GREEN ENERGY INNOVATION AS A DRIVER OF GREEN DEVELOPMENT

Mallika Ishwaran & Nigel Dickens[1]

Shell International

EXECUTIVE SUMMARY

Energy is a key enabler of economic development, and the transition to lower carbon and cleaner sources of energy is essential for green development. Green energy innovation, including in new energy sources, fuels, and technologies, is critical for decoupling economic development and prosperity from some of the negative environmental consequences. The purpose of this paper is to provide greater insights into the innovation pathway, what determines and hinders innovation, as well as tangible steps for innovation policy.

Innovation is the first step in the successful application of technology. Innovation is the conception of a set of ideas as a solution to a perceived problem, and the process of putting these ideas into practice through design and testing. If innovation is successful, the outcome is a technology that can be demonstrated and, ultimately, widely deployed. The energy sector is currently undergoing a period of increased innovation, with new technologies entering the market, from renewable power to unconventional oil and gas to smart meters.

---

[1] Author: *Mallika Ishwaran & Nigel Dickens,* Shell International (supported by Vivid Economics). Reviewers: *Zhang Xinsheng, William Wang,* Shell China Limited.
This document contains information, insights, and recommendations derived from internal and external research coordinated by Royal Dutch Shell, and as such does not represent the company's views or position. Accordingly, investors should not rely on it when making an investment decision with regard to Royal Dutch Shell plc securities.

Further innovation is required if countries are to enjoy modern energy systems that are affordable, secure and sustainable and that support greener pathways to development. While green energy innovation may be at relatively high levels, it's pace needs to increase further if the sector is to address the environmental impacts of energy production and use. For example, the International Energy Agency's 2017 Tracking Clean Energy Progress scorecard of 22 technologies finds that only 3 are on track for wide scale deployment to deliver a low carbon energy system, more innovation effort is needed for 12 technologies, and 7 are not on track. The current set of new energy technologies are built on a pipeline of innovation that was established in the 1970s, and policy-makers need to consider whether a sufficient pipeline of innovation is currently in place to support future innovation and how this can best be supported.

Successful innovation policy manages the tension in innovation: that a large pipeline of innovation is needed, even if only a few technologies are eventually successfully deployed. Supporting a pipeline of innovation requires public resources, due to the market failures and positive spill overs of innovation. This requires government to make choices about which broad areas of innovation to support. Many of the innovations that are supported will not eventually be deployed. If innovation is allowed to fail at the right time, resources spent on unsuccessful innovations are a natural consequence of the uncertainty in the innovation process. Hence, policy-makers must also make choices about when to stop supporting certain areas of innovation.

International experience suggests the following principles for a successful innovation policy:

i. **Prioritise monetary support** to focus on:

- **Early stages of research, development, and deployment**, rather than later stages of niche and wider market deployment. At these early stages, the scale of financing is often relatively small, so limited government budgets can fund a wider range of innovations. The risk is high, which government are better placed to bear because losses can be shared across society as can gains if the innovation is successful.

- **Fundamental innovations that create new classes of technology**, rather than innovations for specific technologies. The private sector will often develop specific innovations if the fundamental knowledge is publicly available, but either does not have adequate incentive to embark on fundamental innovations or could limit societal benefit from successful fundamental innovations.

- **Technologies with high capital intensity and longevity**, but only if alternatives with lower capital intensity and longevity have been explored first. Technologies with high capital intensity and longevity are riskier and hard to experiment with, and, as with early stage innovation, government is better placed than the private sector to support such innovation.

ii. **Encourage and coordinate diverse innovators** by focussing institutional support on:

- **Supporting an ecosystem of innovators.** Innovation has several stages, and different skills, resources and appetites for risk are needed at each stage. Therefore, different types of organisations are needed at each stage, from universities for basic R&D, through to entrepreneurs for entry into niche markets, to large firms for wide deployment of a technology. To achieve this diversity, policies are required that encourage and support the necessary range of organisations to participate along the different stages of innovation.

