and consumers must choose between technologies of unknown merit, technological and institutional lock-in may occur where path dependency on a suboptimal technology develops. This can become even more pronounced when network effects are also at play.

Recommendation: Technology-neutrality in public support at the early stages, when the winners are unclear, is important. Support may be needed to overcome path dependency on established networks.

1.2.4 Coordination externality

Any transition from one system to another requires coordination among the stakeholders. As the energy and transport sector is very capital-intensive, lack of coordination during the transition is very costly. Standardisation is a primary coordination mechanism. According to Swann (2010), there are four different purposes for standardisation: compatibility/interface standards and variety reduction standards are utilised to reduce the fragmentation of a network, and to provide compatibility requirements in order to allow entry into the market. Minimum quality standards are important in ensuring a level of safety for consumers. Information standards are used to homogenise information in order to lower information costs (eg for comparing products).

Thus, standardisation is critical for the development of complex markets. However, standardisation itself is costly, and the incentives to sponsor standardisation do not naturally lead to a welfare-optimal set of standards.

Firms involved in standardisation (typically the first-movers in a market) will have heterogeneous preferences. On the one hand, each firm would prefer a set of standards that increases the value of the capabilities, patents and business model of said firm.

On the other hand, all companies want to avoid a situation in which the adopted standard locks them out of the market. Due to the high number of stakeholders involved, and the complexity of the technical questions, complicated negotiations between stakeholders may emerge. These might take years and consume valuable resources and time. Consequently, first-movers who participate in the coordination of standards impose a positive externality on late-comers by absorbing the costs of standardisation. Late-comers can free-ride on the coordination efforts without paying the price for it.

Due to this market failure, if left to their own devices, first-movers may prefer to form fragmented networks/markets to avoid laborious and costly coordination (see Box 3 for a case-study on a failed standardisation effort). Alternatively, in the absence of other stakeholders in the coordination process, a minority of engaged companies may push through a standard that is clearly not in the best interest of society. Consequently, public intervention might prove valuable for resolving this market failure. Public intervention in standardisation should take place when there is a weak, or no, coordination mechanism between competing companies in a market. Governments may intervene through administering the standardisation process, and/or through financial subsidies to overcome coordination problems at the R&D stage, and/or to mitigate the deployment barriers imposed by market competition. Public-private partnerships are another avenue for facilitating coordination.

It is worth noting that government interests may not necessarily be in line with the short-term interests of companies active in the standardisation process. The public sector puts greater importance on customer interests and on the long-term health of standards infrastructure. Standards-setting can have different effects on innovation and R&D investments depending upon the implementation and strictness of standards (see Box 4 for the pharmaceutical industry case study).

BOX 3: JAPAN AND THE CELLULAR GALAPAGOS

Japanese cellular phone companies have long been leaders in delivering advanced handset technologies and services to their consumers. The first cellular data services were available in Japan in 1997 at extraordinarily low rates. Cellular phones are widely used in Japan as substitutes for financial instruments like debit and credit cards. Yet despite technical leadership that is often years ahead of foreign competitors, Japanese firms have had almost no success selling into foreign cellular device and service markets.

As Kushida (2011) explains, the Japanese inability to capitalise on leadership in network technologies stems from both public and private decisions. Domestically, device and service companies were vertically integrated, allowing them to resolve the tension between network and product introduction by internalising the design and deployment of both. This led to very early, highly competitive markets in cellular data services, perhaps five years before similar markets emerged in the US and Europe. But in practice, competition in an isolated market meant that Japanese products and network standards diverged from international norms in order to deliver ever-more-exotic products to customers.

As a result, when Japanese firms then attempted to take their advanced technologies abroad, they found they were incompatible with the networks those markets depended on. It mattered little that Japanese technology was years ahead of the competition. Japan’s failure to keep international standards and domestic markets in sync locked it out of capturing export benefits from its domestic technical leadership. Like Darwin’s finches, Japanese cellular firms were highly adapted to their isolated market, but bizarre and strange creatures elsewhere.

Take-home message: International coordination and the development of international standards is key. Government policies and firms should pay attention to the developments of other nations and coordinate/adapt to changing international standards so as to be competitive on the global market. Technological sophistication is not enough to ensure the success of a technology.

Source: Kushida (2011).

BOX 4: STANDARDISATION IN THE PHARMACEUTICAL INDUSTRY: A BARRIER OR INCENTIVE FOR R&D?

Excessively strict standards may stifle innovation as they may affect the profitability of certain products. In the case of the pharmaceutical industry, investments in product development are not made on the basis of potential benefits to society, but on the basis of maximal future returns. Therefore, if standards are overly strict, companies may decide not to develop or produce medicines effective in treating life-threatening diseases but which do not meet profitability criteria. Excessive regulatory burden can result in a decrease or cancellation of R&D for certain drugs.

In the past 20 years, several countries and regions (Australia, the EU, Japan and the US), have adopted orphan drug legislation (ODL). Incentives included fast-track procedures for standardisation and reduced registration fees. This legislation has been successful in the promotion of the development of drugs for rare diseases or diseases which are prevalent in poorer countries.

Take-home message: Governments need to ensure in developing standards that their strictness does not make investment in products that are beneficial to society unprofitable.

Source: Reich *et al* (2009).

Public intervention may have different impacts on standards development. Positive effects are generated by the facilitation of coordination activities and the establishment of special bodies for this purpose. Negative effects can emerge when preferences are given to certain technologies by officials, from a political or short-term perspective. Illustrations of a positive and a negative result are provided in Box 5.

BOX 5: EUROPEAN COMMISSION INTERVENTION IN STANDARDISATION IN TV AND TELECOMMUNICATION INDUSTRIES

Failure case: HDTV standard
In 1986, the Commission initiated the development of a high definition standard for TV set manufacturers and broadcasters (HD-MAC). This effort was in response to Japan's attempts to set up the world's first high-definition TV standard. To stimulate early deployment the Commission made the decision to favour a certain technology during the early stages of the process. Due to its high complexity the technology promised higher margins to TV manufacturers. But it was also more expensive for broadcasters and consumers. Consequently, the take-up of the new technology was limited. In 1992, the Commission tried to intervene again and offered financial subsidies for the broadcasting companies in exchange for agreeing with TV set producers to have standards for a new version of HD-MAC. However, it was too late for HD-MAC due to the advance of digital broadcasting technologies. Public support for TV standardisation has now been redirected towards wide screen TV standards corresponding to digital broadcasting.

Success case: GSM standard
In the 1970s, the Commission initiated the Global System of Mobile Telecommunications (GSM) project in order to narrow the gap between US/Japanese telecom companies and European ones. In contrast to the HDTV case the Commission refrained from using secondary legislation and concentrated its efforts on the negotiation of a memorandum of understanding (MoU) between all stakeholders. The MoU committed operators to open procurement to foreign manufacturers, and manufacturers to provide royalty free licenses and to have GSM operational by 1991. This allowed manufacturers to deliver the new generation of GSM infrastructure equipment in a timely way and at reasonable cost. As a result, deployment was rapid, and generated affordable margins throughout the value chain. This eventually tipped the entire European and global market towards the standard. Together with the next generation UMTS standard, the GSM family of standards eventually captured 89 percent of the international market, according to the Global Mobile Suppliers Association.

Take-home message: All stakeholders' opinions regarding the new technology standards have to be taken into account. For this purpose, public support should concentrate strictly on technical problems and avoid politically motivated preferences regarding the choice of standard. An MoU is considered a good tool for bringing all the conflicting interests together and finding a mutually beneficial framework of cooperation to reduce the barriers to investment inside the value chain.
Source: Meyer (2010).

Public authorities need to find the correct balance between socially important standards (eg safety) and promoting R&D in the sector. It may be reasonable not to set standards too strictly during pre-market development, in order to maintain enough stimuli for private investment in R&D.

Often, with weak or no coordination mechanisms in place, if left to its own devices, the market produces too little, too much, or standardisation of the wrong sort. However, public sector involvement is only helpful if properly implemented. Additionally, coordination amongst governments themselves is a key factor in the success of a standard.

Conclusion: Both domestic and international, and public and private cooperation are key to the success of an energy and transport transition. This coordination is costly and may create a positive externality discouraging firms from entering as first-movers. Fragmented networks and markets may arise.

Recommendation: Public intervention into standardisation should take place when there are weak, or no, coordination mechanisms between competing companies in a market. Public authorities should find the right balance when determining standards. Domestic standardisation should take the international standards environment into consideration. Financial subsidies to overcome coordination problems at the R&D stage, and to mitigate the deployment barriers imposed by market competition, are a popular form of intervention. Public-private partnerships are another avenue for facilitating coordination.

1.2.5 Infrastructure externality

A new low-carbon energy and transport system may require a large-scale infrastructure shift due to the use of alternative fuels. First-moving infrastructure providers face a disadvantage because they must pay a large fixed cost in order to establish infrastructure that is the precondition for the deployment of the appliances. Latecoming infrastructure providers may benefit from the established network without having paid the costs of building the network. As latecomers can install the latest technology and larger units they face lower service cost. This cost-advantage allows latecomers to cherry-pick the best locations once the network and market have been established. Consequently, competition from latecomers may decrease prices, and thereby decrease the profit of the first-movers. First-movers may potentially be unable to recover their initial investments. This externality could lead to underinvestment or no investment where competitive prices do not allow recovery of initial investments, and profitability, in the long-term. In the past, several mechanisms to internalise the infrastructure externality have proven successful:

The natural monopoly solution

A natural monopoly emerges when unit costs decrease with the number of clients[12]. In the case of a natural monopoly the presence of an early-mover locks out any latecomers. Water, gas, telephone, broadband and electricity distribution networks are natural monopolies. Consequently, the early-mover can recover any initial investment by raising prices when the network has been established. This stimulates rapid deployment but raises the issue of excessive prices. Consequently, mature natural monopolies are typically regulated[13]. Thus, the main issue for setting up a new network with natural monopoly characteristics is the uncertainty about its future regulation.

The state monopoly approach

Some network industries are not characterised by natural monopoly characteristics, due to the facility of competitive local provision (eg postal services, fueling stations). Governments often create public monopolies in order to ensure country-wide access to services and prevent 'cherry-picking' of the most profitable locations. Typically, governments have linked the provision of a state-monopoly to a certain (sometimes private) provider with a universal service obligation.

The artificial monopoly/oligopoly approach

For some network technologies, infrastructure is not a natural monopoly (eg mobile telecommunication, Facebook), ie multiple infrastructure providers can coexist and compete for network users. Here, some companies attempt to lock in customers by creating artificial barriers (locked SIM cards for mobile phones, non-exportable contacts in social networks) in order to be able to pay their fixed investments in network infrastructure[14]. Technologies that failed to lock in customers (eg email providers) quickly saw their profit margins drop to zero. Companies that can lock in

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[12] More precisely, when the long-run marginal cost is below the average cost of providing the service, no second company has an interest to enter the market.

[13] There is significant literature on the question of if and how to optimally regulate monopolies (eg Troesken, 1996)

[14] The first electricity companies started by leasing light-bulbs to consumers (Hughes, 1977). Thus, the entire value chain was in the hands of one company and it could set a price that covered fixed and variable cost. For the initial electrification of Manhattan, Edison essentially designed each of the components as part of an integrated system where the resistance of the bulb filament was picked to help modulate grid load based on the number of expected service subscribers.

customers by making interfaces incompatible have higher incentives to quickly roll-out of their networks. So they invest more. In welfare terms this positive effect is counteracted by the long-term negative effects from having a monopoly.

The consortium approach

Consortiums are another way to help ensure that the investments in network infrastructure can be recouped. If consortiums can lock out competitors the consortiums might internalise future benefits of creating a new infrastructure. This again might stimulate early deployment but may also have undesirable effects on competition.

The vertical integration approach

The existence of infrastructure is essential for appliance and service providers. Consequently, they might engage in setting up the infrastructure themselves. This is like selling camera bodies cheaply in order to be able to develop a market for lenses. This, of course, requires that competing service/appliance providers are locked out from the network (see artificial monopoly).

The cross-payment approach

A less-integrated approach would be for service/appliance providers to cross-subsidise other parts of the value chain in order to create the network. In Germany, for example, some natural gas distribution companies provide subsidies for natural gas cars in order to develop the market (see Box 12).

The public provision approach

Finally, governments might provide the infrastructure using public funds or regulated returns. To date much infrastructure (such as roads, railways and electricity transmission) is provided by government in most European countries. It has to be noted, however, that the initial technology choice in many of these cases (eg railways) was left to the market – with governments nationalising the infrastructure only after it appeared.

Conclusion: The huge fixed cost of infrastructure construction may not be fully recoverable in a competitive environment, due to newcomers entering and competing without having had to pay the initial fixed cost.

Recommendation: If infrastructure development costs are not recoverable in the long term by the first-movers, support instruments should be considered to encourage development of the necessary infrastructure.

1.2.6 Business exploration externality

In marketing, first-mover advantage is the advantage gained by the initial significant occupant of a market segment. It may be also referred to as technological leadership. This advantage may stem from the fact that the first entrant can gain control of resources or build a brand that later market entrants may not be able to match[15]. It is important to note that the first-mover advantage refers to the first significant company to move into a market, not necessarily the first company. In order for a company to try to become a first-mover, that company needs to work out if the overall rewards outweigh the initial underlying risks. Sometimes, first-movers are rewarded with huge profit margins and a monopoly-like status. Other times, the first-mover is not able to capitalise on its advantage, leaving opportunities for other firms to compete effectively and efficiently versus the earlier entrant. These companies then gain a 'second-mover advantage'[16].

First-movers face risk in both exploring technologies (see section 1.2.2 for further information regarding the innovation externality), and in developing a market. The first companies investing in a new technology face significant risk, as their business models are based on uncertain assumptions. If successful, implementation may quickly be imitated by competitors. Falling margins might make it impossible for a first-mover to recover its initial investment at a return which is commensurate with the risks taken. Followers clearly have some cost advantages of their own. They can, for example, learn from the mistakes and successes of their predecessors, reducing their own investment requirements as well as risks. In addition, followers can frequently adopt new and more efficient processes and technologies, whereas pioneers often remain entrenched in their original ways of doing things. Finally, followers will have lower marketing budgets for convincing the public that the (now familiar) technology works.

According to Boulding and Christen (2001), for instance, pioneers in consumer goods markets and industrial markets gained significant sales advantages, but incurred larger cost disadvantages. Pioneers in consumer goods had an return on investment that was 3.78 percentage points lower than later entrants. And the ROI of first-movers in

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[15] Grant (2003).

[16] Lieberman and Montgomery (1988).

the industrial goods sector was 4.24 percentage points lower than later entrants. Pioneers were less profitable than followers over the long run, controlling for all other factors which could account for performance differences[17].

In some of the standards races that have taken place, such as in personal computers, audio recording media and video cassette recorder formats, the winner was not necessarily the first-mover (Box 6).

The market failure is that the commercialisation of a technology reveals information. This is a valuable input for the decisions of policymakers, of industry and of consumers (see lock-in due to uncertainty in section 1.2.3). In a pure market solution, the risk of failure for a new technology is privatised, while the benefit is socialised to some degree, essentially leading to private underinvestment. Some strategies for companies to internalise these benefits (eg coordination amongst competitors, monopolising the new energy technology) raise competition concerns and might not be welfare-maximising in the long term.

Conclusion: The costs of exploring, and building, new markets is high and may not be fully recoverable given that new entrants may reduce profit margins. Due to the positive externality of business exploration, companies may be reluctant to be first-movers in certain sectors.

Recommendation: Policy should address the business exploration externality where necessary, providing incentives for the exploration and development of promising markets and technologies.

1.2.7 Insurance externality

Energy transitions are inherently subject to a high level of uncertainty. As they are national or global shifts in the way energy is produced and consumed, they are subject to exogenous economic, political, and even geological events. Energy transitions are often characterised by long time horizons from initial R&D investments to full deployment. Large investments are required throughout the process, and, due to the uncertain nature of energy transitions, these investments carry with them a high level of risk. Transitions are very difficult to model. Predictions about the duration and speed of transitions have seldom been accurate. For example, in terms of 2008 primary energy share, coal was still at 20 percent versus a 5 percent share predicted by

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[17] Boulding and Christen (2001).

BOX 6: VIDEO FORMAT WAR: VHS VS. BETAMAX, OR THE CASE OF CORRECT USE OF NETWORK EXTERNALITIES

The classical illustration of technological lock-in was the war of the video cassette recorder (VCR) formats which occurred in 1980s between two first-mover companies – Sony and JVC. Each company began by releasing two different formats: VHS and Betamax.

The cornerstone of VHS's success at the early-market stage was its recording time of two hours as compared with the one hour provided by Betamax. Sony believed that cassette size and transportability were paramount to the consumer, and sacrificed playing time in order to make smaller cassettes. Simultaneously, JVC concentrated its efforts on the availability of VCR machines by setting up rental chains such as Radio Rentals or DER. These rental chains offered an attractive choice for consumers who did not want to spend a lot of money on a system which might become obsolete. The flourishing video cassette rental business of the 1980s was reliant on the VHS format as a more suitable means of storing movies.

When the market matured, the wide availability of recorders and pre-recorded tapes in VHS format became a key factor in JVC's victory, allowing it to become an absolute market leader. Although Betamax initially owned 100 percent of the market, in 1975, the perceived value of longer recording times eventually tipped the balance in favour of VHS. Sony, as the first producer to offer their technology, thought it would be able to establish Betamax as the leading format. This kind of lock-in failed for Sony, but succeeded for JVC. For thirty years, JVC dominated the home market with their VHS, Super VHS and VHS-Compact formats, and collected billions in royalty payments.

Take-home messages:

- First-movers do not necessarily prevail.
- Consumer preferences may tip the scale in a competition between similar technologies. Attention should be paid to accurate evaluation of what aspects of the technology are most important to consumers.
- Investment in downstream (retail) suppliers may help resolve the chicken-and-egg problem.

Sources: Besen and Farrell (1994), Leibowitz and Margolis (1995).

Marchetti in 1970, and the 23 percent share of natural gas was far below the 60 percent predicted (Smil 2010). Predictions even over the course of 40 years are not reliable even though time horizons for energy transitions are very long[18].

Despite the uncertainty of success for individual energy transitions, it is apparent that we are currently at the brink of a new era in energy. A drastic change in the way we produce and consume energy must occur in order to avert a global environmental crisis. The Stern Review (2006) estimates the cost of inaction (with respect to climate change) to be equivalent to losing at least 5 percent of global GDP per annum now and forever, possibly rising to 20 percent if including other risks and impacts[19].

It is difficult to know, at the current stage, the cost-effectiveness or feasibility of different green technologies. Early perceptions of nuclear as 'too cheap to meter' have been incorrect; nuclear is much more expensive than predicted (Cohn, 1997). Similarly, the costs of new technologies may change due to materials availability (eg lithium for batteries, platinum for fuel cell membranes) technological constraints (nuclear fusion) or changing public acceptability (carbon sequestration, nuclear, shale gas). Attempts to predict affordability have sometimes included the use of learning curves – savings in cost due to learning-by-doing and R&D. R&D investments create steeper learning curves (higher cost savings) but their actual impact is difficult to measure due to the lack of availability of private data. Learning curves may be a way to predict future costs but are an imperfect tool as much depends on external factors unrelated to learning. In addition, technologies may have differently-sloped curves and thus some technologies which appear currently expensive may be cheaper in the long run, whereas some immediately viable technologies may have learning curves that level out and will thus remain expensive.

An energy transition for mitigating GHG emissions will require decisions on both public and private investment. High levels of uncertainty, coupled with positive network externalities, may lead individual firms to converge on a technology or energy system that proves suboptimal *ex post*. Rational agents may behave optimally by copying the behaviour of others in order to reduce risk, as opposed to acting solely on the basis of their own information, due to an information cascade effect. This is called herding

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18. Energy transitions are dynamic in nature, and often subject to unforeseeable/unpredictable events (eg the German reaction to the Fukushima accident).
19. This has been a widely debated report, for example, Nordhaus' response (Nordhaus, 2007) strongly questions the discounting method used in the review. However, there is growing concern about the environmental impacts of GHG emissions, as evidenced by the Kyoto Protocol and the EU 2050 goals, and that there will be a huge cost incurred by inaction.

behaviour and can occur when there is uncertainty and imperfect information (Bikhchandani *et al*, 1992). Herding to a single technology might make it very costly for society if this technology proves to be an inefficient or insufficient solution to meet emissions targets[20]. Thus, public intervention to discourage herding and to nurture alternative technologies, as an insurance against the risky nature of any energy transition, might increase expected welfare.

Energy security literature asserts that portfolio diversification is important in the maintenance of current energy security and fuel mix portfolios for individual companies (Roques *et al*, 2008; Lesbirel, 2004). The heavy reliance of some countries on a single technology (eg France on nuclear, Ukraine on gas) poses energy security risks. Investments in new energies and future energy systems should similarly adopt a portfolio approach. Investment in a backstop technology may prove to provide a huge positive insurance externality in the case that the chosen primary technology fails. The benefits of this externality would not be automatically internalised. This is an opportunity for the development of policy instruments to encourage investment in backstop technologies. Although it is expensive to invest in the development of new technologies as an insurance policy, the potential cost savings, in the event that a backstop technology is needed, are huge and there is risk of substantial cost in not doing so.

Conclusion: Diversified investment in alternative technologies may provide an insurance against failure of primary technologies in meeting the energy and climate challenge.

Recommendation: Governments should adopt a long-term perspective in technology investments and diversify support over technology portfolios, possibly including investments in backstop technologies.