- **Creating links between stages of innovation.** A challenge to delivering innovation via a diverse ecosystem of different organisations is ensuring the necessary collaboration across the ecosystem. Government can support collaboration by distributing information and supporting networks of innovators. Policy can also combine financial support to an innovator with support to graduate to the next stage; for example, by helping early stage inventors to develop business plans. Government can also step in if a part of the ecosystem is weak, such as by running demonstration projects, as long as the findings are then handed on to organisations in the next stage of the innovation pathway.

- **Providing standards.** Government can coordinate areas of technology that are common to competing private innovation efforts, such as by developing standards in partnership with industry working groups. This prevents duplication of effort and concentrates innovation on useful outcomes rather than spurious differentiation.

iii. Constantly evaluate and adapt. Innovation is an uncertain and dynamic process, and the case for public support for a particular innovation should be regularly evaluated to take into account new findings and changes in external circumstances. Government may not always best-placed to evaluate the success or failure of an innovation. All decision-makers have biases, and this can be a greater risk for government as decision-making power is often concentrated. Also, a policy-maker's view of a technology may differ from that of end-users, but a technology will ultimately need to succeed in a market context. Thus, as innovations mature, they should be increasingly exposed to market competition.

iv. Be able to fail fast. Government can often face a tension that while it is economically best placed to bear the losses from risky innovations, it can also face greater institutional barriers to accepting failure than the private sector. For example, because of potentially misaligned incentives between saving political and personal reputations and wasting public resources. However, prolonging failure comes at an increasing economic cost, and it is best for an innovation to fail fast before rising costs make that failure inevitable. This requires more than constant evaluation. It also requires a political understanding that innovation is a dynamic, uncertain process, where failure is an inherent outcome of the process.

Innovation is a challenging area of public policy. While international experience suggests broad principles of good innovation policy, countries have tended to take a variety of different approaches. Innovation policy should be tailored to local contexts and should adapt as these change over time. For example, cumulative advances in technology are allowing new types of innovation to occur at an increasingly rapid pace. Innovation policy itself should therefore prioritise its interventions, encourage a diversity of approaches, be under constant evaluation, adapt, and be able to fail fast.

I. The importance of innovation

Innovation is the first step in the successful application of technology. It is the conception of a set of ideas as a solution to a perceived problem, and the process of putting these ideas into practice through design and testing. If innovation is successful, the outcome is a technology that can be demonstrated and, if successfully demonstrated, be adopted in niche markets. If technologies are successful in niche markets, the final step in innovation is mass production of the technology for widespread application. This paper examines innovation, the earlier stage of technology development prior to its widespread application, and its role as a driver of the energy transition, and hence of green development.

Historically, successful innovations (i.e., technologies that achieve high levels of deployment) benefit from a supporting set factors in addition to their narrow technological development. These supporting factors consist of:

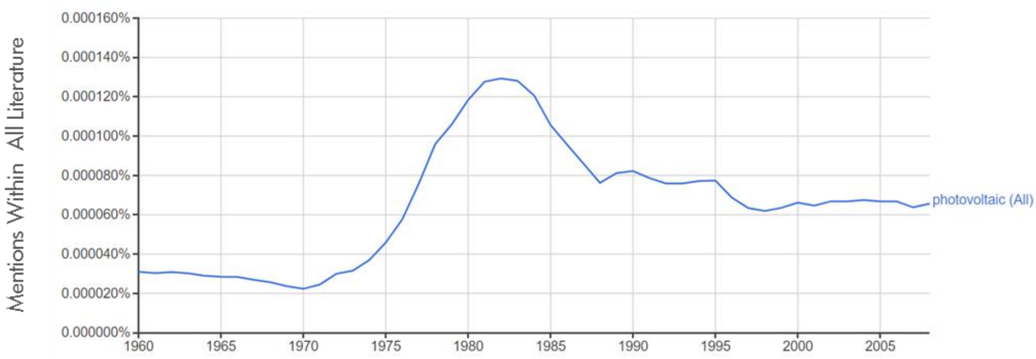
- demand for the services the technology provides, such as clean or secure energy;
- supply of the inputs the technology requires, such as components of the technology or primary fuels; and
- markets that incentivise the deployment of new technology, such as a newly liberalised market that favours a new lower cost technology.