1.2.8 Industrial policy externality

From cost to benefit: can new energy and transport technology policy generate jobs and growth?

Inventing, building and deploying the infrastructure and capital required for a new low-emission energy and transport system presents a range of opportunities to generate employment, renew firm competitiveness in existing sectors, and foster firm

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[20] See section 1.2.3 for further information regarding possible path dependency and lock-in.

competitiveness in new sectors. These opportunities have not escaped the notice of national and regional governments. But most climate policy has emphasised minimising the costs of transition to a low-emissions transport system. States hoping to capitalise on that transition to generate employment and technological leadership face a very different set of challenges.

Modern energy and transport systems provide an array of sophisticated services to industrial economies. At present, it doesn't appear that a low-emissions transport system would make substantial improvements to these services. Rather, it seeks to continue to provide the same services without generating the damaging by-products. Thus the introduction of a new transport system does not offer to radically transform an array of economic domains in the way that the introduction of the railways or the private car did. This reality restricts the potential economic benefits that states may capture during the transition process itself.

As Huberty *et al* (2011) have shown, these benefits come down to essentially three domains:

1. Creation of domestic jobs to build and operate the new energy and transport infrastructure;

2. Creation of domestic jobs to manufacture the capital equipment required to replace the old fossil fuel-based capital stock;

3. Creation of globally-competitive firms in 'green' export markets through domestic investments in research, development and deployment of new goods.

This section discusses each of these in brief. All three of these potential benefits from the adoption of low-emissions transport networks pose novel challenges for transport policy. In particular, translating domestic market growth into command of global export markets traps policymakers between two dilemmas of network selection. Domestically, the choice of the optimum network may require a lengthy process of experimentation to guard against the risks of network lock-in discussed above. But abroad, command of export markets requires that states position their industries to sell into global network standards. Balancing the optimum choice of networks at home with influence on global standards and access to export markets abroad becomes the primary challenge for industrial policy. But, as we shall argue, this challenge differs by state size and existing industrial capacity, further complicating the dilemma posed by green industrial policy for the state and firms alike.

Job creation at home: limits to duration and size

Transport and energy systems in advanced industrial economies are largely already built, and demand for new capacity grows slowly. In that context, domestic jobs from the creation of a low-emissions energy system can come in two forms. In the initial phase, the replacement of significant network infrastructure can create jobs in sectors such as construction and services. Since these jobs are in non-traded sectors, they will almost certainly appear. However, they are necessarily time-limited. With the completion of infrastructure replacement, we should expect the labour demands from the energy and transport sector to return to the pre-replacement equilibrium. Furthermore, these jobs will arrive regardless of the particular kind of technology eventually chosen for the replacement. Because they are not exposed to international competition, jobs in these sectors pose relatively few challenges to the state beyond the general problem of inducing and managing the energy and transportation systems transition.

States may also wish to keep some or all of the jobs associated with capital goods manufacture for infrastructure and appliance replacement at home. This poses far greater challenges to industrial policy. Creating high-productivity manufacturing jobs in new energy and transport technologies is only justified by substantial demand for these products. Small states lack the economies of scale required to justify investment in large segments of the value chain – they simply lack the volume of demand required to pay those investments back. Likewise, states poorly positioned in the core technologies and industrial capabilities required to build either the components of a low-emissions energy and transport system, or act as systems integrators for things like low-emissions automobiles, face very significant start-up costs at the sector level, apart from the costs to invent, pilot and deploy low-emissions technologies.

The opportunities for job creation based on domestic markets alone are thus limited in both time and space. Most economies will capture jobs in non-traded sectors like construction as they replace the infrastructure of today’s fossil fuel energy and transport system with low-emissions substitutes. But capturing high-productivity, high-technology manufacturing jobs to supply the capital goods required will require that states make careful choices about the scope and position of their investments in the value chain that will supply those goods.

Capturing export markets abroad: learning-by-doing, international standards, and the risks of network mismatch

The limits to domestic markets in all but the largest economies have encouraged states to look to export markets as sources of 'green growth'. If national economies can translate domestic expertise in new low-emissions energy and transport technology into international competitiveness, export-led market growth can create a range of domestic benefits through access to markets much larger than domestic demand alone.

The history of export-led market growth provides some evidence that national policy can generate significant returns. As Box 7 shows, the experience with 'green' goods such as wind turbines has shown that aggressive domestic market expansion in low-emissions goods can generate significant 'learning-by-doing' benefits for domestic firms. In many industries, the only way to become truly skilled at designing, building and deploying new technological systems is to actually design, build and deploy them. Promoting the domestic growth of low-emissions fleets of technologies such as hydrogen fuel cell electric vehicles may generate substantial opportunities for domestic firms to gain valuable knowledge about how new technologies perform under real-world conditions. This may give them advantages in international markets, through both technological expertise and overall industrial productivity, that translates into international competitiveness and export-led growth.

However, translating domestic market growth into international competitiveness poses a major dilemma for industrial policy when network technologies are involved. As the previous sections have discussed, externalities can create substantial technological inertia. Overcoming that inertia to promote a low-emissions energy and transport system may require states to support simultaneous increases in both the demand for low-emissions energy and transport options like hydrogen fuel cell vehicles and the supply of the corresponding network services. But in doing so, states face the challenge of ensuring that national economies do not become locked into early and perhaps sub-optimal technology choices. Thus promotion of competition early on, and piloting of new transport systems before major commitments are made, are warranted as means to try and minimise these risks.

But translating domestic expertise into export-led growth requires very different actions. Access to export markets in network technologies depends on the compatibility of national firm products with the network standards chosen abroad. Significant differences between domestic and foreign choices in this regard may radically limit the possibility of capturing export benefits through improved firm competitiveness. This is not an idle concern. As Box 3 shows, Japan has long had far more advanced cellular technology than the rest of the world. But early state and market incentives left Japan with a suite of network technologies wholly incompatible with those of its trading partners. Thus despite its technological excellence, Japan failed to capitalise on domestic learning-by-doing experience, and lost out to competitors from Scandinavia, Korea and the United States.

Whether states can influence the choices of their trading partners in their own favour depends on both market and non-market factors. Sufficiently large markets may have implicit standards-setting authority merely because of the size of their domestic demand. In this sense, the United States commanded significant authority in the semiconductor and communications network markets not only because it was a first mover in those technologies, but also because it constituted the largest single market for them. It could thus export not just the technologies, but also the standards that went with them.

Absent either market power or first-mover advantages, states may find that they can best capitalise on export-led market growth through command of universal niches in emerging markets. Qualcomm Corporation is a particularly successful example of this kind of strategy. Through both aggressive R&D and patent acquisition, Qualcomm came to command almost 50 percent of the patent portfolio required to build complete CDMA-based cellular phones[21]. The revenue from that portfolio has persisted through several generations of change in the cellular markets, but Qualcomm has maintained its revenue stream through both first-mover advantage and control over technological niches. States lacking the size, industrial capacity or political power to shape international standards in their favour may find that niche strategies offer more promising avenues for industrial policy than pursuit of the low-emissions energy and transport sector as a whole.

Regardless of what the specific answer here is, however, we emphasise that capturing international benefits from early adoption poses a direct challenge to conventional climate policy. Carbon pricing, we should remember, is attractive because it relieves the state of the burden of technological choice. Rather, the choices are supposed to emerge from the change in relative prices brought about by the carbon price itself. But nothing about that process provides the state with tools to affect or set the choice of network standards at home, nor to assure that those standards either dictate or are compatible with standards in emerging export markets abroad.

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[21] CDMA: code division multiple access.

Industrial policy in the fuel cell sector

The dilemma states face, between domestic deployment and capture of international markets, challenges conventional policy recommendations. But that does not mean, conversely, that governments should simply pick and subsidise a standard without further information. Instead, the challenge for policy is how best to establish early indicators of optimal network choice, in a period of international flux, and then move quickly to deployment and potential influence over standards adoption abroad.

For fuel cell electric vehicles (FCEV), the control of innovation and production capacity appears to come down to two important questions of technological, operational and standards control:

1. **Who commands an early lead in fuel cell innovation?** Today, most innovation in fuel cell technologies originates from the US, Canada, Japan and Germany. From 1998-2006, these four countries generated 90 percent of all fuel cell patents granted by the United States Patent and Trade Office.

2. **Who commands an early lead in automotive systems integration?** The standards-setting problem is particularly acute at the level of systems integration, where component technologies are built up into FCEVs. Here, the dominant auto manufacturers in the US, Japan and Germany clearly hold a major technological and logistical lead. The only likely challengers at present are Korea's rapidly emerging global automobile industry, and China's nascent but ambitious (and heavily state-supported) sector.

For FCEV, it remains to be seen if the US, Japanese and German firms can capitalise on domestic innovation systems to gain an early lead in the expertise required to integrate fuel cells into viable personal transport vehicles. Doing so without exposing national economies to the risk of lock-in to suboptimal networks will require states to proceed rapidly but carefully in network evaluation. How best to do so in an economical fashion becomes the core challenge.

Here, Farrel *et al* (2003) have proposed that the fuel-cell industry capitalise on niche networks that still offer significant scale. The learning captured in those networks can provide information subsidies to the later deployment of hydrogen fuel cell electric vehicles, act as a proving ground for new network standards and technologies, and do so without the risk of large-scale failure that might doom both future government policy initiatives and consumer enthusiasm for FCEVs.

This would imply that the fuel-cell industry should seek a range of trial markets, such as medium-distance goods transport, whose properties allow the deployment of a more limited, less full-featured network. These markets, moreover, are typically quite heavy polluters (given their reliance on heavy diesel fuel), and thus represent attractive targets for emissions mitigation. They thus pose substantially fewer risks to either government policymakers or to the fuel-cell industry itself.

In practice, the EU and its member states have already done much of this. Particularly in the case of public transport, local and regional governments have used government purchasing to expand FCEV fleets and install networks of refuelling stations at modest scale. Expanding on those initiatives to include other transportation niches thus represents a natural and promising policy direction for informing network choice.

But the EU should continue to maintain vigilance about the challenge of international competition. The problem of state size and international standards-setting would suggest that the EU should converge on a single standard for FCEV and promote that standard both domestically – to secure learning-by-doing benefits – and internationally, to secure access to external markets. But in doing so, it will face intense competition from large national markets in China, Japan and the United States. China in particular has the potential to deploy new vehicle technology much more rapidly than the EU or US, given the expected growth of its vehicle market over the next several decades. Ensuring that EU FCEV firms and supply chains are not locked out of global markets that converge on Chinese or American standards poses a particularly difficult policy challenge that is separate from the problem of domestic deployment. But it is critical to resolve this challenge if the EU is to capture narrow economic benefits from its pursuit of comparative advantage in new FCEV technologies and systems.

In resolving the tension between domestic and international competitiveness, however, the EU and its member states should keep in mind that failure can come from other sources than unfavourable developments in international standards. The isolation of Japanese cellular phone firms emerged in part from how market competition shaped firm choices. But it also came apart because of how the choices of Japanese regulatory bodies affected cellular standard-setting, market competition and firm investment choices.

Furthermore, the rapid development of new domestic sectors may lead to near-term distortion of labour and capital markets, with negative effects for other high-productivity sectors. The goal of FCEV development is not, of course, the replacement but rather the supplementing of employment in sectors with related skills. Pulling skilled labour out of highly competitive sectors to pursue FCEV may put those sectors at a disadvantage, in pursuit of international advantages in highly risky network technologies.

Finally, competitiveness is not comparative advantage. Comparative advantage is a function of relative productivity, not raw sales. Highly competitive firms may still prove enormously vulnerable to international competition from better-positioned economies, particularly if dependent on state subsidies or other forms of support. That a country can use domestic deployment of a new low-emissions energy and transport sector to create internationally competitive firms does not make that a necessarily optimal strategy, particularly if it costs the broader economy competitiveness elsewhere. Capitalising on environmental policy to create economic opportunity and growth requires not just careful attention to the opportunities of these new sectors and technologies, but to the enduring risks of market distortion and state action.

Conclusion: Domestic deployment of new energy and transport technologies does not promise significant new employment opportunities. However, early-movers with large markets are often able to set global standards that help them to secure a competitive advantage in growing new industries with high value-added. Government support to establish corresponding new markets requires costly policy choices with significant uncertainty.

Recommendation: In their industrial policy efforts governments should focus on sectors were they can build on prior strength. To identify potential targets, growing out of niches is a relatively cheap approach to gathering information on the viability of a technology. Governments should avoid costly support that just shifts employment from one promising (market-driven) sector to another.

1.3 Conclusion

Transforming the energy and transport system is essential to meet European climate targets. Side-benefits such as reduced dependence on fossil fuel imports and lower local noise and pollution emissions, as well as industrial policy motives make this transformation even more beneficial.

Because of a number of market failures, private actors will not carry out this transition on their own. The social benefits of individual carbon mitigation, innovation, initial deployment of green technologies and infrastructure are not properly compensated. Thus, the public sector is needed to adjust the private incentives.

BOX 7: LEARNING-BY-DOING IN THE WIND POWER SECTOR

Denmark has enormous weight in the global wind power industry. Domestic firms such as Vestas have achieved this kind of global leadership even as they have been challenged by industrial giants in Germany and the United States. The Danish experience provides a valuable lesson in translating domestic adoption of low-emissions technologies into global comparative advantage.

As Heymann (1998) shows, the Danish wind sector had far greater success, far earlier on, than either American or German firms. Furthermore, it also spent less on pure research and development. Instead, while both American and German firms spent time and money on laboratory research into wind turbine component design, Danish firms instead chose to actually go out and build turbines. In practice, it turned out that lab-optimised turbine designs were poorly suited to actual operating conditions. By comparison, Danish firms made marginal, continuous improvements to their turbines based on real-world data, data unavailable to firms that had not started early deployment.

Denmark has continued to capitalise on the process of learning-by-doing. As the international wind turbine sector has become more competitive, Denmark's initial lead has eroded. But Denmark has now one of the few high-wind-energy electricity systems, making it an ideal testing ground for the next phase of intermittent generation technologies. Once again, it has capitalised on its first-mover domestic status as a laboratory for building and operating successful networked systems.

Take-home message: Aggressive domestic market expansion in low-emissions goods can generate significant 'learning-by-doing' benefits. In many industries, the only way to become truly skilled at designing, building and deploying new technological systems is to actually design, build, and deploy them.

Sources: Heymann (1998), Aarhus Kommune (2010).

2 Analysis of commercial and policy gaps: the case of fuel cell electric vehicles

Although the wheels of a transport-energy transition are in motion, the policies fuelling the shift to a low-carbon transport and energy sector are disjointed and insufficient to facilitate a speedy transition. To illustrate the gaps in the current policies supporting the transport-energy transition, we perform a mapping of current policies to the externalities identified in chapter 1, in the context of a potential entrant technology.

We focus on the example of fuel cell electric vehicles (FCEVs) as the potential breakthrough technology. FCEVs are an interesting case as the transition to such a technology would suffer from most of the impediments described in chapter 1. FCEVs are not competitive against incumbent technologies, for cost reasons, and require large-scale downstream changes to become commercially viable. However, FCEVs are candidates for replacing internal combustion-engine cars because they offer a combination of low-carbon emissions[22] with a range and level of comfort comparable to conventional cars. They have been both the beneficiaries and victims of fads (being highly promoted for a time, and then facing steeper competition more recently, though the 'best' technology was not and is still not clear). FCEVs still have the potential to become a breakthrough low-carbon transport technology, among several others. Additionally, FCEVs are more sensitive to the infrastructure externality and path dependencies than technologies such as battery electric vehicles (BEVs), and would serve better for illustrating the problems faced by similarly infrastructure-sensitive technologies[23]. We will examine how current policies may support or hinder a hypothetical transition to this technology, so as to highlight more tangibly the problems facing most, if not all, potential alternative transport technologies.

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[22] This only holds if a low-carbon production mix is used to generate the hydrogen fuel.

[23] Hybridisation and a large niche market (suburban commuters) could allow an initial deployment of battery electric vehicles without substantial public infrastructure investment.

However, massive market penetration is currently constrained by technical shortcomings, high cost and many of the aforementioned market failures. In the following sections, we will analyse the key factors required for the success of this technology, identify the techno-commercial gap by comparing corresponding target values to the present situation, catalogue the current policies in place and identify the potential policy gaps which would need to be addressed.

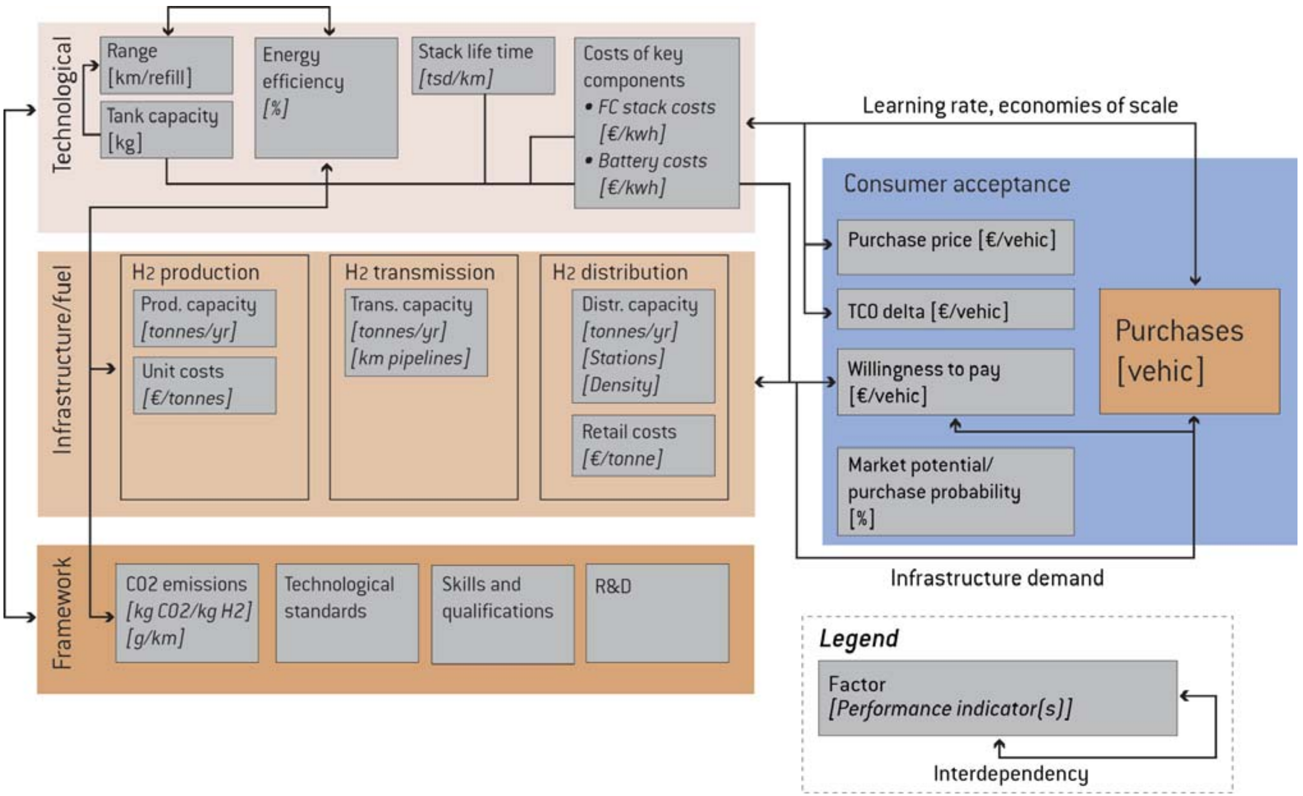
2.1 Identifying the relevant factors for success of FCEVs

The first step in the gap analysis consists of identifying the relevant factors necessary for FCEVs to become a competitive technology option. Based on factors identified in the existing literature, the key challenges to a FCEV rollout were mapped and grouped into the following categories:

1. Propulsion technology (technical requirements, cost development of key components);
2. Infrastructure and fuel (infrastructure demand, fuel cost development);
3. Framework factors (norms, technical standards, skills and qualifications);
4. Consumer acceptance (willingness to pay the difference with established technologies, market share potential).

Furthermore, analysis of the literature delivered insights into the interdependencies of the factors. For example, the cost development of the propulsion technology will have a vital impact on consumer acceptance of FCEVs and the achievable future market share. The number of cars sold and produced has an impact on how quickly scale economies and learning-by-doing effects lead to cost reductions. However, the market share achieved has an impact on the profitability and supply of fuel station infrastructure, and the supply of infrastructure, in turn, has an impact on the purchase decision of the consumer. Figure 1 provides a schematic overview of the factors identified, possible indicators to track them, and selected linkages.

Figure 1: Overview of identified success factors and relevant performance indicators



Source: ESMT (2011).

Understanding these interdependencies and modelling them to identify potential gaps between the factor targets and the model predictions is the research objective of this chapter.

In each of the following sections, we briefly discuss the relevant factors, suitable progress indicators, required milestones, time lines and any mismatch between target states and business-as-usual development.

In this section, we consider which technical factors determine the progress of hydrogen fuel cell propulsion technology towards becoming a competitive alternative to existing and emerging technologies. These include:

1. Technological pre-conditions (range, tank capacity, fuel cell stack life time, fuel cell system efficiency);
2. Cost development of key components (fuel cell stack costs, battery costs).

2.1.1 A model-based approach to detecting the technological and commercial gaps

At the centre of the gap analysis are two questions: (1) what conditions are needed for fuel cell electric vehicles to become a successful technology and (2) how much of these will the market provide autonomously in the business-as-usual case without policy intervention? To answer those questions we use a model based approach. It utilises the *Market Model Electric Mobility* (MMEM) – a simulation tool developed by the European School of Management and Technology (ESMT, 2011). While the underlying assumptions are based on the German car market, the results can generally be transferred to the European context (see the Appendix for more information on the modelling approach).

Specifically, to answer the two key questions, we simulated the following scenarios:

1. **The 'industry forecast scenario'** in which we simulate a world where the main inputs such as FCEV production costs, hydrogen costs and infrastructure supply take the values of the industry forecasts made in McKinsey & Company (2010) report, *A portfolio of power-trains for Europe: a fact-based analysis*. We then estimate the achievable market shares where all the targets and milestones are met, in line with the requirements stated by the stakeholders.
2. However, meeting the targets from the McKinsey & Company (2010) study is by no means assured and depends on a number of factors. Therefore, in comparison to the 'industry forecast scenario', the **'business-as-usual scenario'** (BAU) explores

what autonomous development might occur. That is, how will critical factors such as the production costs of fuel and vehicles, infrastructure supply and, in consequence, the market uptake of FCEVs, develop without any policy intervention? For the forecasts to be realistic, the modelling approach and assumptions must reflect the interdependencies between the success factors for a FCEV roll-out (this is illustrated in Figure 1). For example, the infrastructure supply should reflect how many charging stations can be operated profitably given the number FCEVs on the market. The number of charging stations, in turn, should influence car buyers' willingness to pay and, therefore, the market share achievable. These interdependencies are implemented in MMEM, the model used to simulate the two scenarios.

To provide a quick overview, Table 1 summarises the assumptions made, and approaches used, in the two scenarios.

Table 1: Comparison BAU and industry forecast scenario approach and assumptions

Indicator	BAU modelling approach	Industry forecast scenario	
		2020	2030
Hydrogen fuel production costs [€/kg]	Two-Factor-Learning curve approach	-4.5	-4.0
Hydrogen vehicle cost components [€1000s/vehicle]	Two-Factor-Learning curve approach	-29	-25
Infrastructure supply [% station density]	Break-Even-Model	-1.5%	9%

Source: ESMT (2011), McKinsey & Company (2010).

For each of the factors identified, we first define the industry forecast scenario – ie what targets and milestones need to be met based on the literature review and stakeholder views. Secondly, we model the BAU scenario to derive an estimate of how much development is likely to occur without any policy intervention. Any discrepancies between the two scenarios can be interpreted as the technological-commercial gap. This gap will be particularly useful when comparing consumer acceptance of FCEVs in the two scenarios (see section 2.2.1).

2.1.2 Technical pre-conditions for commercial deployment of hydrogen vehicles

Hydrogen-powered cars rely on a fundamentally new drive-train technology. As such, the technology faces substantial challenges when compared with other alternative vehicle technologies. These challenges need to be resolved before FCEVs are able to achieve any significant market potential or commercial readiness. The most relevant technological pre-conditions are range, tank capacity and design, fuel cell life time and net efficiency.

Currently, tank capacity and design seems to be the main challenge to the commercial deployment of hydrogen cars. Indeed, in order to achieve ranges of over 300 kilometres per refilling, the storage tank needs hold around 4-6 kg of hydrogen (Blesl *et al*, 2009). However, the technology – 700 bar high-pressure hydrogen tanks – required to achieve such capacity carries with it a significant cost and weight impact. Indeed, the prerequisite for commercial use is a significant reduction in the cost of hydrogen storage (Roads2HyCom, 2009). Thus, prior to any deployment, tank capacity – measured in kilogrammes of hydrogen stored – needs to achieve the target of 4-6 kg while allowing for the vehicle shapes of all segments.

A similar technical challenge has been the fuel cell stack lifetime. For the technology to become commercially viable, fuel cell system lifetime needs to be comparable with the lifetime of a conventional engine. While this has been an issue in the past, recent tests and pilots have shown an improvement in durability. The industry now claims a stack lifetime of around 115,000 km and expects this to increase to 180,000 km for the commercial launch in 2015 (McKinsey & Company, 2010).

Finally, the energy efficiency of the fuel-cell system is another critical issue. The United States Department of Energy has set a target of 60 percent net efficiency. This would be roughly twice the efficiency of conventional gasoline internal combustion engines. Achieving this target is also important given the costs and technical constraints of storing large amounts of hydrogen. As of 2007, a pilot study of 77 first generation fuel-cell vehicles found that they achieved 53-58 percent net efficiency (NREL, 2007). As such, the energy efficiency target is likely to be met.

The studies and industry forecasts reviewed indicate that these technological barriers can probably be overcome by 2015. This shifts the focus from the technical factors related to key components to achieving sufficient cost reductions.

2.1.3 Cost development of key components

Using hydrogen to propel electric vehicles requires that an electro-chemical device turn hydrogen into electric energy. The key components of such a fuel cell system are:

- The fuel cell stack;
- Periphery components (air compressors, fuel reformers, pumps, cooling systems, etc);
- Electrical systems (electric engine, control electronics);
- Battery;
- Hydrogen tank.

Common characteristics of these components are their complexity and novelty. The technology is as yet untested, and produced in low numbers in unautomated processes. Consequently, it is expensive. In order to present a viable alternative propulsion technology, the production costs of fuel-cell systems need to fall substantially.

A decline in production costs, and in the purchase price, would require production of FCEVs in significant numbers. Scale economies and learning-by-doing effects can be utilised to lower the price. Additionally, investments in research and development are needed to lower production costs via technological advancement. Given the importance of key component cost development to the commercial success of FCEVs, the evolution of costs needs to be tracked closely via suitable indicators. The following section explores the status quo and the required cost developments for the major components of FCEVs.

Status quo and forecast cost reductions

Fuel cells are not yet being produced on an industrial scale. Unsurprisingly, the costs of fuel cell stacks are still very high – between €300-500 per kilowatt delivered. For a compact car with a 75 kilowatt fuel cell, the cost of the fuel cell system would exceed €30,000 per vehicle.

Table 2: Forecast fuel-cell system costs, €/kw

	2010	2015	2020	2030
HyWays (2008)	n/a	n/a	100	50
Blesl *et al* (2009)	600	n/a	150	40
Industry Forecast	500	110	43	43

Sources: Blesl *et al* (2009), Roads2HyCom (2009), McKinsey & Company (2010).

While the available forecasts are conflicting regarding the extent and speed of the achievable cost reduction, the studies reviewed all expect that costs could fall to €40-50 per kilowatt in the medium term if fuel-cell systems are produced on an industrial scale[24] (see Table 2). This would represent an almost 90 percent decline in the production costs of fuel-cell stacks.

A second cost component and success factor for FCEVs is the production cost of the

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[24] For an informative review of cost development see for example Blesl *et al* (2009).

hydrogen tank. Indeed, given the low mass-energy ratio and transient nature of hydrogen fuel, storing a sufficient amount of it presents a significant technical challenge (Roads2HyCom, 2009). Only 700 bar tanks would provide the storage capacity needed for FCEVs to exceed ranges of 300 kilometres per refill. The costs of energy-storage systems are still very high and need to be reduced through investments in research and through learning-by-doing effects. Reflecting technical uncertainties, forecasts of cost developments in the literature are vague. Blesl *et al* (2009) suggest current production costs of around €775 per kg tank capacity and consider a cost decline to €270 realistic. We use this forecast as our benchmark for the required cost decline for hydrogen tanks.

Other relevant cost components of FCEVs, which need to come down in order for the purchase price to become competitive against competing propulsion technologies, are the costs of the electric engines, control electronics and battery costs. These components are common to other electric propulsion technologies and one can expect spillover effects from a commercial deployment of plug-in hybrid, range extender and battery electric vehicles. Indeed, with mild hybrid cars already being produced in significant numbers, cost reductions in this area have already taken place and are likely to continue well ahead of those of actual fuel cell components. We expect battery cost to fall significantly from the €700-800 per kWh to below €300 per kWh over the next decade, reflecting the increasing market share of electric vehicles and investments in research and development. This is based on expectations from battery industry stakeholders expressed during the 'National Platform Electric mobility (NPE)' consultation process conducted in Germany in 2010 and 2011 (Nationale Plattform Elektromobilität, 2010). We will use this forecast as our industry forecast scenario for battery cost development.

Can cost reductions be achieved in the BAU case?

Cost reductions on the scale required to meet the targets expressed by industry and literature can only be achieved through substantial investments in new production and material technologies. Furthermore, only production on an industrial scale is likely to achieve the learning-by-doing effects required. We therefore modelled the extent of cost reductions possible in different scenarios, in order to identify whether cost-reduction targets can be achieved. The model is based on a two-factor-learning-curve approach for estimating how costs will develop in response to increasing production capacity and accumulated learning (see Box 8). The cost decline of the FCEV components determines the actual purchase prices of hydrogen vehicles and their competitiveness. The feedback loop between market uptake and learning-by-doing is inherently considered in our modelling approach, and allows for establishing how a slower or faster market uptake may impact cost declines and vice versa (see also section 2.2.1 for a short description of the simulation tool used).

BOX 8: USING TWO-FACTOR-LEARNING CURVES TO SIMULATE COST DEVELOPMENTS OF KEY FCEV COMPONENTS

Understanding the future technical progress of innovations is crucial when discussing the prospects of innovative propulsion technologies. In the context of FCEVs, innovation theory, using learning curves, can shed light on the technical change process and the impact on unit costs. The concept of learning as a distinct source of technical change was presented in Wright (1936) and Arrow (1962), and is often called learning-by doing. Technical change through learning effects is generally derived from learning curves. Progress is typically measured in terms of the reduction in unit cost as a function of experience gained from the increase in cumulative capacity or output (Jamasb, 2007).

Two-factor learning curves reflect the fact that both capacity deployment and R&D may impact the rate of technical progress and cost reduction. Learning effects can therefore stem from learning-by-doing or learning-by-research. The following formula summarises the approach:

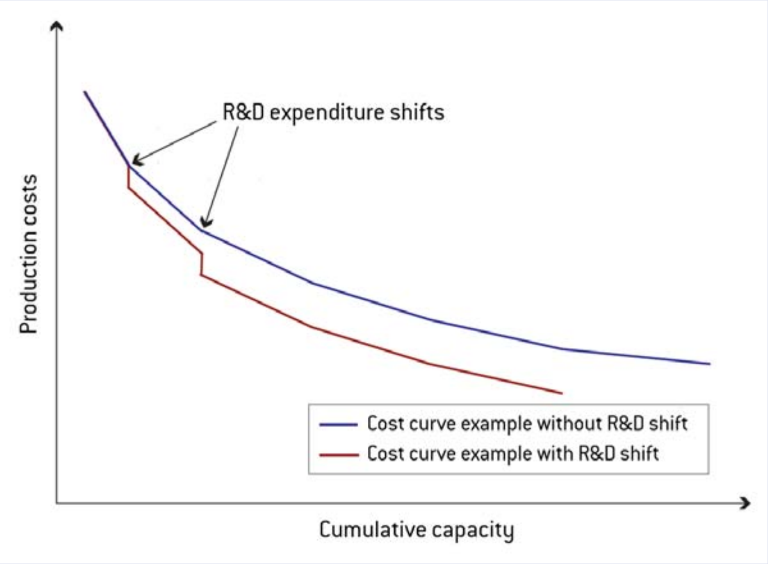
$$C_t = (1-\varepsilon)C_o \left(\frac{Q_t}{Q_0}\right)^{-\alpha_t}\left(\frac{R_t}{R_0}\right)^{-\beta_t} + (\varepsilon)C_o$$

With Q_t denoting cumulative production in the current period, R_t cumulative research expenditure, C the unit costs, and ε the share of non-learning cost (for example raw materials). α_t and β_t are the learning-by-doing and learning-by-research cost reduction coefficients. They reflect the cost reduction effect which additional capacity or R&D expenditure can induce.

Learning curves are not an economic law but an empirically observed relationship. Figure 2 depicts an illustrative example of how the approach can be used to predict cost development for batteries.

Thus, past relationships between the cumulative number of units produced, R&D expenditure and unit costs can be used to forecast the possible cost trajectories of other technologies. Clearly, such an approach is inherently uncertain and can only be indicative. Nevertheless it is a useful tool for modelling cost developments under different assumptions.

Figure 2: Two-factor-learning-curve for battery costs



Source: ESMT (2011), based on Blesl (2004).

We mostly use the industry assumptions on learning rates reported in McKinsey & Company (2010) for our modelling purposes.

Table 3: Learning rate assumptions

	Learning by doing rate	Learning by research rate**
FC cost component	15%*	20%
EV typical components	10%*	20%
Battery costs	15%**	20%
Hydrogen fuel production costs	5%*	20%

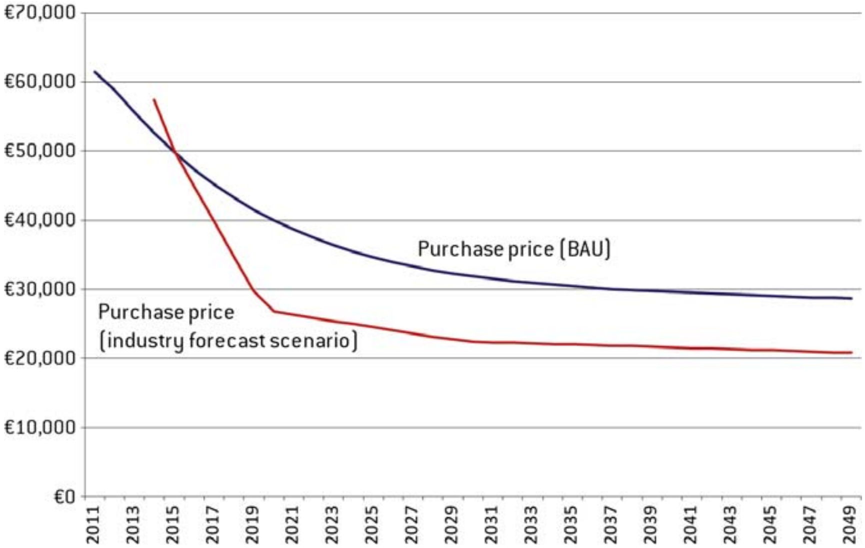
Sources: * McKinsey & Company (2010), ** based on Jamasb (2007).

Clearly, the underlying assumptions about learning rates (and initial production experience) have a significant impact on the trajectory of the learning curve and the cost reductions that can be achieved with increasing market penetration. A learning rate of 15 percent suggests that each doubling of cumulative production reduces (the learning part of) unit costs by 15 percent.

Sources: Jamasb (2007), Blesl (2004).

The model results suggest that, in the business as usual scenario, the costs of the main components will not decline as quickly as required to meet stated targets and milestones. This is the result of the combined effect of low market penetration and a lack of R&D investment. With the costs of key components declining less than necessary to meet the industry forecast scenario, purchase costs (excluding tax and margins) of FCEVS will fall less than what is deemed necessary for successful market deployment (see Figure 3).

Figure 3: Production costs BAU vs. industry forecast scenario, €/vehicle

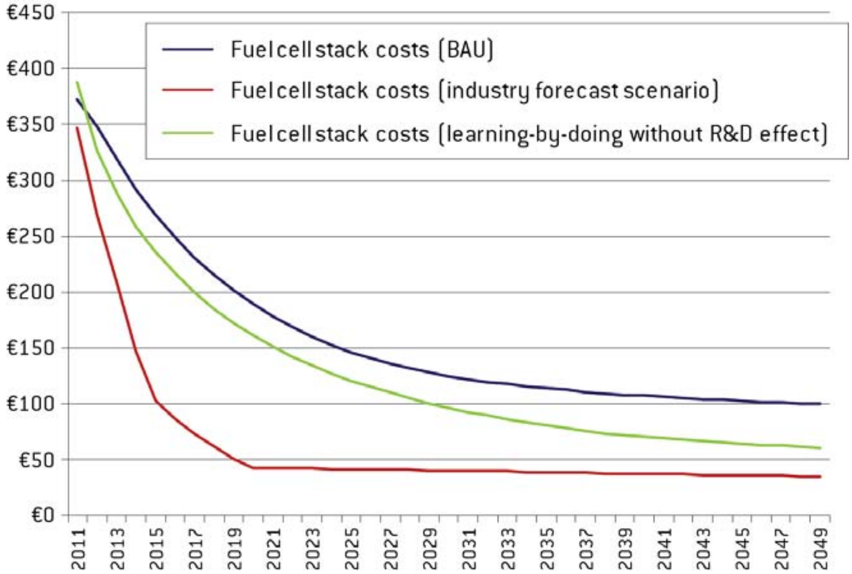


Source: Bruegel/ESMT based on ESMT (2011) and McKinsey & Company (2010).

A more detailed look at the cost development of fuel-cell stacks underlines the negative feedback loop between a slow decline in costs and a slow uptake (see Figure 4).

However, even the achievement of an optimistic market uptake (around 25 percent of new registrations by 2050 – one of the targets voiced by stakeholders) does not lead to the cost decline deemed necessary for the purchase price to become competitive in the medium term. This is not surprising as the cost reductions are unlikely to be achieved through capacity increases alone. As the example in Box 8 shows, R&D-induced cost reductions, especially in the pre- and early-commercialisation phases, have a role to play in shifting the cost curve downwards.

Figure 4: Cost development fuel cell stacks, €/kw



Source: Bruegel/ESMT based on ESMT (2011) and McKinsey & Company (2010).

The status quo for fuel-cell stack costs reflects the early pre-commercialisation phase of the technology. Current prototypes are being produced manually, leading to very high production costs. While this means that there is a huge potential for cost reduction, realising it relies on sufficient scale of production. Additionally, investments in research, to develop efficient material use and production methods, are required to provide sufficiently low production costs for an initial commercial deployment in the medium term. It is uncertain though if the market will autonomously reach the cost reductions required. In particular, there is a large gap between target costs and the cost outcomes in the BAU case, suggesting that the targets will be missed. Given the overall cost share of this component, the gap will significantly impact the purchase price of FCEVs, and may impede the market-share growth of the technology. Our analysis suggests that reducing the costs in line with industry forecasts would require a concerted approach.

Table 4: Cost development of key component: summary of success factors and suggested progress indicators

Progress indicators	Status quo	Industry forecast scenario 2020	Industry forecast scenario 2030	BAU Scenario 2030	Gap
Purchase price [€1000s]	113	29	25	31	24%
FC stack costs [€/kw]	367	98	44	125	182%
Battery costs [€/kwh]	871	300	260	260	0%
H2 tank costs [€/kg]	775		270	300	11%

Source: Bruegel/ESMT.

2.1.4 Production infrastructure: hydrogen production cost

Although the hydrogen distribution infrastructure is still in its infancy, a hydrogen production infrastructure already exists. Thus, an extension of existing capacities could be utilised to provide hydrogen in the initial phase of the FCEV deployment.

Current situation and consensus forecast for hydrogen costs development

Hydrogen production costs depend on the mix of production technologies employed (see Table 5). While currently mostly a side product of other processes, some cost reduction can be achieved when hydrogen is produced on an industrial scale. Falling equipment costs of decentralised production facilities will also add to the cost reduction potential. However, the cost decline from increasing the output of conventional production methods may be partly offset by increased costs as production moves towards sustainable and decentralised production methods. Indeed, there seems to be a targets conflict between reducing the carbon emissions of hydrogen production and achieving low production costs.

Table 5: Production cost for selected production methods

	Coal steaming	Coal CCS	Gas reforming	Biofuel reforming	Electrolysis
Costs [EUR/GJ]	4.4-7.5	4.9-14.3	5.6-21.8	10.4-21.2	11.4-22.7
GHG emissions [kg/GJ]	193	8.8	73-87	0	n/a

Source: Blesl *et al* (2009).

A review of the literature, and the forecasts made therein, suggests that hydrogen production costs have little cost reduction potential. Production costs (excluding any tax and excise duty) are currently around €5/kg. Only marginal declines are expected by 2020 and most observers are expecting a floor of around €3-4/kg in the long term (Table 6).

Table 6: Hydrogen production cost development (excluding taxes, fuel excise duty), €/kg

Row Labels	2010	2020	2030	2040	2050
HyWays (2008)	n/a	4.0	3.0		
The Connecticut Center for Advanced Technology Inc. (2011)	n/a	3.0	2.9	2.8	2.8
McKinsey & Company (2010)*	4.5	4.5	4.0	4.0	3.8

Source: Roads2HyCom (2009), McKinsey & Company (2010), The Connecticut Center for Advanced Technology, Inc. (2011). Note: * excluding transport and retail margin.

To simulate the interdependence between consumer choice, market uptake and hydrogen fuel costs, we again use a two-factor-learning-curve approach (described in Box 8). Unlike the fuel cell vehicle component costs, however, the level of hydrogen fuel cost reduction achieved via learning-by-doing is expected to be considerably lower. This is partly due to the fact that production methods used for hydrogen are already well established. With decades of experience with some of the methods of current production, costs are likely to be on a much lower point of the learning curve. McKinsey & Company (2010) suggests a learning rate between 3-7 percent, which is significantly lower than the 15 percent stakeholders expect to see for fuel cell production[25].

In conclusion, current hydrogen production costs are already relatively close to the target values stated in the literature and by stakeholders. The challenge ahead lies in increasing the share of low emission production methods while keeping production costs low.