Thus, it is often very hard to predict with certainty which technologies will be deployed, and consequently there is a tension between the need to fund a constant and large pipeline of innovation and the uncertainty about which specific technologies are eventually adopted.

Innovation policy is ultimately about resolving this tension. Supporting a pipeline of innovation requires public resources, because of the market failures and positive spill overs of innovation. However, many of these innovations will not be deployed. If innovation is allowed to fail at the right time, resources spent on unsuccessful innovations are a natural consequence of the uncertainty in the innovation process. The signals that indicate which innovations no longer warrant support are complex and are often masked by prolonged public support. Policy-makers, therefore, need to balance providing sufficient support so that there is a fertile set of technologies available with withdrawing support at the appropriate time so that only viable technologies survive.

The focus on green development has meant energy systems increasingly shifting towards delivering cleaner and more sustainable energy, creating common demand for low carbon energy technologies. Combined with increasing globalised energy and materials markets providing supply and increased levels of energy market reform to accommodate low carbon energy, the supporting set of factors are in place and the marginal impact of innovation is potentially greater now than it has been. Moreover, modern energy systems encompass a wide range of energy sources, technologies, and energy end-use applications, enlarging the scope of innovation. Countries tend to now utilise a greater array of primary fuels, energy carriers, transmission mechanisms, and energy end-use applications than at any other point in history. Thus, the increased array of potential avenues for transition has also increased the scope for innovation.

Figure 1. **Technology innovation can have long lead times, as illustrated by the peak in hype around photovoltaics in 1982 but the 1.1 per cent share of global electricity in 2015**



Note: *3-year averaging period used*

Source: *Google Ngrams*

The innovation policy challenge arises from innovation and technology deployment being a long-term process – innovation needs to be prioritised now for the next generation of technologies to emerge. It can also take decades before new technologies begin to have a material impact. Many of the technologies currently leading the low carbon transition began development over 40 years ago and may still require years to materially change the energy system. For example, Figure 1 shows that mentions of solar energy as a share of written English peaked in the 1980s, but solar energy still has yet to have a significant impact in the majority of global energy systems.

The fundamental role of energy in economic development, the increased opportunity for technology in the current energy transition, the large scope for technology deployment, and the long-term process to deliver innovation make innovation support a priority. To this end, it is important to better understand the factors that inhibit innovation and how governments can pragmatically accelerate the process. To better illustrate the process of innovation and the associated challenges, four case studies are considered (see Figure 2 below). These case studies cover a range of types of innovations, and each has lessons relevant for policy-makers looking to support innovation. The case studies are:

- Synthetic fuels innovation, in the USA, from 1979;
- The Human Genome Project, in the USA, from 1990;
- Early wind turbine development, in Europe and the US, in the 1970s; and
- Bio-ethanol fuels, in Brazil, from 1975.

Figure 2. **The chosen case studies cover a range of interventions and learnings**

	Motivation	Intervention	Lessons
Synthetic Fuels USA (1979)	Supported due to high predicted oil prices, energy security benefits and high capital costs • Synfuels are created by liquefying coal and act as a oil substitute • Post 1979, oil prices were predicted to increase rapidly and make synfuels cost competitive • The process is expensive and gains were only expected in the long run – this hindered private investment	R&D support followed by large, incentivised niche market deployment • Government provided research funding in the 1950s-70s, but low oil prices limited development • 1980-1986: large niche market deployment supported by government subsidies • Goal of 0.5 million barrels by 1986 and $12.2 billion (1980$) initial budget	Shows the need for flexible goals and policy in response to new circumstances • Oil prices already falling when niche market deployment just begun • 1985 – projects produce only 2% of 1986 targets • 1986 – Project cancelled, total cost of $4.5 billion (2010$)
Human Genome Project USA (1990)	Access to the genome sequence would be restricted by patents if a private firm accomplished the sequencing first • 1986 – invention of automated sequencing machines made deciphering the human genome feasible • The data is of huge value to drug producers and medical research • Threat of a private company patenting sections of the genome accelerated intervention	A government programme raced against a private venture to complete the sequencing • Government funding estimated at $5.6 billion (2010$) • 1990 – Project officially begins with completion date of 2005 • 1998 – Celera Genomics begins sequencing, public effort intensified • 2000 – Drafts announced, public programme is ahead by 3 days • 2003 – Full release	There can be value in government replacing private sector funding, but the benefit to society must be clear • The economic impact of the HGP to 2012 has been valued at $965 billion • For this style of intervention to be justifiable the project must have unequivocal benefits • Argument that competition helped HGP come under budget and 2 years ahead of schedule