2.1.5 Retail distribution infrastructure: network density

With little indication of a policy gap with respect to the actual production costs, attention moves towards providing an adequate retail infrastructure for FCEVs –

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[25] The learning-by-doing cost regression coefficient expresses the cost decline that can be achieved with each doubling of cumulated production experience.

specifically, the trade-off between low hydrogen fuel retail prices and the profitability of fuel stations. Indeed, the main driver of hydrogen fuel costs may not actually be production costs but ensuring a retail margin which provides enough incentive for an adequate hydrogen fuel station network in the early commercialisation but which does not deter consumers.

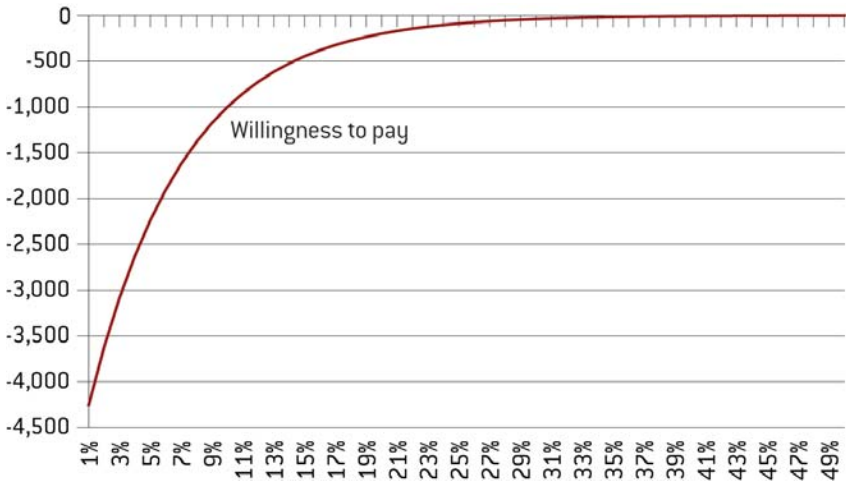
Similar to conventional vehicles, FCEVs require a dedicated refilling infrastructure. Sufficient network density is a pivotal factor for the successful market adoption of hydrogen vehicles. As such, a sufficient minimum infrastructure will have to be provided in parallel to the commercial launch of FCEVs. However, with the number of users likely to be low in the early stages of market deployment, the profitable provision of infrastructure is unlikely. Central to the analysis are two questions: how much infrastructure is required to provide sufficient consumer acceptance, and how much of this infrastructure will be provided autonomously by the market?

Infrastructure demand: how much infrastructure is needed?

A lack of infrastructure reduces the utility of vehicles as users are faced with uncertainty, search costs, and the need to calculate detours in order to refuel their cars. Consequently, car buyers value dense networks of refuelling stations and would choose a propulsion technology with a high network density over an alternative with low density, *ceteris paribus*. However, determining the actual utility of refuelling stations is less conclusive. Often, the existence of refuelling stations for emerging alternative vehicles is measured by calculating the network density – the share of the existing refuelling network offering the alternative fuel.

In Achtnicht *et al* (2008), and Ziegler (2009), the marginal utility of refuelling is a constant and their models exhibit a very strong effect from these variables. The calculated willingness to pay ranges from €200-300 for each percent network density. However, a limitation of these results is that they rely on a constant marginal willingness to pay, while it is more than likely that the marginal utility of refuelling stations will be decreasing. This shortcoming is addressed in an approach by Greene (2001), where the utility of refuelling stations can be represented as an exponential function.

Figure 5: Estimated willingness to pay for network density, € per vehicle



Source: ESMT (2011).

There is a trade-off between the cost of providing sufficient infrastructure and the increase in willingness to pay for a higher network density. The willingness-to-pay estimates of the various stated preference surveys indicate that a network density of above 10 percent is enough to reduce disutility of low network density to a sufficient level. McKinsey & Company (2010) argue for a density of around one percent in 2020 to increase to one of around nine percent in 2030[26], and to one of about twenty percent by 2050 (see Table 7).

Table 7: Literature review infrastructure demand, refilling stations (thousands)

Source	2015	2020	2025	2030	2050
HyWays (2008)	0.9	10.0		20.0	
Industry forecast		0.8	2.3	5.1	18.2

Source: McKinsey & Company (2010), Roads2HyCom (2009).

Infrastructure supply: how much infrastructure will be provided by the market?

Currently, the number of refuelling stations available in Europe is limited to a low number of demonstration sites. This reflects the pre-commercialisation phase of the

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[26] Estimate based on around 60,000 conventional refuelling stations in Europe.

technology. Taken together, the number of stations does not exceed 100 – this compares to an estimated 60,000 conventional fuel stations across Europe. In Germany, a consortium of industry representatives has recently agreed to double the number refuelling stations to around 60-80 stations by the end of 2015.

Looking at supply, the number of refuelling stations provided by the market is strongly determined by the size of the hydrogen vehicle fleet. Consumer acceptance of the technology is, in turn, influenced by the existence of adequate network density. This negative feedback loop can lead to an under-provision of infrastructure in the market, especially if future demand is uncertain. To model this interdependency, a simple break-even modelling approach was used. The break-even model estimates the number of charging stations that can be profitably operated for a given number of FCEVs in the vehicle stock, the current equipment costs, and the retail margins of hydrogen refuelling stations.

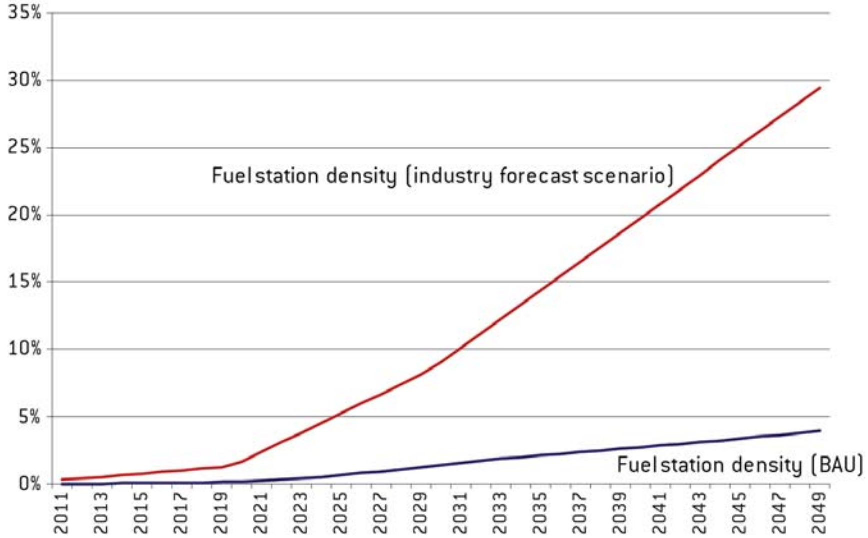
Table 8: Assumption hydrogen stations break-even analysis

Assumption	Value	Source
Equipment costs	€1 million (2012) - 0.5 million (2050)	Weinert *et al* (2007)
Capital costs (WACC)	7% p.a.	McKinsey & Company (2010)
Operating costs	10% of equipment costs p.a.	Weinert *et al* (2007)
Retail margin	15% of H2 retail delivered price	Own assumption
Asset life time	20 year	McKinsey & Company (2010)
Fuel station capacity	500 kg/day	Own assumption

Unsurprisingly, using these assumptions indicates that in the BAU scenario, the number of charging stations profitably provided by the market will remain significantly below the consensus target. This reflects the aforementioned negative feedback loop between a sluggish up-take and hence low demand for hydrogen fuel, and low willingness to pay for hydrogen cars due to the lack of infrastructure (see Table 7). However, even a scenario where the market penetration targets are met may see an insufficient number of fuel stations provided in the short and medium term.

Clearly, such a straightforward break-even analysis suffers from a number of shortcomings. For example, it neglects investor expectations regarding the future development of demand. Investors may tolerate losses in the early commercialisation phase hoping that these would be compensated as soon as the market for FCEVs evolves. This notion supports the view that transparent policy objectives and clear commitments can go a long way in providing certainty for long-term investments in hydrogen fuel stations. In fact, this self-fulfilling prophecy can work in both directions – supporting market uptake if investors are positive about the prospects of FCEVs, but inhibiting market uptake, and hence infrastructure demand, when expectations are low or uncertain (or both). Consequently, it is our view that the business as usual scenario is a conservative, but not unrealistic, scenario reflecting a negative feedback loop between sluggish demand and lack of infrastructure.

Figure 6: Number of hydrogen stations BAU vs. industry forecast scenario



Source: Bruegel/ESMT based on ESMT (2011) and McKinsey & Company (2010).

Unlike some other emerging propulsion technologies, hydrogen vehicles require dedicated refuelling infrastructure. In order to gain competiveness, 10-20 percent of existing stations need to be equipped with hydrogen refuelling facilities. Considering the profitability of such infrastructure, there is a strong likelihood that the market will not provide an adequate number of hydrogen refuelling stations in the short and medium term. This could lead to a negative feedback loop between FCEV demand and fuel station provision, resulting in the technology missing the deployment targets envisioned by the industry.

In addition to adequate production and retail infrastructure, a mass-market rollout of hydrogen vehicles would require a suitable and cost-effective transmission infrastructure to link retail and production sites. Unlike other infrastructure components, there are currently already several viable transport options available. Indeed, pipeline transport of hydrogen has been used for more than 50 years. Existing pipeline networks for industrial use in Belgium and Northern France (more than 1000 km) could form the basis for future network extensions (Blesl *et al*, 2009).

Truck and trailer-based transport provides a flexible and economically viable option for transporting hydrogen. For example, compressed gas-tube trailer trucks could be used – especially for distances under 200km, and in regions where low demand would not justify a dedicated pipeline infrastructure. However, the actual mix of transport techniques would depend on the prevailing production mix (centralised versus decentralised production), and the trajectory of demand (Roads2HyCom, 2009).

In conclusion, providing suitable hydrogen infrastructure is likely to be one of the key factors for a successful roll-out of hydrogen vehicles. This requires the development of adequate and cost-effective production capacity with a hydrogen production cost target of around €4/kg in the medium term. The challenge here seems to be increasing the share of low emission production techniques while keeping production costs at an affordable level. This would require both a sufficient scale of demand and investment in R&D, to reduce production costs for new decentralised facilities.

Another prerequisite for a mass market launch is the existence of a basic retail infrastructure (roughly 10 percent network density). There is indication that, especially in the early stages of market development, sufficient density cannot be provided profitably. Sufficient density might only be provided with high retail fuel costs as low utility rates would lead to excessive retail margins. Table 9 summarises the main infrastructure and fuel success factors with their indicators.

Table 9: Infrastructure and fuel factors and relevant indicators

Progress indicators	Status quo	Industry forecast scenario 2020	Industry forecast scenario 2030	BAU Scenario 2030	Gap
Number of refuelling stations [thousand units]	0	5.4	12.55	0.6	-95%
Network density [Share of existing fuel stations]	0	9	21	1	-95%
H2 production costs [€/kg]	5.0	4.5	3.6	4	12%

Source: Bruegel/ESMT based on ESMT (2011) and McKinsey & Company (2010).

2.2 Consumer acceptance and the technological and commercial gap

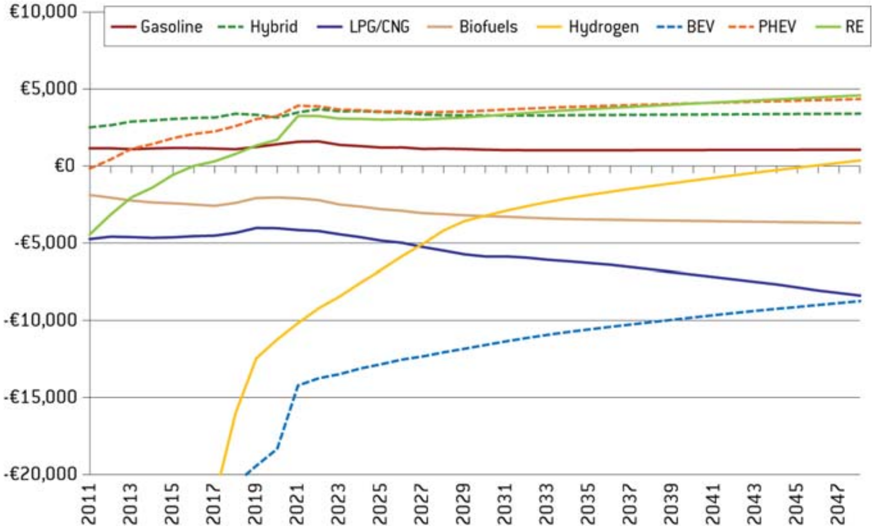
Only the combination of suitable infrastructure with a competitive propulsion technology will make FCEV a success. Based on the factors identified above, we ask how certain outcomes of those indicators will affect acceptance among consumers. Consumer acceptance will be measured by estimating the willingness-to-pay difference to established technologies, and the actual market share of new registrations which can be expected. The results are derived using the *Market Model Electric Mobility* (MMEM). Initially, we will model the outcomes of the industry forecast scenario and the BAU scenario described previously. Hence, we can compare how consumer acceptance develops in a world where all targets and milestones are met (as assumed in the industry forecast scenario) to how it would develop endogenously if no market intervention were to take place.

2.2.1 Consumer acceptance of FCEVs

The core assumption of the industry forecast scenario is that all key factors identified will meet their targets and milestones (see section 2.1.1). In this case, the *a-priori* expectation would be to see FCEVs gaining competitiveness in the medium term and becoming a comparable technology option in the long run. To investigate how competitiveness develops when the targets are reached, we estimate the willingness-to-pay gap compared to a conventional diesel engine. The willingness-to-pay gap expresses how much more or less a consumer is willing to pay for vehicles compared to a typical diesel car. As Figure 7 shows, if the targets are met, FCEVs can quickly gain in competitiveness. However, even based on this optimistic scenario, hydrogen vehicles will only be perceived as an equal option after 2040.

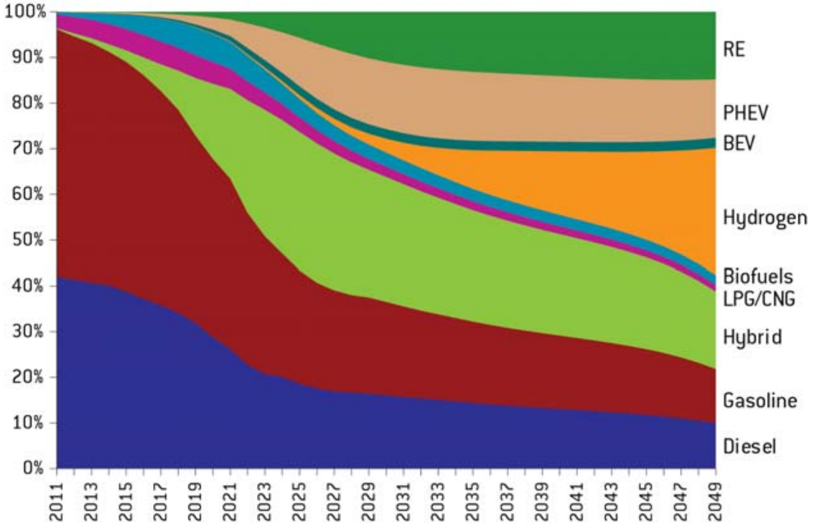
This is also reflected in the actual market share forecast for the different technologies shown in Figure 8 (the orange shaded area shows the market share development of hydrogen vehicles). Following their commercial launch in 2015, it will take until the mid-2030s for the technology to gain a significant market share. Further ahead, we would expect a market share of around 25 percent in 2050 if the factor targets are met. Thus, the modelling results of Figure 8 are in line with the prediction of McKinsey & Company (2010) that FCEV can achieve a market share of about 25 percent if the industry forecasts on all key factors materialise. Clearly, given the time horizon of the forecast, and the uncertainty regarding the development of the inputs, there is a considerable margin of error associated with the forecasts. However, this and the following forecast can still deliver valuable insights regarding the trends and shifts in different scenarios.

Figure 7: Willingness to pay gap 2012-2020, €/vehicle difference to diesel engine, industry forecast scenario



Source: Bruegel/ESMT based on ESMT (2011) and McKinsey & Company (2010).

Figure 8: Market share forecasts 2012-2050, industry forecast scenario

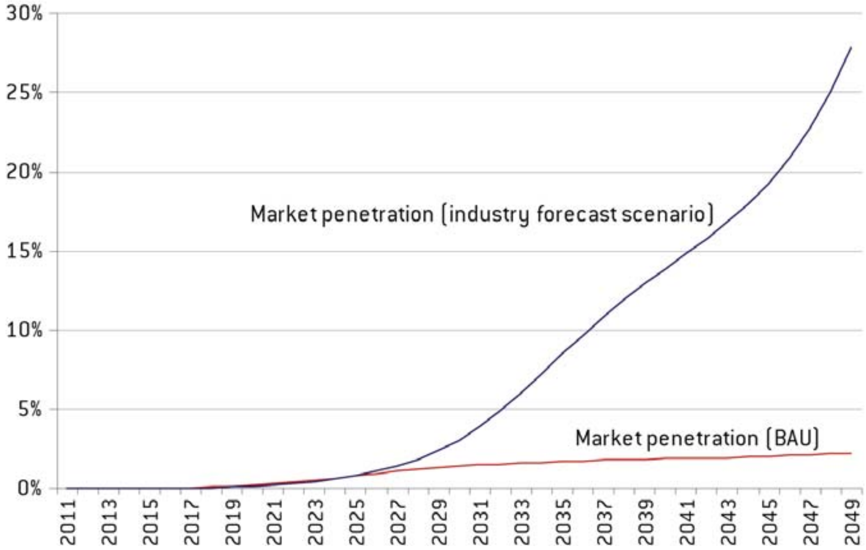


Source: Bruegel/ESMT based on ESMT (2011) and McKinsey & Company (2010).

2.2.2 FCEV market penetration under selected scenarios

The industry forecast scenario described previously is based on the rather optimistic assumption that the objectives formulated in the previous sections are met. If these are not met, the market potential of FCEVs is likely to be severely constrained. High purchase prices, fuel costs and the lack of infrastructure would mean that hydrogen-powered vehicles would remain a niche technology. Indeed, a negative feedback loop between slow market uptake, missing learning-by-doing cost reductions and, hence, high fuel and purchase costs and low consumer acceptance, would cause a far lower market penetration trajectory when compared with the Industry forecast scenario (see Figure 9).

Figure 9: Market penetration of FCEVs BAU vs. industry forecast scenario



Source: Bruegel/ESMT based on ESMT (2011) and McKinsey & Company (2010).

To put the findings into perspective, the BAU scenario in Figure 9 includes some strict assumptions. The BAU assumes a complete absence of autonomous research and development investment as well as no change in mobility and energy taxation policies, reflecting the policy status of 2011. However, while conservative, it is our view that the business as usual case describes a realistic scenario. Indeed, our analysis indicates that a concerted effort will be required for hydrogen vehicles to achieve competitiveness. If that is not the case, a negative feedback loop and mutual amplification between the key factors leads to the technology remaining a niche product. Additionally, the nature, scope and timing of measures taken can have a significant impact on the market adoption trajectory of the technology.

Finally, this raises the question of how some of the shortcomings which lead to the outcome of the BAU scenario can be addressed. To illustrate the impacts of some measures, a number of selected scenarios will be discussed here:

- **Scenario 1:** An increase in R&D to achieve an early reduction in production costs of both fuel and vehicles;

- **Scenario 2:** Infrastructure build-up to increase infrastructure deployment to the level of industry forecast;

- **Scenario 3:** Carbon pricing – inclusion of the car industry in the EU Emissions Trading System, which would see manufacturers having to obtain emission certificates for the estimated life time emissions of each vehicle sold. This would increase the purchase costs of high-emitting technologies and improve the competiveness of low-emission technologies such as FCEVs[27].

- **Scenario 4:** The scenario that all measures described above will be employed together.

Figure 10 shows the results of the simulation exercises. Applied without any other measures, R&D funding is the only instrument likely to increase market uptake significantly. An infrastructure investment on its own, while the vehicles are still uncompetitive in terms of purchase prices, would not lead to any significant increase in the future market share. Similarly, an inclusion of the car industry in the Emissions Trading System (ETS) would not suffice to improve competitiveness of FCEVs enough to overcome the remaining shortcomings.

These initial simulation results suggest that a comprehensive package of measures is needed to close the gap between hydrogen and other established or emerging

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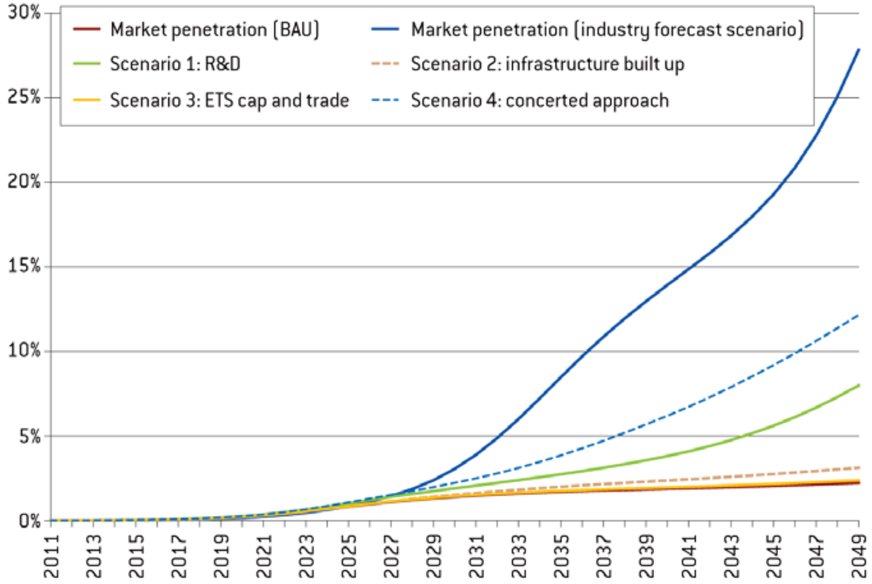
[27] Specifically, we have assumed that car manufacturers need to buy certificates for the life time emissions of each vehicle produced. We assume an ETS price of €15/tonne CO2 increasing to €80/tonne CO2 by 2050. Assuming life time emissions of around 20 tonnes CO2 per vehicle this would mean a penalty of €300-€1600 per vehicle. While this has a significant impact in long run, the incentive is effective too late to assist market uptake for FCEVs in the early commercialisation phase.

Figure 10: Simulation results, FCEV market share

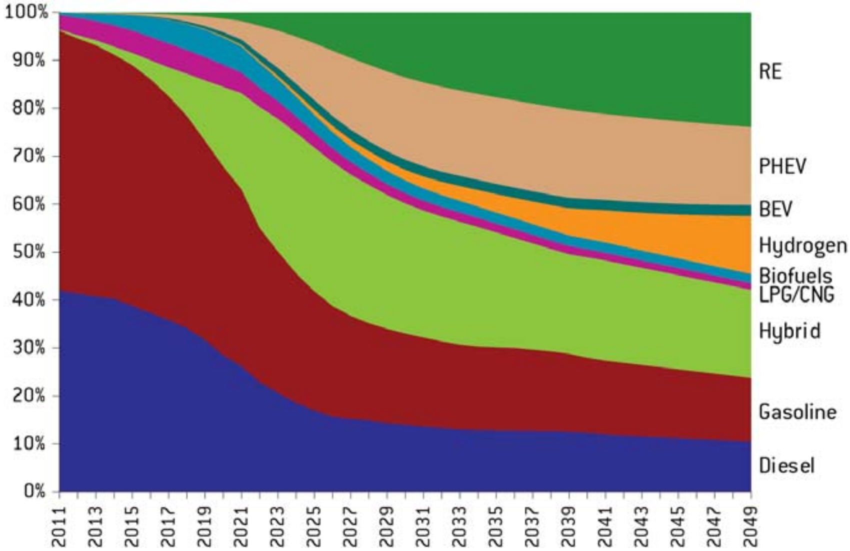


Source: Bruegel/ESMT based on ESMT (2011) and McKinsey & Company (2010).

propulsion technologies. Indeed, the results indicate that only a concerted approach is likely to lead to any significant increase in the market share of FCEVs in the foreseeable future. Employing a package that would combine infrastructure support, R&D funding, and ETS inclusion is likely to lead to a market share approaching 14 percent in 2050 (scenario 4, blue line). While this is still below the industry forecast scenario of 25 percent in 2050 (orange line), it would serve to establish FCEVs as a mass market technology in the foreseeable future.

Figure 11 indicates that the stronger deployment of hydrogen cars in the industry forecast scenario, as compared to the concerted approach, crowds out some of the growth in the share of cars with Range Extender (RE) and Plug-in Hybrid Electric Vehicles (PHEV).

Figure 11: Market share forecasts 2012-2050, concerted approach



Source: Bruegel/ESMT based on ESMT (2011).

2.3 Current policies

The EU, all its member states and many sub-national entities have devised instruments to support new energy and transport technologies. Some of these instruments explicitly or implicitly target fuel cell electric vehicles. Currently, most of the identified market failures are partially addressed (see also the policy table in the appendix).

2.3.1 Climate externality

Due to the absence of an international climate agreement beyond 2013, there is currently no global long-term carbon price signal. Fuel taxes for fossil fuels and, in some countries, road tolls are partially internalising some of the negative externalities of road transport emissions. However, these taxes/tolls are supposed to correct many externalities at the same time: local pollution, noise emissions, congestion, import dependency, land consumption, road construction and other road traffic-related cost. As the number of externalities being addressed is large it is likely that taxes/tolls under-compensate in correcting the climate externality.

In contrast to conventional fuels, hydrogen and electricity currently do not pay fuel taxes in most member states. However, electricity consumption (eg for the production of hydrogen from electrolysis) is taxed in many countries and subject to the EU ETS. Furthermore, some forms of hydrogen production are subject to the ETS. Consequently, an inconsistent situation exists. While, the fuels of FCEVs and battery electric vehicles are largely subject to the EU ETS, fossil fuels are not covered. Thus, if the share of FCEVs and battery electric vehicles were to increase dramatically, on the one hand their fuels might become significantly more expensive as they would absorb more of the valuable emission rights and thereby increase their price. On the other hand, the prices of fossil fuels would be unaffected (or even decrease due to lower demand), creating a rebound effect.

For the purpose of including emissions cost, the Commission proposes a minimum harmonisation (proposal for directive amending Directive 2003/96/EC, published on 13 April 2011). The key idea behind this tax is to increase the retail price of fuels used in transport and heating to a level that makes them competitive with alternative ones. Currently, it is suggested that the minimum tax rate be split into two parts:

- Carbon component => €20 per ton of CO2

- Energy content component => €9.6 per gigajoule for motor fuel and €0.15 per gigajoule for heating fuels

For incentivising car manufacturers to conduct long-term investments in low-carbon vehicles, the EU has devised a vehicle fleet emission standard[28]. Based on this standard, each manufacturer has to ensure that the average emissions per kilometre of all cars he sells in Europe are below a certain threshold. Currently, EU Regulation (EC) No 443/2009[29] sets a target value of 130 grammes CO2 per kilometre [g CO2/km] by 2015 and of 95 g CO2/km by 2020 for new passenger cars. The target is gradually phased in: in 2012, 65 percent of each manufacturer's newly registered cars must comply, rising to 75 percent in 2013, 80 percent in 2014, and to reach 100 percent by 2015. These vehicle fleet emission standards provide incentives for investment and R&D in the absence of a long-term carbon price.

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[28] The scheme is comparable to the US Corporate Average Fuel Economy (CAFE) programme. The US programme requires cars sold in the US to meet a minimum fuel economy (miles per gallon of fuel) standard. The penalty for not meeting this standard is $5.50 per tenth of a mile per gallon for each tenth under the target value times the total volume of those vehicles manufactured for a given model year.

[29] http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0001:0015:EN:PDF.

Public support gap

The transport sector is responsible for almost 20 percent of the EU emissions. This share will rise to 30 percent by 2050 due to lower reduction targets compared to other sectors. Still, the fossil fuels for transport are not included in the EU ETS. Consequently, there is no dedicated instrument to incentivise consumers to adapt their day-by-day driving decisions to the need for emission reductions. As alternative fuels such as hydrogen and electricity fall under the ETS, these technologies are put at a disadvantage with respect to conventional fuels. Consequently, a consistent approach towards including the transport sector in an economy-wide emission reduction is missing.

2.3.2 Innovation externality

Individual firms under-invest in R&D because they do not fully internalise the social benefits of R&D investments. Patent protection, public R&D as well as financial support to private R&D are the most prominent tools to resolve the innovation externality. While patent legislation is essentially a horizontal exercise, support to R&D needs to be targeted. The question of technological choice becomes a pressing one as alternative technologies begin to mature. Path-dependencies that might have the force to lock in suboptimal technologies that experience an early advantage – eg above-proportionate public support – make the issue of technology choice for public funding even more pressing. At some point in the realisation of an energy transition, government must make a choice over competing technologies. Public budgets are limited and, thus, equal financial support to overcome market failures for all technologies might lead to underfunding for all alternatives. In the worst case, all clean technologies then fail to become competitive. With a constrained budget, supporting some promising technologies at the right level might be superior to complete technology-neutrality and underfunding to all technologies. Furthermore, attributes of an energy system, such as infrastructure or standards, are, by nature, technology-specific. Consequently, the public sector has to decide which, when, and how to support different technologies.

How are technologies selected for support?

Support schemes for encouraging R&D exist at the regional, member state and EU level. Member states do not currently coordinate with each other in developing their support mechanisms.

EU level support for new technologies is focused on support for R&D. Strategic plans are developed and outlined via packages (such as the Strategic Energy Technology Plan, or SET plan). Packages do not allocate funding nor do they possess funds to be granted. For example, the Green Cars Initiative is funded by money from the EU Seventh Framework Programme and loans from the European Investment Bank. Packages are strategic documents outlining priorities. Priorities in eight different energy technology areas are currently determined by long consensus-building process between the EU, industry, and academics. European technology platforms[30], consisting of industry stakeholders, the EU and academic work to determine funding. Consensus-building is a major exercise, which has the latitude for short-term changes to address needs. For deployment, the EU currently provides no money – the money comes from member states, regions, and industry. Packages are long multiannual programs for funding with year-to-year disbursement. There are mid-term assessments for the whole framework and for the different parts. The assessments are conducted by experts groups from the respective fields, though they are led and facilitated by the European Commission's Directorate General for Energy.

Part of the SET plan established consortia (bringing together industry, the research community, and the Commission in public-private partnerships). The establishment of the Fuel Cells and Hydrogen Joint Undertaking (FCH JU) was accomplished via this regulation. These formalised structures are created by council regulation to help ensure long-term programme stability through the oscillations of technology hype. The funding for FCH JU projects comes from both the public (via the EU Framework Programmes) and private sources. The scheme calls for 50-50 cost-sharing and facilitates coordination amongst stakeholders and confidence among public and private investors. Currently, the FCH JU has a nearly €1 billion budget, jointly contributed by members.

At the member state level, one highly developed support scheme, to encourage R&D investment, is that of the German government. The German National Organisation for Hydrogen and Fuel Cell Technology (NOW) programme is wholly government-owned, but encourages partnership with industry via co-financing of fuel-cell related projects. It has €1.4 billion in total budget for the period 2007-16. Half of this comes from the Federal Ministry of Economics and Technology, and the Federal Ministry of Transport, Building and Urban Affairs; and half comes from industry.

Regional support for hydrogen and fuel cells also exists. For example, the Flemish government funds R&D via the IWT-Vlaanderen and the FWO-Vlaanderen. These channel

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[30] The technology platforms are formalised into six European Industrial Initiatives (EII) and one Joint Technology Initiative (JTI).

public R&D funds to both industries and universities. The regional support takes a bottom-up approach, although some participation in larger programmes also takes place.

Support programmes in Europe to encourage innovation entail either direct financial support or consortia-arranged financial support approach. Other types of public instruments have been employed elsewhere, for encouraging innovation and R&D. For example, the Japanese Top Runner Programme sets energy-efficiency standards on a periodic basis and does not incur a large public cost. It selects a 'top-runner' standard which companies must meet. This is not yet in place for new technologies such as hydrogen and fuel cells but may be an interesting policy consideration for the future (Box 9).

BOX 9: JAPAN TOP RUNNER PROGRAMME

The Top Runner Programme is aimed at increasing energy efficiency via the establishment of standards. The programme is iterative, and covers a wide variety of products, including gasoline, diesel, and LPG passenger vehicles. Regulators iteratively test the available products in the market for use-phase energy efficiency, and set as the new standard the energy-efficiency of the 'top-runner' product. Energy-efficiency standards also take technical potential into consideration and compliance is evaluated by the corporate average.

The programme itself goes through multiple revisions, addressing the scope of covered products (eg phase-out of cathode-ray tube television sets). It avoids the implications of its stringent standards on trade as most products covered are largely supplied by the internal market. Standards and target dates are set collaboratively with industry. The programme does not stipulate the 'how' and regulators take no official action until the target years are reached. The programme is strictly supplier-oriented – relating to technical performance and not aggregate energy impact.

In the transport sector, the Top Runner Programme relates to fuel-efficiency (similar to the US CAFE programme or the EU vehicle fleet emission standards). Ideal fuel efficiency has been improved due to the fuel efficiency improvement of new cars. Real running fuel efficiency has also been improved since the introduction of Top Runner. There was a 22.8 percent improvement in fuel efficiency for gasoline passenger vehicles from 1995-2005, and a 21.7 percent improvement in diesel freight vehicle fuel efficiency.

Evaluation (Nordqvist, 2006):

- Few revisions have been carried out and, as such, there is a lack of quantitative data. There is little information regarding the energy impact of this programme, or the cost, due to the lack of data. Costs of the programme may have been passed by manufacturers onto consumers, although consumers may be expected to recoup the costs through savings in energy. Its cost to public funds is low.
- There is a danger (due to evidenced over-compliance) that standards set may already be achievable with products not on the market. Therefore, this policy may not actually be spurring technological innovations. In addition, care needs to be taken in defining product categories such that the standards do not stifle competition.

Policy implications:

- Adoption in Europe would require alterations to the Japanese Top Runner Programme: to account for imports, sanctions, different national standards already in place, and parallel policies.
- Historically, there has been a close cooperation between Japanese government and industry, and this may not be true in Europe.
- The advantage of this type of policy is that it is not technology-specific and adopts a collaborative approach to motivate technological advancement.
- The potential pitfall of the collaborative approach and the use of benchmarking may be a lack of incentive to set high enough benchmarks or a lack of incentive to be the top-runner (eg when the market is small, it may be easier for a firm to wait before releasing technology to the market which meets a new standard).
- Consumer awareness may play a role as energy efficiency rankings and information are provided to customers.

Public support gap

The EU and its member states have an established system of supporting research and development. It has, however, been argued that the EU has missed its Lisbon strategy target for R&D investments relative to GDP. In particular, as demonstrated in Table 10, it lags behind the US and Japan in terms of green innovation (Veugelers, 2011).

Table 10: Green innovation

	Size	Specialisation	Concentration
	Share of country in world clean- energy tech patents	RTA in clean-energy tech patents	Herfindahl across clean-energy tech technologies
Top six			
Japan	0.297	0.99	0.72
US	0.159	0.87	0.33
Germany	0.152	1.05	0.28
Korea	0.056	1.21	0.82
France	0.039	0.7	0.26
UK	0.036	0.98	0.28
EU	0.32	1.01	0.25
BRICs			
China	0.009	1.11	0.36
India	0.003	1.44	0.45
Russia	0.002	1.11	0.27
Brazil	0.002	1.51	0.41

Source: Veugelers (2011)[31].

Thus, more incentives for innovation and more targeted incentives for 'green' innovation are essential.

How can the current technology choice methodology be improved?

Although the current method for determining technology choice is iterative, consensus-building, and focused on the long-term, support is fragmented between technologies. There is no consensus-building amongst regions, member states and the EU. International coordination is also currently lacking. As the process is fragmented and decentralised, there is currently no overall portfolio or technology view. Additionally, support for individual technologies is determined largely on

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31. Source: Bruegel based on UNEP/EPO/ICTSD (2010). Note: Patents are counted on the basis of claimed priorities (patent applications filed in other countries based on the first filed patent for a particular invention). A Top 6 country has at least two percent of world clean-energy technology patents; together the Top 6 represent 74 percent of world clean-energy technology patents. RTA = share of the country in world clean-energy technology patents relative to the share of the country in total world patents; RTA > 1 measures specialisation in clean-energy technology patents; Herfindahl is the weighted sum of the share of each clean-energy technology in total country's clean-energy technology patents, with the weights being the share. The Herfindahl ratio varies between 0 (maximal dispersion) and 1 (perfect concentration).

performance promises by industry and advice from industry-experts. The incentives for industry to provide over-optimistic information are great as, by providing over-optimistic projections, industry may obtain additional funds and delay losses on their investments. Although JTIs are important for avoiding oscillations in enthusiasm for different technologies (fads), they may also create some institutional inertia[32]. Although initiatives and packages are subject to mid-term reviews, these are performed by industry experts. Expert industry-specific knowledge is required for proper assessment of technology progress, but experts may also be biased toward technologies in their field. For example, scientists working with nuclear may generally be in favour of nuclear.

Most importantly, there is not enough transparency as regards to the technology-choice mechanism. The European Commission has published a transport white paper as a roadmap to a single European transportation area. Although it includes modelling of different scenarios, it does not include a transparent technological choice methodology. A fuel-specific strategy document, the Future Transport Fuels Report, was published with a comprehensive alternative fuel strategy. This report contains the current state of affairs, and potential, for the different alternative fuels, and outlines an alternative fuel strategy. A similar report on infrastructure build-up is due out in 2012. These reports address EU policy and clean transport system strategies and goals but a more transparent methodology for choosing the portfolio is still missing.

2.3.3 Infrastructure externality

A major obstacle for the deployment of vehicles propelled by alternative fuels is the absence of a corresponding refuelling/recharging infrastructure. For example, final consumers will only accept FCEVs if a sufficiently dense network of hydrogen fuelling stations exists. The value proposition of FCEVs (as compared to battery electric vehicles) is to replace conventional cars in terms of range implies that all European destinations within reach of a fossil fuelled car should essentially be accessible by FCEVs as well. Thus hydrogen fuel stations will at some point have to cover the entire European market. Figure 12 summarises the number of existing hydrogen refuelling stations, in European countries. This provides clear evidence that refuelling infrastructure in Europe is developing at very different speed.

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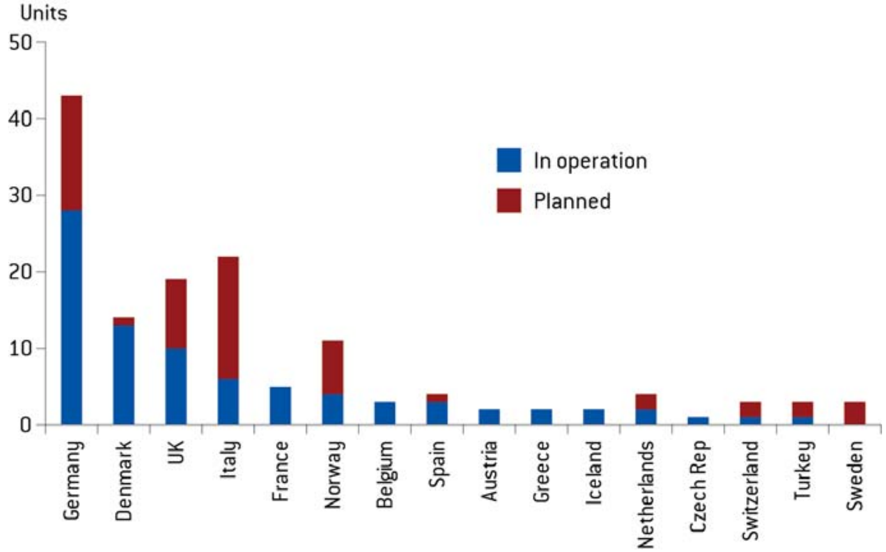
[32] See section 1.2.3 for further information regarding institutional path dependency.

Figure 12: Number of refuelling stations in EU-27 plus Switzerland, Norway and Turkey



Source: http://www.h2stations.org/

As the deployment of hydrogen fuelling stations is not yet commercial due to the absence of FCEVs, the majority of existing stations is based on bottom-up initiatives from different demonstration projects. Those are concentrated in particular countries, regions or even cities. There are four primary approaches observed in Europe for solving the problem of FCEV refuelling infrastructure deployment.

1. **Defining the need:** the HyWays project concentrated on analysing the problem of optimal roll-out of hydrogen fuelling stations in metropolitan areas based on census and traffic density data. The results indicate that 13,000-20,000 refuelling stations would be required in Europe by 2025 to supply up to 10 million vehicles (NextHyLights, 2010).

2. **National coordination:** H2 Mobility (Germany) provides good example of a national coordination programme involving industry and the public sector. The programme was initiated by Daimler and Linde, assembling a group of companies for addressing the infrastructure issue in terms of developing unified fuel station standards, costs and risks sharing between private and public sectors and appropriate policy support instruments.

3. **Cross-border coordination:** the Scandinavian Hydrogen Highway Partnership initiative constitutes a transnational networking platform that catalyses and coordinates collaboration between three national networking bodies – HyNor (Norway), Hydrogen Link (Denmark), and Hydrogen Sweden (Sweden) – and based on regional clusters that involve major and small industries, research institutions, and local/regional authorities.

4. **Large-scale demonstration projects in pilot regions (cities):** currently Germany has shown the strongest progress in unfolding large scale demonstration projects. The 'Clean Energy Partnership' is the largest hydrogen demonstration project in Europe. Moreover, through the National Hydrogen and Fuel Cell Technology Innovation Programme (NIP) Germany has developed the most ambitious FCEV programme with a total budget of €1.4 billion, even surpassing the European programme for that purpose.

Infrastructure initiatives in the US and Japan may serve to inform the European model. The US model is noteworthy for its scheme driving the supply-side investment in and development of Zero Emission Vehicles (Box 10). Additionally, the example of the Japanese demonstration programme provides possible methods to encourage greater involvement of industry in the demonstration and testing phases (Box 11). Germany has already coordinated with the Japanese FCEV programmes in order to share experiences. However, further international coordination in infrastructure development and standardisation should be undertaken (for example, at the EU level).

BOX 10: CALIFORNIA CLEAN CARS CAMPAIGN

The California Clean Cars Campaign promotes low-emissions vehicles through the Zero Emission Vehicle (ZEV) programme and the Clean Fuels Outlet (CFO) regulation. Both were established in 1990.

The Zero Emission Vehicle standard applies to passenger cars, light-duty trucks, and medium-duty vehicles which produce zero exhaust emissions of a criteria pollutant. The ZEV regulation requires that a manufacturer maintain a certain percentage of ZEV certified vehicles in the vehicles delivered for sale in California. For 2012-14 this is 12 percent and 15 percent for 2015-17 Zero and Partial Zero Emission Vehicles. The pure ZEV requirements were 2.5 percent for 2009-11, 3 percent for 2012-14, and 4 percent for 2015-17. Only large-volume manufacturers are subject to the ZEV requirements, while intermediate-volume manufacturers can meet requirements with PZEV (ICCT Review, March 2011; and ZEV Regulation as of December, 2009). This regulation has contributed to the over 750,000 Californians driving partial zero-emission vehicles.

The Clean Fuels Outlet regulation exists to help ensure that there would be sufficient infrastructure for the refuelling of zero emission vehicles. It is seen as a backstop in case other approaches fail to result in sufficient infrastructure. It is currently triggered at 20,000 vehicles of a particular type of clean fuel in California. Noncompliance results in fines – if owners of outlets fail to equip the required number, they are fined $500/car for the first 10 cars fuelled with gasoline each day of the violation; if the owners fail to provide clean fuels at a specific outlet, or fails to meet supply and amenity requirements, the fine is $500/car for the first 5 cars fuelled with gasoline daily. Currently, this legislation is applicable to all alternative fuels certified to Low Emission Vehicle Standard. There is discussion about limiting to ZEV fuels only and to focus on GHG reductions.

Evaluation (ICCT Review, March 2011; and NDRC Report, May 2010):

- Currently there are discussions around (i) moving from the zero emission vehicle standard to a fleet average GHG requirement (like the federal or the European approach) and (ii) taking into account and standardising the upstream GHG emission calculations.

- Reliable estimates of the implicit economic cost of the CFO and the ZEV are not available.

Policy implications:

- The Zero Emission Vehicle programme provides a framework for ensuring a minimum number of zero emission vehicles.

- The Clean Fuel Outlet programme is a regulatory approach to solve the infrastructure externality in a technology neutral way. A final evaluation of this programme would require to understand (i) whether the trigger value for the number of cars prevents a solution to the chicken-and-egg problem and (ii) what the economic cost of this programme are.

BOX 11: JAPANESE HYDROGEN AND FUEL CELL DEMONSTRATION PROJECT (JHFC)

The JHFC includes two projects: the 'Fuel Cell Vehicle Demonstration Study' and the 'Hydrogen Infrastructures Demonstration Study'. This research was subsidised by the Ministry of Economy, Trade and Industry. The project had a larger budget than the US Freedom Car programmes and the US Hydrogen Fuel Initiative combined.

Fleet testing was conducted by third-parties – including Mercedes-Benz Japan, Nissan, Honda and Toyota. Demonstration data were used by the Japanese Hydrogen and Fuel Cell Demonstration Project to conduct environmental impact studies. Furthermore the project analysed technology and policy trends, and developed public relations and education strategies.

Comparison with other demonstration projects:

- The JHFC is the first national project to obtain driving data systematically via demonstration testing;
- CaFCP was the world's first driving test on public roads for data and promote public awareness;
- The Japanese project had the largest budget per year, followed closely by Europe and then the US. However, the test budget and vehicle subsidies were less than the US, greater than Europe. Data collection was largest in the US but limited in both Japan and Europe;
- JHFC saw the largest participation of global automakers and Japanese infrastructure companies. In the US it was mostly US automakers and no Japanese automakers. In Europe it was mostly European automakers and this had the fewest participants. Several key energy companies also participated in JHFC and helped to promote communication between automakers and energy companies.

Lessons learned:

- Perhaps a consortium approach is useful – JHFC was able to involve many global players. The transition will need to be a global one to increase profitability.
- The number of fuelling stations and registered FCEVs in Japan is comparable to the US and Europe. As Japan as a region covers a smaller geographic area, their

demonstration projects may have brought them closer to 'implementation'.

- IJHFC asserts that predictable government policies supporting technology R&D are needed to enable technical development of the FC related industries (Source: JHFC Demo Project Brochure).

Public support gap

Currently, the national and European initiatives for early-market deployment of hydrogen fuelling stations are not coordinated in terms of timeframe, stakeholders, areas to be covered, standards, and roll-out plan. EU level (HyWays), regional (Scandinavian Hydrogen Highway Partnership) and member state initiatives (eg Germany, Denmark) are too small in scope to give clear signals for a regional, let alone European, infrastructure expansion. The idiosyncratic projects lack a general framework. Thus, a comparative evaluation is not possible.

2.3.4 Other market failures addressed by current policies

Other externalities introduced in the first chapter are also partially addressed by current public policies. These include pollution and noise, import dependency, the coordination externality, business exploration externality, industrial policy externality, and the insurance externality. Policies currently in place typically do not target these externalities separately. Therefore, we address these jointly in this section.

The SET plan partially addresses the coordination externality with its creation of Joint Technology Initiatives. The Fuel Cell and Hydrogen Joint Undertaking facilitates coordination between industry, government, and academia. The inter-industry nature of fuel cell electric vehicles, involving car manufacturers, the chemical industry, utilities and electricity production, and the information technology industry, further highlights the requirement for coordination among the different players. One aspect of this policy area is the development of technical and safety standards. Here, binding and transparent guidelines are required to alleviate concerns amongst consumers regarding the safety of FCEVs in everyday use. Currently, there is no mechanism for facilitating the coordination of EU-level standards, let alone international ones. One exception is the labelling directive of the EU, which helps companies to coordinate on information standards important for creating consumer acceptance.

Institutional lock-in occurs due to institutions (both academic, governmental, and industry associations) created for a specific technology. Educational institutional lock-in is especially pertinent to a transport and energy system transition. A transition through the increased use of low-emission vehicles is likely to be accompanied by a change in demand for relevant skills along the value chain. Accordingly, the National Platform for Electric Mobility, a stakeholder network set up in Germany to consult the electric mobility policy process, set up a working-group to coordinate corresponding efforts.

Super-credits, granted by (EC) No 443/2009, encourage business-exploration into the low-emissions vehicle market[33]. Combined with the emissions targets regulations (also stipulated by (EC) No 443/2009), these legislative measures encourage businesses to explore green transport technology markets such as hydrogen FCEV. Public procurement initiatives both at the EU level (Clean Vehicles Directive 2009/33/EC), and at the member state level, such as procurement initiatives in France, also help to encourage business exploration and innovation by creating a demand for low-carbon technologies.

The insurance externality is partly addressed by funding basic research in all types of energy technologies. A specific effort to create a portfolio of back-stop technologies is, however, not observable.

Some zero-carbon technologies, such as hydrogen FCEV, emit no harmful air pollutants (such as nitrogen oxides, volatile organic compounds, ozone particles and sulphur oxides), and less noise. Thus, they already comply with the strictest European emission standards that will enter into force in 2013-15 (the so-called Euro VI standards). In addition, various regional laws have targeted pollution directly. For example, German environmental zoning legislation in some cities prohibits certain types of cars from entering areas of the city. The aim of this legislation is to improve air quality. In many countries, speed limits have been put in place partially to combat noise pollution. Although these regional policies exist, they are fragmented and not economically-minded.

In contrast to renewable energy technologies, the deployment of FCEVs is currently neither mandated nor directly supported (apart of the mentioned super credits). At the EU level, the Clean Vehicles Directive (2009/33/EC) requires that public procure-

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[33] Vehicles with CO2 emissions below 50 g/km receive super-credits. Each such vehicle is counted as 3.5 cars in 2012 and 2013, as 2.5 cars in 2014, 1.5 cars in 2015, and as 1 car from 2016. That is, super-credits allow car manufacturers to maintain more carbon-intensive vehicle fleets than stipulated by the vehicle emission standard, if they deploy some low-emission vehicles.

ment take into account pollutants in addition to CO2 emissions. National vehicle taxation schemes and national consumer subsidies in France also encourage cleaner vehicles. These policies support development of green technologies such as hydrogen FCEV. Consequently, the creation of positive industrial policy spillovers and the internalisation of the business exploration externality are at the moment only backed by the discussed horizontal schemes.

Additionally, some alternative transport technologies are able to meet or exceed fuel efficiency standards. Hydrogen FCEVs have been found in a 2007 pilot to have 53-58 percent net fuel efficiency (NREL, 2007). This provides additional benefits – in addition to the reduction in CO2, less fuel will need to be produced and consumed. Thus, FCEVs decrease the fuel import dependency for the EU area. This side-benefit is partly remunerated through the exemption from fuel taxation and incentivised by vehicle fleet emission standards.

Public support gap

Although there are currently public policy instruments in place which encourage investment into low-carbon technologies, they are insufficient for addressing the larger needs of a transport energy transition.

The coordination externality is heightened by a highly fragmented European domestic market. There is currently no process for determining a pan-European industrial policy with regards to low-carbon technologies. The issue of the creation of a green internal market has been raised but Europe is far from achieving an unbroken domestic market for low-carbon and green technologies. Another issue is that domestic deployment of new energy and transport technologies brings with it significant risk in terms of near-term distortion of labour and capital markets. Any pan-European industrial policy should take these risks into account. There is currently no public instrument to evaluate and address these near-term labour and capital markets risks.

Infrastructure initiatives are fragmented across countries, with individual countries prioritising electric charging, natural gas outlets, biofuels or hydrogen. Infrastructure development for the energy transition requires a concerted effort and a careful consideration of technology choices and compatibility. The future of European transport depends on an infrastructure which allows for a large domestic European market and ease of travel, to establish competitiveness for whatever technology is chosen. Infrastructure is the backbone of any transport technology transition and, as such, should be uniformly decided upon via consensus-building. Despite Europe's lead in some green technologies, such as Germany's strength in FCEV, there is a risk of a 'leaders without followers' phenomenon without a cohesive policy. Europe may lose its competitive edge without the development of a strong domestic market. Any energy transition must also take international competitiveness into consideration.

Industrial policy support for new technologies must be carefully chosen due to the risky nature of investment into nascent markets and technologies. Currently, support for various clean energy technologies is fragmented and highly politically driven.

Current green technology investments and support may not be enough to ensure viable alternative technologies to address the insurance externality. There is currently no holistic mechanism to assess this gap.

Policy gaps exist in mechanisms to overcome path dependencies on institutions and technology that have developed for the current transport technologies. Policies must be implemented to address institutional lock-in and prevent future institutional lock-in for the chosen technologies. Network effects on the consumer side must be compensated for or addressed in order to develop sufficient demand and encourage business exploration into new markets. First-mover disadvantages of business exploration may also be examined as these are not directly addressed by current policies.

3 Policy response

The purpose of this chapter is to develop precise recommendations for policymakers, for supporting the development and possible deployment of new technologies in the transport and energy sectors in Europe in the long term, in the context of the EU's 2050 energy and climate goals. These recommendations aim to address the gaps in existing support policies, which have been identified in chapter 2.

3.1 Resolving the climate externality

A price on carbon is the first-best solution for resolving the climate externality. To ensure economic efficiency, the carbon price needs to be aligned across sectors, over time and across regions:

1. **Marginal abatement costs have to be aligned across sectors** to minimise welfare losses, ie emissions should be reduced in those sectors in which it is cheapest to do so;

2. **The price signal must have a long-term component**, ie it should signal that pollution rights will be scarce beyond 2020 in order to encourage low-carbon investment;

3. **The price signal has to account for international spill-overs**, eg there should be incentives for investments in low-carbon technologies that help to reduce emissions outside Europe.

Current carbon pricing applications fail when measured against these criteria. Europe's emissions trading system is unilateral (only EU), short-term (EU legislation beyond 2020 is subject to revision) and partial (only some sectors are covered in the EU). In the absence of a universal and long-term price on carbon, complementary instruments are needed to increase economic efficiency. In the following we propose three complementary policies to improve efficiency.

3.1.1 Inclusion of road transport in the ETS

A cap-and-trade system such as the ETS is designed to put a coherent and credible price on carbon. ETS participants are required to surrender an emission allowance for each emitted unit of CO2. Currently only about half of the EU's carbon emissions are covered by the ETS[34]. Including road transport in the ETS, so that the price on emission permits reflects the marginal cost of emissions, could influence the day-to-day driving behaviour of final consumers and freight operators, and shape their vehicle purchase decisions.

In the absence of a price on carbon for fossil fuels, day-to-day driving behaviour might be marked by a rebound effect. A rebound effect is often observed when more efficient technologies are introduced. Consumers start to use the technology more because the efficiency improvement leads to lower variable cost (price effect), and consumers have more income available to purchase the service (income effect). Thus, if a car becomes more efficient, it also becomes cheaper to use and consequently people might drive more. The rebound effect is the behavioural response to the cost reduction of an energy service. The rebound effect for the transport sector can be addressed by increasing the price of fossil fuels. Furthermore, Popp (2002) and Aghion *et al* (2011) find that higher prices for conventional fuels drive the rate of energy-efficiency innovation. Thus, internalising the climate externality in the cost of fossil fuels can stimulate innovation.

An arbitrary price on carbon is, however, not efficient. The proposed carbon component in the fuel tax[35]is insufficient to ensure efficient, economy-wide greenhouse gas mitigation. Only a broad scheme providing a single carbon price across sectors would ensure cost-optimal abatement. Including transport in the ETS could achieve this. Implementation could take the form of obliging fuel outlets to buy emission allowances for the fuel they sell. This would result in the harmonisation of the carbon price across sectors and incentivise the use of the cheapest available abatement options. This is important because, if a carbon tax were to be implemented for road transport, and was different from marginal abatement costs in others ETS sectors, efficiency would be compromised because transport fuels produced in different sectors would have different abatement costs. For example, the electricity used in electric vehicles (or for electrolysis to produce hydrogen) is covered by the ETS, while gasoline is not. Furthermore, inclusion of transport in the ETS would increase the depth of the carbon market and make the system more resilient.

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[34] The ETS covers power generation and heavy industrial plants, and, from 1 January 2012, airlines flying into, out of, and within the EU.

[35] Commission proposal of 13 April 2011 for amending Directive 2003/96/EC.

Consequently, including the transport sector in a general carbon trading system is a necessary (but not a sufficient) condition to efficiently address the climate externality.

3.1.2 Financial instruments to lock-in a long-term carbon price

The framework underpinning a long-term carbon price should be credible in order to support the large investments needed. Currently, the EU emission cap for 2020, the sectoral coverage, the institutional setting beyond 2020 and other key elements of the ETS are subject to change. Thus, the ETS lacks credibility and fails to provide clear long-term investment signals[36].

As it might be politically and institutionally impossible to lock-in a credible long-term commitment to a tight emissions trading system in the absence of an international agreement, second-best options for creating investment certainty should be considered. A carbon floor price might seem attractive to today's low-carbon investors. However a general floor price is a rather inflexible tool. In case future carbon reduction potential turns out to be much cheaper than anticipated (eg because of new technologies or lower economic growth) a high floor price could result in carbon reductions becoming needlessly expensive. In addition, a politically set floor is subject to change and hence not credible in the long term.

A more targeted alternative could be bilateral option contracts between public institutions and investors. The public institutions would guarantee a certain carbon price to an investor[37]. In case the realised carbon price is below the guaranteed price, the public institution (the option writer) will pay the difference to the investor (the option holder)[38]. Hence, in case of a low carbon price that might be detrimental to the competitiveness of a low-carbon investment the investor gets some compensation. Thus, the investor's risk is reduced. At the same time, if the public institution issues a large volume of option contracts, it creates an incentive not to water down future climate policies. Policies that reduce the carbon price will have a direct budget impact by increasing the value of the outstanding options. This would tend to increase the long-term credibility of carbon policies.

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[36] The low emission allowance prices in 2011 are a telling example of the lack of confidence of investors in the current legislation. If market participants were confident in the stipulated tightening emission cap beyond 2020 and the crisis-induced short-term oversupply of storable allowances would not lead to dramatically deflating prices.

[37] Such contracts have been proposed (Ismer and Neuhoff, 2007) as instruments for promoting investment in low-carbon technologies.

[38] Menus of option contracts with different characteristics (strike price, option type, maturity) might be offered to investors.

Such instruments could be provided by a green investment bank – as described in section 3.4. For example, long-term loans to green investment projects would not be repayable unless the carbon price rises above a certain level. Consequently, the political risk is transferred back from the company to the public sector, which is at the origin of this risk.

Financial instruments that transfer the risks of future climate policy from the private sector back to the public sector are welfare enhancing.

3.1.3 Schemes to drive supply-side investment

In the absence of a global carbon price, companies will under-invest in low-carbon technologies because consumers outside Europe will be unwilling to pay a mark-up for low-carbon products. Consequently, incentives should be established for companies to invest more in green technologies. The legislation on vehicle fleet emission standards (see chapter 2) that requires car producers to ensure that their cars sold in Europe have average CO2 emissions per kilometre below a certain threshold is an example of an effective approach. Predictably, imposing stricter thresholds gives producers an incentive to invest in clean alternative technologies. For many consumers, reasonable vehicle emission standards will come at no additional cost, as the higher purchase price of vehicles is largely compensated for by fuel savings associated with emission reductions. It has been argued that markets alone might not be sufficient to incentivise consumers to pay a premium for low-consumption vehicles, the higher costs of which are recovered through later fuel savings. Consumers do not properly account for future fuel savings when buying vehicles, in particular because buyers of new cars that shape the future car fleet are typically less price sensitive than buyers on the secondary market that eventually end up driving most of these cars[39].

International experience shows that setting environmental standards in large markets has positive spill-overs on the vehicles offered in markets that are not directly covered by the standard. For example, the emissions standards for conventional pollutants set by the California Air Resources Board have become quasi-standards for most internationally sold models. Correspondingly, ambitious European vehicle-fleet standards for greenhouse gas emissions are likely to induce other regulators to follow. In order to comply with domestic and European emission standards, non-European car producers will invest in low-carbon technologies.

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[39] Some consumers, essentially those characterised by a low annual mileage, will however pay a premium that they will be unable to recover through fuel savings.

Reducing the cost of low-carbon vehicles, and regulatory convergence, will stimulate the uptake of low-carbon vehicles outside the European market and result in global emission reductions.

3.2 Resolving the infrastructure externality

Chapter 1 showed that the market will not provide the optimal level of infrastructure deployment, while chapter 2 demonstrated that a lack of infrastructure will hamper the deployment of new technologies. Consequently, establishing proper incentives for early investment in infrastructure is crucial.

3.2.1 Option 1: public funding

In the phase after their installation, most stations for newly introduced low-carbon fuels (such as hydrogen, exchangeable batteries, biofuels, natural gas) will see limited use. Due to the initial low load, most stations might only be able to cover their variable costs in the first decade. Without a clear prospect of recovery of their fixed costs, private companies would refrain from installing new fuelling stations. Public funding could compensate for the initial investment cost. A sufficient network of hydrogen fuelling stations would, for example, involve about 1000 new fuel stations in Germany alone, according to industry experts. At a unit-cost of €1 million[40], this would add up to an investment of €1 billion in Germany.

One could envisage different approaches for sourcing/channelling this money. It might be a direct subsidy. Alternatively, it could be organised by placing obligations on existing suppliers to provide clean fuels (eg the German implementation of the EU biofuels directive[41]) or by implicit cross-subsidies from fossil-fuel consumers (such as German feed-in tariffs for electricity generated from renewable sources).

Whatever the funding approach, three issues would arise:

First, due to the initial low density of fuel stations, there would be a lack of (local) competition. Consequently, each fuel station would have an interest in exercising

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[40] According to the NextHyLights (2010) study, the investment cost of 'Small fuelling stations (100 kg/day)' is €570,000, of 'Medium size fuelling station (300 kg/day)' is €670,000 and of 'Large fuelling stations (1,000 kg/day)' is €1,930,000.

[41] Directive 2003/30/EC on the promotion of the use of biofuels and other renewable fuels for transport stipulated that by 2010 5.75 percent of transport fossil fuels should be replaced with biofuels. Germany, for example, implemented the directive by obliging all fuel outlets to comply with this (tradable) quota (Biokraftstoffquotengesetz, 2007).

market power by setting fuel prices significantly above their marginal costs. This could lead to high fuel prices and consequently low penetration of FCEVs[42]. Thus, the state would need to regulate prices in order to ensure the optimal uptake of the new technology. This is challenging in such a new market. Due to the different load factors of the fuel stations, the variable cost per unit of fuel (eg labour cost) would vary significantly. Thus, the optimal fuel price is different at each location, which makes regulation difficult. That is, even if the state supports the deployment of new fuel stations it could then not simply let competition work to determine the optimal prices.

Second, there are a number of individual transport technologies claiming that infrastructure is the missing ingredient preventing them becoming a competitive solution to the clean-transport challenge. Compressed natural gas, liquefied natural gas, electricity, battery switching, hydrogen and others are competing for infrastructure roll-out support. Funding for refuelling infrastructure for all of these technologies is unlikely because of the high cost and because only some of the technologies will ultimately prove successful.

Third, in the current environment of the economic and financial crisis, direct financial commitments that risk leading to visible failures (unused fuel stations) might be very unpopular.

Consequently, direct subsidies, or indirect finance through higher fossil fuel prices, for fuelling stations for a certain technology will be very difficult to implement politically.

3.2.2 Option 2: establishment of a temporary infrastructure consortium

Individual private actors have an incentive to provide too little new infrastructure, too late and at a too high price, thus delaying the implementation of new technologies. One way to overcome this is to increase private incentives to invest by reducing temporarily the threat of competition for early investors. As argued in the first chapter, most past infrastructure development has benefited from the presence of a natural or artificial monopoly. Even today, the European Commission can exempt new electricity and gas interconnectors from requirements to open them to third parties on a case-by-case basis. Such exemptions allow the investor to use infrastructure exclusively for a

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[42] One alternative to regulation would be to grant subsidies to any hydrogen fuel station investment. Then, competition would bring hydrogen retail prices close to the variable cost. This would, however, lead to an expensive duplication of investments.

limited period of time. They are provided if the Commission finds that a corresponding installation would not have been built without this exemption and the provision is pro-competitive in the long term.

Because the individual investments are significantly lower, refuelling stations only enjoy natural monopoly conditions in small local markets. As the market grows, the fuel stations lose their monopoly status because new players enter the local market (possibly at lower cost) often before the incumbent can recover its initial fixed cost. To avoid this, the optimal strategy for individual fuelling stations would be to start with high hydrogen prices in order to quickly recover their fixed costs[43]. If all fuel stations act in this way, the price of hydrogen will be high and the technology will not proliferate.

Thus, we suggest creating a temporary consortium that develops a roll-out strategy for refuelling stations. All new refuelling stations and their fuel price would be approved by this consortium. In addition, it might be agreed that car manufacturers and/or hydrogen producers have to pay a premium into the consortium for each car/kg of hydrogen they sell in the country.

The consortium could be a public-private entity bringing together representatives from the government, the car industry, the hydrogen industry, the fuel retail sector and the drivers' association. This would ensure that industry and consumers take ownership of the project. Based on its roll-out strategy, the consortium might auction off specific geographical locations in order to ensure full coverage of the country. The multiple bids of the fuel retail companies for each slot might consist of a fuel price (formula), a lump sum and the duration of exclusivity. The lump sum might be either positive or negative. 'Sweet spots' at highways or in agglomerations might call for a premium payment for the right to establish (positive lump sum). For remote areas with low potential load, monetary incentives might be required (negative lump sum). This money could be collected from auctions of 'sweet spots' as well as from vertical arrangements with car manufacturers and hydrogen producers that have an interest in the development of the infrastructure[44]. This self-regulated, vertically integrated consortium should be able to work without additional public support and its exemption from competition should automatically end (after 10 years for example).

The consortium's institutional structure and the inclusion of the public sector and

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[43] Initially, competitors would refrain from entering this location, as the incumbent credibly threatens to reduce prices in case of entrance. This deters newcomers that would not be able to recover their fixed costs.

[44] Alternatively, a standard contract could be proposed and the company that accepts more potentially unprofitable slots gets access to more potentially profitable slots.

consumer representatives should ensure that it is not misused for establishing collusion within the fuel-retail sector or any other adjacent sector (car manufacturers, hydrogen producers).

One important issue is time consistency. That is, it should be ensured that governments will not breach the agreement (exemption from competition, no administrative price regulation) after the irreversible investments have been made. In addition, the regulatory model for the period when the consortium finishes should be sketched out to enable consistent investment decisions. *Ex-ante* price or revenue regulation or *ex-post* price control are potential models that would require an in-depth analysis.

The cost (potential anti-competitive effects) and benefits (faster roll-out of the infrastructure) of such an entity need to be carefully balanced. A corresponding analysis that takes account of competitive effects at all stages of the value chain goes beyond the scope of this study. Only after a positive evaluation of the dynamic effects, might the European Commission's Directorate-General for Competition grant the necessary temporary exemption.

One recent example of such a consortium is the initiative for natural gas vehicles in Germany (see Box 12).

The establishment of a consortium for the deployment of refuelling infrastructure could effectively address the infrastructure externalities without direct public budget support. Competition policy concerns need to be addressed *ex ante* in order to ensure time-consistency.

3.3 Financial support

Providing public financial support is a common way of compensating private actors for the positive spill-overs their investment/consumption decisions create for others[45]. (Co-)funding industrial R&D and demonstration projects, for example, is supposed to enable commercially non-viable but socially beneficial private investments in new technologies to break even. However, simple across-the-board co-funding tends to be not very well focused (see Box 13 for some numerical illustrations of pro-quota co-funding schemes). Thus, more sophisticated measures for risk sharing (see next

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[45] In economic terms: internalising the positive externalities.

BOX 12: THE CASE OF COORDINATION: DEPLOYMENT OF NATURAL GAS VEHICLES AND REFUELLING STATIONS IN GERMANY

Use of natural gas and bio-methane in motor fuels has recently been stepped up in the EU as one of the ways of decarbonising the transport sector (natural gas has 24 percent lower carbon emissions than petrol and produces less other pollutants, such as soot and nitrogen dioxides). Currently, Germany has about 900 compressed natural gas refuelling stations and approximately 90,000 natural gas vehicles. But natural gas only makes up 0.3 percent of the fuel used for road transport. As most natural gas vehicles can switch between natural gas and gasoline they require no full coverage and thus significantly fewer refuelling stations than non-hybrid technologies.

The deployment of natural gas vehicles in Germany was partly driven by natural gas suppliers which continue to cross-subsidise the purchase of natural gas vehicles. In Berlin, for example, the local gas supplier grants a €333 cash subsidy to natural gas vehicle buyers. Other suppliers grant a number of free refills to new natural gas vehicles.

Germany is the kick-start market for natural gas vehicles. Car producers, refuelling infrastructure providers and natural gas suppliers agreed to coordinate their efforts in the 'Natural Gas Mobility Initiative', which is coordinated by Deutsche Energie-Agentur GmbH (DENA). The core task of the Initiative is to support and coordinate the deployment of refuelling infrastructure. The initiative updates the fuelling station planning based on which petroleum companies, natural gas companies and a jointly set-up company are expected to invest in new fuelling stations.

Take-home message: The deployment of natural gas vehicles in Europe is an interesting learning case for cross-subsidisation along the value chain and coordination of fuel station deployment for emerging technologies in the transport sector.

Source: DENA (2011).

BOX 13: NUMERICAL ILLUSTRATION OF A PRO-QUOTA CO-FINANCING SCHEME

To illustrate possible weaknesses in the public co-finance model, we present different scenarios with different realisations of the unknown benefits and cost which result in different social welfare impacts. We assume in each scenario that the *total cost* of each project is 100 but that public co-funding of 50 has been provided, such that the *private cost* of each project is 50. Different scenarios for *total benefit* (*private benefit* and *positive externality*) are assumed for each project.

For all Scenarios:
Cost: 100
Co-funding: 50

Scenario 1: windfall profits
Private benefit: 80
Positive externality: 30

Total benefit = private benefit + positive externality = 80 + 30 = 110
Private gains = private benefit – cost + co-funding = 80 – 100 + 50 = 30
Social welfare = total benefit – cost = 110 – 100 = 10

Here, we find that there are windfall profits and the project is socially beneficial.

Scenario 2: windfall profits and no additivity (investments would happen without public support)
Private benefit: 110
Positive externality: 10

Total benefit = private benefit + positive externality = 110 + 10 = 120
Private gains = private benefit – cost + co-funding = 110 – 100 + 50 = 60
Social welfare = total benefit – cost = 120 – 100 = 20

Here, we find that there are windfall profits and the project is socially beneficial but there is no additivity – ie private investment would have occurred without any co-financing due to the private benefit of 110 being greater than the cost.

Scenario 3: potential social benefits are not reaped

Private benefit: 49
Positive externality: 151

Total benefit = private benefit + positive externality = 49 + 151 = 200
Private gains = private benefit – cost + co-funding = 49 – 100 + 50 = -1
Social welfare = total benefit – cost = 200 – 100 = 100

Here, we find that the project does not occur, because, even with co-financing, the private gains would be negative. Investment does not occur. Insufficient co-financing leads to underinvestment and the potential social welfare surplus of 100 is lost.

Scenario 4: windfall profits

Private benefit: 60
Positive externality: 0

Total benefit = private benefit + positive externality = 60 + 0 = 60
Private gains = private benefit – cost + co-funding = 60 – 100 + 50 = 10
Social welfare = total benefit – cost = 60 – 100 = -40

Here, we find that a socially detrimental project is funded. This project is funded because public co-funding has made an unprofitable project profitable for the private firm, by reducing the cost of the project to the private firm. Therefore, an otherwise unprofitable project was undertaken at the cost of social welfare.

The different scenarios illustrate the many different outcomes that can occur with public co-financing. Due to imperfect and asymmetric information, it is suboptimal to adopt such a schema. Such a schema can result in either social benefits or social costs depending on uncertain parameters.

section) and co-funding have been introduced (see section 3.6 for an evaluation of the current co-funding schema).

One way to avoid overcompensation (scenario 1 and scenario 2 in Box 13) is to disburse public funds in the form of reimbursable grants (or non-reimbursable loans)[46]. Reimbursable grants allow mitigation of the technology and market risks for new technologies by providing reimbursable public funding to demonstration and early deployment of innovative technologies/products. In case market introduction is a success, these grants are wholly reimbursed (with interest) by the receiving company. In case of failure only a fixed amount needs to be refunded.

If properly structured, this scheme allows the risk a private actor cannot control to be shifted to the public sector. In this context it is important that the risks the private sector can control (eg the management of the project) are not shifted, as otherwise the private incentives to ensure success are biased.

Reimbursable grants are already used in some member states to stimulate research and innovation. This is for example the case with some French innovation agencies, whose methods of funding have been analysed by the European Commission[47] (see Box 14).

If properly designed, reimbursable grants can reduce the risk that private actors are overfunded.

3.4 Shifting risk

Low-carbon projects are currently often more risky than conventional projects for various reasons: (1) The cash-flow of many low-carbon projects is critically dependent on the hard-to-predict future carbon price. The carbon market is not yet well-established. There are no clear accounting rules for carbon credits and no good models for hedging corresponding risks. (2) Currently, low-carbon projects rely primarily on government intervention schemes (subsidies, feed-in tariffs, obligations, emissions allowance trading) which provide neither a stable nor a long-term price signal for investors. (3) Moreover, the payoffs of low-carbon projects are subject to various levels

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[46] An alternative disbursement method is discussed in section 3.6.3 where a menu of loans is used to extract quality and potential viability information from industry. This method can possibly be incorporated with the reimbursable-grants instrument if the information revelation component may somehow be preserved in the amalgamation.

[47] C(2008)279, Aide d'état n° N 408/2007 – France, *Régime d'intervention OSEO Innovation en faveur de la recherché, du développement et de l'innovation*.

BOX 14: FRENCH REIMBURSABLE GRANTS FOR INNOVATION SUPPORT

Reimbursable grants are attributed by the funding agency to a company or a consortium. The grant is characterised by (a) the ratio R between the reimbursable grant and the total cost of the project and by (b) the terms of the refunding procedure. The ratio R cannot exceed a maximum value that depends on the nature of funded projects (basic research, experimental development, industrial innovation, etc).

The refunding procedure is negotiated by the funding agency and by the grantee, based on the nature of the project, the inherent risk, the maturity of the technology and the market. The terms of the refunding procedure are commonly established by the funding agency and the grantee, based on a shared business plan and include:

1. The schedule of repayments, depending on the nature of the project, the inherent risk, the maturity of the technology and the market, etc.

2. A fixed amount that is systematically owed by the grantee to the funding agency, even in case of project/market failure. It is only if the company goes bankrupt that this amount is not reimbursed. This systematic reimbursement usually ranges from 10 percent to 50 percent of the total grant.

3. The amount of the effective reimbursement, taking into account technical and commercial success of the project:

    - In case of success (i.e. when the cumulated turnover generated by the project reaches a first threshold), the grants are reimbursed by the grantee. This includes a rate of interest that is greater than or equal to the applicable rate resulting from the application of EU rules relative to the calculation of reference and actualisation rates. This implies that, in case of success, the grant is totally recovered by the funding institution. Using an actualisation rate ensures that no financial advantage is granted to the company.

    - If the cumulative turnover generated by the project crosses a second threshold, profit can be shared between the funding agency and the grantee, in the form of a percentage of sales (with a limited duration and a maximum amount that is specified in the refunding procedure).

    - In case of partial success, the amount to be refunded is negotiated, taking into account the technical and commercial achievements of the project.

- In case of project/market failure, the grantee only refunds the fixed amount presented in point 2.

Scenario: simplified reimbursable grant
Cost: 100
Grant: 60
Positive externality: 100

Case 1: success (50 percent probability)
Private benefit in case of success: 150
Reimbursement in case of success: 60
Positive externality in case of success: 100

Total benefit = private benefit + positive externality = 150 + 100 = 250
Private gains = private benefit – cost + grant – reimbursement = 150 – 100 + 60 - 60= 50
Social welfare = total benefit – cost = 250 – 100 = 150

Case 2: failure (50 percent probability)
Private benefit in case of failure: 0
Reimbursement in case of failure: 5
Positive externality in case of failure: 0

Total benefit = private benefit + positive externality = 0
Private gains = private benefit – cost + grant – reimbursement = – 100 + 60 - 5= - 45
Social welfare = total benefit – cost = 0 – 100 = -100

Expected results
Expected private gains = 50%*50 + 50%*-45 = 2.5
Expected social welfare = 50%*150 + 50%*-100 = 25

Consequently, some of the project risk is shifted to the public sector. Thereby, the implementation of this instrument is critical to its effectiveness – ie the establishment of thresholds, adequate penalties for non-repayment, and profit accounting criteria.

of political, technical and regulatory uncertainty. Recent regulatory shifts in European renewables support schemes are telling examples of the political volatility of public support. For example, Spain and other countries cut their feed-in tariffs for existing and new solar installations because of the financial crisis. This resulted in a wave of bankruptcies of solar companies and a loss of confidence of investors in corresponding schemes throughout Europe. Regulatory downside risk is not matched by a corresponding regulatory upside. The reason is that regulatory changes are typically targeted at creating 'additionality' and thus only compensate for investments induced by the new regulation but ignore existing low-carbon projects. (4) Furthermore, the regulatory framework for new infrastructure assets (eg hydrogen fuelling stations) and new appliances (eg technical standards for FCEVs) remain unclear. These regulatory risks are further exacerbated by the often long-term and capital-intensive nature of low-carbon investments.

Political, technical, and regulatory uncertainty is a significant impediment to private finance. Uncertainty, in contrast to risk, cannot be properly quantified or managed. Consequently, the absence of a robust regulatory environment and a credible and sufficient carbon price signal translates into higher costs of capital for low-carbon projects. Private investors face a risk of stranded, or redundant, costs which are difficult to manage. This leads to the inability of low-carbon projects to attract long-term debt and equity finance, while public funding is insufficient to cover all the gaps in investment.

A potential solution to the financing issues faced by low-carbon projects is being explored by the UK. The UK Green Investment Bank (GIB) has been proposed as a publicly-driven intermediary structure. The core tasks of this institution would be to address the market failures faced by low-carbon projects, and to attract private investment by managing the inherent risks of low-carbon projects. The novel aspect of this proposal is a shift from the current public support policies of simply providing higher subsidies, to a public support system that reduces risks for private investments. The GIB will start its operations in 2012, with an initial capitalisation of £3 billion.

The UK GIB will help to reduce investment risk in three key ways. First, it will **pool and restructure currently dispersed government grants** for funding emerging low-carbon technologies. Second, it will be responsible for issuing **green bonds.** In the set-up phase, low-carbon projects are financed by equity. At the end of this phase, when the projects start to generate positive cash-flows, the GIB will buy up these low-carbon projects. This allows equity investors with an appetite for high-risk investments to sell their mature projects in order to generate funds for launching new low-carbon projects.

The GIB can later issue 'green bonds' to refinance its activities based on a wide portfolio of such cash-flow generating low-carbon projects, and possibly ensuring high ratings through additional state guarantees. That is, ultimately, the GIB allows institutional investors, with an appetite for low-risk investments, to finance low-carbon projects. Third, the GIB will **unlock project finance** through:

- Equity co-investments at the early stages of low-carbon projects.
- The purchase and securitisation of low-carbon project finance loans (or pooling of the loans provided by commercial banks for low-carbon projects). In this way, it can mitigate their risks and increase the lending for these kinds of projects.
- Long-term carbon-price underwriting or the provision of guarantees on a stable level of a long-term (or floor) price for investors.
- Providing the insurance products for mitigation of the inherent risks related to a non-sustainable regulatory framework and possible market failures (eg offering to buy completed renewables assets, extreme events insurance, contingent loans facilities).

Comparable instruments have also been implemented in other member states (see Box 15). They do not, however, share the unique institutional framing of the GIB. The main drawback of the GIB is its legally-limited borrowing power. The current legislation only permits the GIB to borrow until 2015-16, on the condition that public sector net debt will decline as a percentage of GDP[48].

Even though, it is too early to evaluate the success of the GIB, the idea for the establishment of a special financial institution that will be responsible for managing the special risks of low-carbon projects is well worth exploring. Such an institution might play a major role in attracting the long-term private capital needed for funding commercial low-carbon investments critical to the success of a post-carbon transition. Furthermore, **a public financial institution that is largely exposed to low-carbon investment projects, through its portfolio, could be an important signal to other market participants that the public sector is committed to its support policies**. This signal reduces the perceived risk of abrupt support-policy changes, and might make

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[48] Sources: *Unlocking investments to deliver Britain's low carbon future*, Report of the GIB Commission, (2010); 'Accelerating green infrastructure financing: outline proposals for UK green bonds and infrastructure bank', Climate Change Capital briefing note, March 2009; Helm *et al* (2009); http://www.businessandleadership.com/sustainability/item/29090-uk-green-bank-plan-doesnt

it easier to finance low-carbon projects through commercial banks. Thus, the establishment of public instruments that serve to create credibility and to lower investment risk for private actors, and not merely to subsidise, may prove essential to the success of a post-carbon transition.

BOX 15: EXAMPLES OF GREEN FINANCING SUPPORT SCHEMES

=> France: Subsidised Green Loans (*Prêts Verts Bonifiés*). These loans are intended to finance competitiveness investments that include environmental protection considerations or that promote the marketing of products relating to environmental protection and reducing energy consumption (OSEO, 2010).

=> Dutch Green Fiscal Fund: Dutch banks currently benefit from a government-led Green Fund initiative launched in 1995. By purchasing shares in a green fund, or investing money in a green bank, citizens are exempted from paying capital gains tax and receive a discount on income tax. Investors can therefore accept a lower interest rate on their investment, while banks can offer green loans at a lower cost to finance environmental projects. To date, Rabobank has established one of the more successful green funds; in 2005, its fund had acquired 63,000 investors and provided €2 billion in green loans.

=> Carbon Funds: Collaboration between multilateral development banks and private financial institutions has led to the emergence of a variety of carbon funds to help finance GHG emission reduction projects. Acting as a collective investment scheme, a carbon fund receives money from investors either to purchase CO2 emission reduction credits (including, but not limited to, Certified Emission Reduction credits or Emission Reduction Units) from existing emission reduction projects, or to invest in new projects that will generate a stream of CO2 emission reduction credits. Where government-led carbon funds offer a compliance tool for governments to meet their Kyoto objectives, private carbon funds offer regulated companies a cost-effective compliance instrument. They also provide traditional investors with the potential for cash returns, and marketing and corporate social responsibility opportunities.

=> UK Green Finance Deal (Carbon Trust/Siemens) £550m green financing initiative. The scheme offers a corporate version of the UK government's proposed Green Deal scheme[49], giving companies the opportunity to cover the cost of financing through the energy savings that result from improved efficiency.

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49. The Green Deal is the UK carbon emissions reduction project. The purpose of the Green Deal is to encourage as many people as possible to take measures to make their homes more energy efficient by providing upfront loans for such measures.

A European institution (such as the European Investment Bank) could be used to attract private capital for low-carbon projects by offering services comparable to those of the UK Green Investment Bank. Beyond making finance available for commercial low-carbon projects, this could also signal the commitment of the public sector to establish support instruments.

3.5 Public procurement mechanisms

Networked technologies such as transportation pose a fundamental public policy dilemma. The lack of a ubiquitous network may limit the utility of the new technology to consumers; and, as we have seen, reduce the home country's ability to capitalise abroad on its technological leadership. But choosing a network early on poses significant risks of lock-in, and invites rent-seeking on the part of industrial interests.

The public sector is one of the biggest customers for new vehicles. Furthermore, some branches of the public sector have very narrow utilisation profiles. Consequently, strategic public procurement to develop such niches could create a sustainable node for further development. Public policy may therefore wish to provide opportunities for small-to-medium scale trials of technological alternatives. These trials would generate experience in real-world operations, provide opportunities for learning-by-doing, and enable better choices about which network or networks to roll out.

Farrell *et al* (2003) and others have suggested that municipal transportation fleets – buses and government vehicles – provide a suitable environment for these trials. Municipal governments require transportation infrastructure, operate at significant scale for a single buyer, and potentially coordinate between operations and monitoring and evaluation. However, we note that relying on municipal governments alone poses several risks. First, no municipal government wishes to make large-scale and technologically risky investments. Like firms investing in innovation, municipal governments quite sensibly want to provide good services for their citizens first, and experimenting with innovation is only a distant second priority. Second, firms might be tempted to concentrate their lobbying and pilot project efforts on municipalities whose characteristics are best suited for a given technology. This would potentially skew the evaluation of the new technology and its potential for widespread deployment.

Instead, we propose that national governments or European institutions cooperate with municipalities to structure a coherent series of trials of new transportation technologies. Regional or national governments may have the capacity to support part of the financial cost of the trial, insulating municipal governments from the risk of failure. In exchange for backstopping all or some of the risk, however, national governments or European institutions should insist on a coherent approach to selecting the technologies that are deployed in different circumstances. In an ideal world, this could take the form of a randomised experiment. The theoretical difficulties of effectively structuring such an experiment for large infrastructure projects may forestall this option. But even if this proves impractical, the government assuming the risk should also insist on a neutral approach to selecting and deploying the technologies in question, and should design universal evaluation criteria.

Germany's E-energie programmes may provide an example of a well-structured project in a different industrial domain. The E-energie programmes provide six trial projects for another example of networked technologies, the smart grid. Like low-emissions transport technologies, the smart grid offers huge promise for efficiency improvements and emissions reduction, but massive technological risk. It also provides little utility without widespread deployment. By providing six different trial programmes, with different industrial consortia, the E-energie programme enables comparison of different approaches to the smart grid without commitment to a single network standard. A similar approach to alternative transport technologies may yield similar dividends.

Using public procurement to conduct real-world experiments could uncover valuable information. This requires that the responsible local, municipal or regional public authorities are able to accept failures in the trials they conduct. Consequently, federal or European compensation mechanisms might be necessary.

3.6 A consistent policy response

In the following we argue that a purely technology-neutral approach is not feasible for economic and political reasons (section 3.6.1). Hence, policymakers have to choose certain technologies and decide when and how to support them (3.6.2). But the current approach towards technology choice is not efficient (3.6.3). A more sound and predictable support mechanism is necessary (3.6.4). Combined with horizontal policies such technology specific support could form a consistent policy response (3.6.5).

3.6.1 Limits of technology neutrality

Some horizontal policies already exist, targeting for example the climate and innovation externality. Carbon pricing, patent legislation, taxes on fossil fuels, funding for basic research and education, and other horizontal measures are largely technology-neutral. The approaches proposed in this report, to compensate for inefficient or insufficient climate policies, are not technology-specific either. Furthermore, the suggested infrastructure consortium might likewise be applied to other emerging green technologies that require a dedicated infrastructure. However, the existing and proposed measures will not eliminate all externalities identified in this report.

Hence, governments have implemented menus of additional support mechanisms specifically targeted at certain green technologies. Public R&D (co-)funding policies target the innovation externality, and public financial support for demonstration projects target the business-exploration externality. These policies may reap eventual industrial policy spill-overs and break unwanted path dependencies. They are, by nature, more technology-specific. Technology-neutral across-the-board funding would be infeasible due to limited public finances and the spatial/resource requirements of such endeavours. Funding large-scale demonstration and deployment projects for all technologies would not only be extremely expensive[50], it would also ignore the fact that different technologies are contemporaneously in different stages of their development.

3.6.2 The technology choice challenge

Decisions about which technology to support, and when and how to support it, are extremely difficult, as they involve the evaluation of technologies of unknown future merits. Furthermore, the social value of each technology is not self-standing, but depends on the performance of all competing technologies. Thus, simply funding all technologies according to their – already difficult to establish – individual societal value is not optimal in the presence of competing technologies.

And errors could be costly. The argument that doing a bit too much for one green technology might be forgivable, on the basis of erring on the safe side does not necessarily hold. In the presence of multiple new technologies that compete not only for a market but also for production factors, excessive support to one technology might even slow development. Government action may provide a focal point for a 'less-efficient' technology, directing not only its own financial resources but also other production factors (skilled labour, capital, etc) away from the more efficient

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[50] For example, as discussed in section 3.3, undifferentiated co-financing could create significant windfall profits and wastage.

technologies. Thus, an eventual break-through of the more efficient technologies may be delayed. In the presence of network effects, a more efficient technology might become locked out due to early support of a less efficient competing technology.

In addition, because of the high uncertainties inherent in an energy and transport system transition, it is likely that some technologies will not live up to their promises. Selecting a portfolio of technologies is warranted in order to make the vital transition resilient to unexpected shocks. Consequently, the question is how to design a mechanism that evaluates all available technologies in order to ensure that public support is channelled to a portfolio of technologies, in order to underpin the most effective and efficient transition.

3.6.3 Status quo

Current support policies are not technology-neutral. Typically, governments define budgets to support individual technologies. These budgets are then allocated by the administration with the clear aim of making the individual technology viable. In the political process, priority is given to technologies that allow quick visible deployment, are supported by strong vested interest and/or are in fashion. The technology-choice decisions are often justified by modelling results. However, the corresponding models are typically proprietary and ambiguous to the outsider. The key assumptions for these models are usually submitted by stakeholders with vested interests. Furthermore, coordination of support (eg controlled experiments discussed in section 3.5) rarely occurs on the international, or even European or national levels, and strongly deviating national support measures might point to hidden state aid[51]. Consequently, current technology choice decisions are picking 'winners' but the choices are hardly predictable.

3.6.4 A consistent and predictable support mechanism

A level playing field for public support for new technologies requires that governments' choices of a technology portfolio should not be driven by the question of 'which' but by the question of 'how'. Governments should adopt choice mechanisms that are dynamic and adaptive, able to digest new information and optimise support in a quick, reliable and effective manner. A flexible mechanism is essential for dealing with shifting exogenous economic and political events, and unforeseeable developments

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[51] Consequently, technology-specific support is regularly subject to state aid inquiries by national and European competition authorities.

in technology. An adaptive technology-choice mechanism, able to self-evaluate and evolve to meet changing technology choice needs, would also serve to avoid institutional lock-in[52]. As in all policy fields there is a trade-off between flexibility and reliability. Locking in bad decisions for the sake of reliability is just as bad as not creating credible long-term investment signals so as to maintain flexibility. The solution to this dilemma is building transparency into the mechanism. Transparency is critical for the success of any choice mechanism, so that industry and consumers can form the right expectations over the direction of technology. The only way to control the potential impacts of public policy on industry investment choices is through a transparent policy clearly communicating government priorities and decision parameters. Transparency also promotes fair competition and inspires trust on the part of industry and consumers. Stakeholder trust is fundamental to the success of energy transition policy. Finally, it is important to note that the mechanism should be utilised to select not only one, but a portfolio of technologies[53].

The first step in constructing a technology-choice mechanism is to define a transparent set of metrics and priorities (which may later be updated, as the demands of society and climate action change). The interest of governments is to support the optimal portfolio of technologies in terms of certain metrics – such as costs, timeline, efficiency, benefits and safety. These metrics and priorities should be as technology-neutral as possible, and should be the driving force behind the technology-choice mechanism.

All stakeholders involved in the selection of new technologies face the problem of imperfect information. In the initial demonstration and early market phases, information about payoffs and costs is not fully known. Much of the progression along learning curves occurs during the commercialisation stage (Schoots *et al*, 2010). In the case of FCEVs, the timeline and scale of cost reductions from commercialisation are as yet unknown. Other factors, such as consumer expectations, trust, research capacity and connection with higher learning, also play roles in determining the success of a technology. These are hard to measure or even predict. However, industry possesses the best information about the prospects of their new technology, and this information is not necessarily accessible by the government (asymmetric information). Thus, it is the responsibility of industry to report this information to government if it desires public support. However, the developers of different technologies may have an interest in overstating the capabilities, or understating the cost, of their respective technologies

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[52] Institutional lock-in is described in section 1.2.3: Path dependencies.

[53] The merits of a technology portfolio are discussed in section 1.2.7.

in order to attract more support (or even lock out competitors). Therefore, the public technology-choice mechanism must be one that iteratively elicits unbiased estimates from industry.

One example of a mechanism for achieving this would be for companies/consortia/academia to offer a 'menu' of different support options for the development/deployment of their new technologies. This menu would contain promises on the metrics defined in the first step of the mechanism's design, and the expected form and volume of support. Attached to each option would be a requirement to meet certain quality metrics by a certain date, penalties for failing to meet the metric by the date, and a reward for achieving it (a low interest rate for example). Thus, using monetary incentives, government may be able to elicit more accurate cost and quality information from industry.

An open and transparent energy and transport transition model would be used to evaluate the proposed packages. The model would suggest a combination of support options to develop a sufficiently resilient portfolio of technologies at lowest cost. The model should be run and maintained by a central authority such as the Agency for the Coordination of Energy Regulators, the Strategic Energy Technology Information System, or a new institution.

This process should be repeated after a certain interval to update assumptions and adapt to a changing technological environment. If feasible, a trigger should be defined so that this process is initiated outside of the predetermined cycle when new developments warrant it. The definition of such mechanisms is beyond the scope of this report, but the field of microeconomic engineering holds promise for potential solutions to information issues faced in technology decisions for the transport and energy transition.

At the very least, such mechanisms may provide a better avenue for choice mechanism definition than a simple 'shot-in-the-dark' definition of thresholds or numbers (such as 50-50 co-financing or one-million cars in 2020). A European mechanism for allocating support to technologies can create a level playing field for competing technologies. It may promote more coordination between regions, nations and companies. The cost of the transition is put at several percentage points of GDP[54]. Therefore, large-scale government intervention will be unavoidable. Consequently, a

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[54] According to the German Council of Economic Experts (2011), in 2011 the NPV of all feed-in tariff obligations alone amounts to €80 billion. This is about two percent of Germany's GDP.

structured approach adapted to the complexity of the challenge is warranted to avoid extensive inefficiencies.

3.6.5 Conclusion

We have demonstrated that market barriers hamper the introduction of new low-carbon energy and transport technologies. Resolving each of these market failures individually with the most technology-neutral approach appears efficient. If, however, a new technology does not take off after all externalities are corrected, this does not indicate that more support is needed. In such a case, the lack of development, in fact, signals that the technology is not (yet) ready for the market or that better technologies exist.

Political and practical constraints limit the applicability of technology-neutral approaches. Some market failures are better dealt with by technology-specific instruments. However, there is a significant risk of government providing support to the wrong technologies at the wrong point in time with the wrong instrument.

A predictable and economically sound mechanism for allocating support could reduce the cost of transition to a new transport and energy system. This would require that policymakers move from ad-hoc allocations to specific technologies to a more model-based approach towards the provision of support. Even if policymakers are unwilling to cede discretionary power over support decisions to a European transition model, building up open and transparent public modelling capabilities is a no-regret option. It would step-up the level of discussion over modelling assumptions and hence the optimal policies.

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Appendix

A.1 Modelling consumer acceptance and policy impacts

MMEM (*Marktmodell Elektromobilität*) is a simulation model designed to forecast and evaluate policies that aim to promote the diffusion of alternative-fuel vehicles. Its core component is a market simulation module that is based on discrete choice modelling to forecast the evolution of different automotive technologies on the German market. It covers nine competing technologies (gasoline, diesel, hybrid, biofuels, LPG-CNG, battery electric vehicles, range extender, plug-in hybrid, fuel cell). The car market is divided into different submarkets (privately owned household cars, rental cars, cars purchased by resellers, company cars for private use, corporate fleet including company cars, and public procurement), which are characterised by differing purchase mechanisms. In this section, we concentrate on household vehicles, which constitute the single largest submarket.

In addition to the differentiated characterisation of consumer groups, the model takes the different vehicle segments of the market into account, corresponding to different vehicle sizes. The level of decomposition in the model is larger than in other existing models, and is based on the *Kraftfahrtbundesamt* (KBA – Federal Motor Transport Authority) categorisation in use in the German administration. It includes 11 vehicle size categories (microcar, subcompact car, compact car, mid-size car, upper medium-sized, executive car, sports utility vehicles, sports cars, minivan, people-carrier, and light freight vehicles). The model is ‘dynamic’, ie the market shares of respective technologies and segments are a function of the time-dependent value of car attributes.

The car purchase discrete choice model is based on a meta-analysis of stated-preference surveys and constructs a synthetic utility function based on willingness-to-pays (WTP) and elasticities found in the literature. The model also contains a ‘diffusion’ module, that uses the discrete choice model as input data (to be understood as ‘potential market shares’), and computes adjusted market shares based on a Bass-like diffusion model (Bass, 1969). The model can be run for a reference scenario which represents the most likely scenario. It can also be run for a variety of policy scenarios which activate a series of policy measures (purchase incentive, fuel taxation, etc). The model provides the data for computation of CO2 emissions in the reference and policy scenarios, which can then be performed as discussed in the next section.

The modelling results can help answer a number of questions. Firstly, will achieving the target with respect to the factors described above lead to the achievement of the market penetration objectives posed by the various stakeholders – namely a 25 percent share of new purchases by 2050? Secondly, what are the consequences of missing the targets to the market uptake? Furthermore, different support scenarios can be assessed to establish how measures such as R&D funding, infrastructure support and others might affect the speed of FCEV market uptake.

A.2 Selected existing support instruments

Battery electric vehicles (BEV) and FCEV policy incentive schemes (currently applied at EU level, and in Germany and France)

Policy tool	European Union	Germany	France
Framework support (Initiatives/plans/legislation)	Super credits (EC 443/2009) – Super credits: In calculating the average specific emissions of CO2, each new passenger car with specific emissions of CO2 of less than 50 g CO2/km shall be counted as: – 3.5 cars in 2012, – 3.5 cars in 2013, – 2.5 cars in 2014, – 1.5 cars in 2015, – 1 car from 2016. CO2 Emissions Reduction Requirements (EC 443/2009) – Car manufacturers must reduce CO2 emissions for new cars to 130 g/km (65 percent compliance required by 2012, 100 percent compliance required by 2015). Euro 5 and Euro 6 (EC 715/2007) – Type approval of motor vehicles with respect to emissions. Framework for Production and	National Development Plan for Electric Mobility (NEPE): joint initiative by 4 German ministries (Environment, Economics, Transport and Research) aimed at the promotion of R&D, preparation and introduction of the market for BEV up to 2020. National targets: 1 million EV by 2020 and 5 million EV by 2030. National Hydrogen and Fuel Cell Technology Innovation Programme (NIP): a part of high-tech strategy of Germany and ties in with Federal Government's Fuel Strategy. National Economic Stimulus Package II: contains a €500 million programme regarding development and deployment of EV in the next years. Transport Energy Strategy (TES): an	The Car Tag *'écoprofil'* Programme (Type III environmental labelling, ISO TR 14025): CO2 emission based tag system. This scheme is used for vehicle taxing, within public procurement as well as for fiscal incentives. Complementary regional incentives: eg provided by the Poitou-Charentes Region (comprehensive EV grants plan). Legislation: Law No 2005-781 (Art 4) on the National Energy Policy: tax credit for purchase of clean vehicles, primarily EV; provisions for public authorities of EVs/hybrid electric vehicles purchase. Law No 2006-1771 (Art 1): tax exemption on Company Cars (TVS) according to CO2 emission levels. Law No 2009-967 (Art 22): R&D on the capacity of batteries, electric and hybrid

	Promotion of Energy from Renewable Resources (EC 2001/77) – Stipulates that member states should build the necessary infrastructures for energy from renewable sources in the transport sector by: * ensuring that operators guarantee the transport and distribution of electricity from renewable sources; * providing for priority access for energy from renewable sources. Labelling (Directive 1999/94/EC) – Requires that information relating to the fuel economy and CO2 emissions of new passenger cars offered for sale or lease in the EU is made available to consumers.	initiative launched by vehicle manufacturers and coordinated by the Transport Ministry primarily dealing with new fuels that are based on renewables and have extremely low CO2 emissions along the entire energy chain.	traction chains. Decree No 2007-1873: grant system for the purchase of clean vehicles (eg hybrid electric vehicles whose CO2 emissions are under 135 g/km), bonus/malus tax system.
Undertakings for resolving of specific tasks (Public/private/PPP)	FCH JU (Fuel Cell Hydrogen Joint Undertaking) – Industry-led PPP under the SET Plan. The FCH JU was established to implement the FCH Joint Technology Initiative (JTI) which established a public-private partnership. The three members of the FCH JU are the European Commission, fuel cell and hydrogen industries represented by the NEW Industry Grouping, and the research community represented by Research	National Platform Electric Mobility: joint initiative of German government and industry. Investments (paid by industry) in RTD and EV. National Organisation for Hydrogen and Fuel Cell Technology (NOW): NIP component for development and commercialisation of hydrogen and FC technologies. Funding: €1.4 billion for 2007-16 (50/50	

	Grouping N.ERGHY. Nearly €1 billion in joint funding.	Federal Government and industry). Clean Energy Partnership (CEP): Joint political initiative lead-managed by Ministry of Transport and industry; emerged from the TES.	
Monetary incentives			
Vehicles taxation	N/A. There is no EU-level vehicle taxation.	Annual car tax: cars with CO2 emissions below 120 g/km as well as EV are exempted from it for five years from the day of first registration. No specific provisions for VAT for EV.	Bonus/malus Scheme: tax deductions/penalties system for new cars linked to tank-to-wheel CO2 emissions. Exemption from car registration tax: for vehicles running with alternative fuels/low-emission vehicles (according to CO2 emission). Applicable for second-hand cars, whereas new cars benefit from the bonus/malus system. Corporate car taxation: annual tax progressive taxation. Tax rates: from €2/g CO2 less than 100g/km CO2 emission level to €19/g CO2 for more than 250g/km. Tax exemptions for clean vehicles (GNV, electric, hybrid, E85, LPG).
Taxation of fuels	Pending: overhaul of Energy Directive 2003/96/EC – a proposal for a Council directive amending Directive 2003/96/EC was published on		

	13 April 2011. Its purpose is to restructure how energy products are taxed, including accounting for CO2 emissions and energy content. The proposal is expected to enter into force in 2013. Key Elements: A splitting of the minimum tax rate into two parts: €20 per tonne of CO2. €9.6/GJ for motor fuels, and €0.15/GJ for heating fuels. This will apply to all fuels used for transport and heating.		
Subsidies (Consumers/producers/ investors)		No specific provisions.	Grants system for customers when acquiring new car: €5000 for purchase a car with CO2 emissions are less than or equal to 60 g/km; €2000 for hybrids, LPG/CNG cars with CO2 emissions that are less than or equal to 135 g/km. ‘Cash-for-scrap scheme’ (*prime à la casse*): for replacement a vehicle aged over 10-years by a new one. *Agence de Services et de Paiement* grants: specific for the purchase of EV.
Infrastructure			Installation of charging network for PHEV

			and BEV: working group set up in 2009 focusing on a national network for plug-in hybrids. Strategy focuses on a number of provisions/quotas for local governments and commercial property sites for installing charging stations.
Public procurement	Clean Vehicles Directive 2009/33/EC – decisions over public procurement of vehicles must take the energy and environmental impacts linked to the operation of vehicles over their whole lifetime. These lifetime impacts of vehicles shall include at least energy consumption, CO2 emissions and emissions of the regulated pollutants of NOx, NMHC and particulate matter. Purchasers may also consider other environmental impacts.		2008-12 public procurement plans: public-private order of 5000 cars hybrid and electric vehicles, plus plans to procure 10,000 cars by 2012. Planned launch of joint public call of 20 large French companies and public authorities for tender for building a fleet of 100,000 vehicles until 2015. The purchasing case is managed by the UGAB.
R&D and demonstration	EU Framework Programmes – FP5, FP6, and FP7 fund hydrogen research. EU Green Cars Initiative – Package for support of BEV, Citi Logistic, and ICE. €4 billion in loans from EIB and €1 billion from FP7. Demonstration Projects – Projects funded by FCH JU and/or EU such as: * H2Moves – Hydrogen refuelling station and 15 FCEVs in Oslo	Part of €500 million package in National Economic Stimulus Package II is directed on research activities funding regarding: - R&D of battery technologies and electric vehicles. - EV demonstration projects in several German cities (Berlin and others). The lithium ion battery research programme (LIB 2015) => €60 million by	French government: €400 million for R&D and demonstration for low carbon vehicles. €57 million is already allocated for 11 projects. The research on electric vehicle technology is funded by €90 million. Two national research platforms on the development of battery technology and

	* HYFLEET CUTE – Hydrogen bus project * HYCHAIN – Hydrogen vehicles project * ZeroRegio – Hydrogen cars project * Roads2Hycom – Hydrogen research roadmap * HyApproval – Handbook for the approval of hydrogen refuelling stations * HyWays – European hydrogen energy roadmap	German government for 2008-15 with further investments of €360 million by an industry consortium.	electric and hybrid vehicles will be financed by an interministerial fund.
Standardisation (Industrial/ infrastructure standards)	Directive 79/2009 – Requirements should be developed by the Commission regarding hydrogen gas mixtures. Commission should support internationally harmonized motor vehicle standards, including considering whether to adapt any Global Technical Regulations (GTRs) adopted for hydrogen. Directive 2009/28/EC- By 31 December 2011, the Commission shall also present, if appropriate, a proposal for a methodology for calculating the contribution of hydrogen originating from renewable sources in the total fuel mix.	Common plug standards: industry initiative for plugs standard (capacity of 400 voltage).	

The great transformation
Decarbonising Europe's energy and transport systems

Europe's energy and transport systems face the major challenge of cutting their carbon footprint to near zero. Due to the limited carbon-reduction potential of incumbent technologies, new low-carbon technologies will have to enter the mainstream market. Some of those new technologies offer significant side-benefits such as reducing local pollutant and noise emissions. Decarbonising the economy based on new technologies is also likely to generate growth.

This report, which is based on research that received funding from the Fuel Cell and Hydrogen Joint Undertaking, argues that to change a system that is so locked in to incumbent technologies, and to make decarbonisation growth friendly, a consistent policy approach is needed. The scope, geographical coverage and duration of carbon pricing should be extended. By setting a higher carbon price, incentives for developing and investing in new low-carbon technologies are created. Temporary consortia for new infrastructure to solve early-phase market failures could be put in place. This is discussed using the example of hydrogen vehicles. Finally, an open and public transition model is needed so that second-best transport solutions are not given a head start that later cannot be reversed.

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