Wind Turbines Global (1970s)	**Was a clean, alternative power source but was uncompetitive in the 1970s** • Interest in wind power grew after the oil crises highlighted energy issues • Lack of efficient turbines, low lifetime of generation assets and limited appreciation of pollution externalities meant private investment in this technology were limited	**Different approaches by different countries – Denmark regarded as the most successful** • US: large subsidy programme delivered capacity, but unreliable and led to market crash • Denmark: focus on supporting small scale turbines, knowledge sharing and market support • Germany: R&D focus on large turbines, but no significant market support, hence little demand for unproven and unreliable technology	**There needs to be support across stages and communication between agents for effective deployment** • Germany spent 5 times more on R&D than Denmark up to 1990 but achieved no notable wind capacity. • The Netherlands created a competitive market that discouraged knowledge sharing • The US had a booming market driven by large subsidies, but a lack of standards hampered reliability and led a market crash
Bio-ethanol Fuel Brazil (1975)	**Ethanol is easily produced in Brazil and can both regulate sugar prices as well as increase energy security** • 1975 – Oil and sugar price shocks in the 1970s led to the "ProAlcool" programme • Innovation in upscaling ethanol production and increasing usage rather than producing ethanol itself • Support for development and deployment of ethanol only vehicles and "flex-fuel" vehicles	**Ethanol subsidies, agricultural R&D funds and support for ethanol vehicles at varying levels over time** • Mandatory fuel blending of ethanol with gasoline creates demand • Incentivised supply with low interest loans and guaranteed prices • Grants provided for agricultural research to increase crop yields • 1986 – Guaranteed ethanol prices reduced below average cost of production due to oil price collapse	**Exposure to market forces drives cost reductions and supporting technologies can be essential for success** • 1980 – beliefs of increasing oil prices meant no concentrated effort was made to improve efficiency • Post 1986 – subsidies were rolled back, leading to cost reductions across the production chain • Post 2004 – introduction of flex-fuel cars re-energises the programme

Source: Vivid Economics

II. Factors determining the rate of innovation

Innovation is a process of experimentation, and the rate of innovation depends on the nature and number of experiments that can be undertaken. A technology is rarely, if ever, invented in a single 'eureka' moment. Instead many rounds of experimentation are often required. For example, Thomas Edison tested over 1,200 designs for an incandescent lightbulb before achieving a demonstration version. In broad terms, the process of experimentation, and therefore the rate of innovation, can be characterised in terms of frictions and capital characteristics.

i. Frictions

Frictions occur throughout the process of innovation, but these can be reduced by policy. The process of innovation is complex and inherently uncertain. It consists of several stages, each with different characteristics, such as scale of investment at risk and range of skills and knowledge. Furthermore, the outcome of innovation is very rarely known at the start of the process, and large surprises are a fundamental characteristic of innovation. These are common issues that all technologies face, and there is a role for public policy to actively minimise these frictions.

Misaligned economic incentives between investors and society can create additional frictions. If innovation is left entirely to the private sector, instances will arise when the goals of private agents are not aligned with what is most beneficial for society. This occurs most prominently when externalities exist. Whenever an innovation has spill overs or positive externalities, the full social gains from that innovation cannot be captured by a private agent, leading to suboptimal levels of investment. Imitation creates an additional risk, when competitors do not compete on innovation but copy the market leader with minor, and often unnecessary, differences. This is most wasteful when products are imitated, rather than concepts.[2] The minor differentiation that often comes with imitation can lead to similar products with competing standards that are not interoperable, which is less desirable from a societal point of view to having a common inter-linked system.

Governments have a key role in reducing these frictions and ensuring an optimal outcome is realised. The issues of misaligned incentives, the high risk of innovation, and changing parameters of investment along the innovation pathway

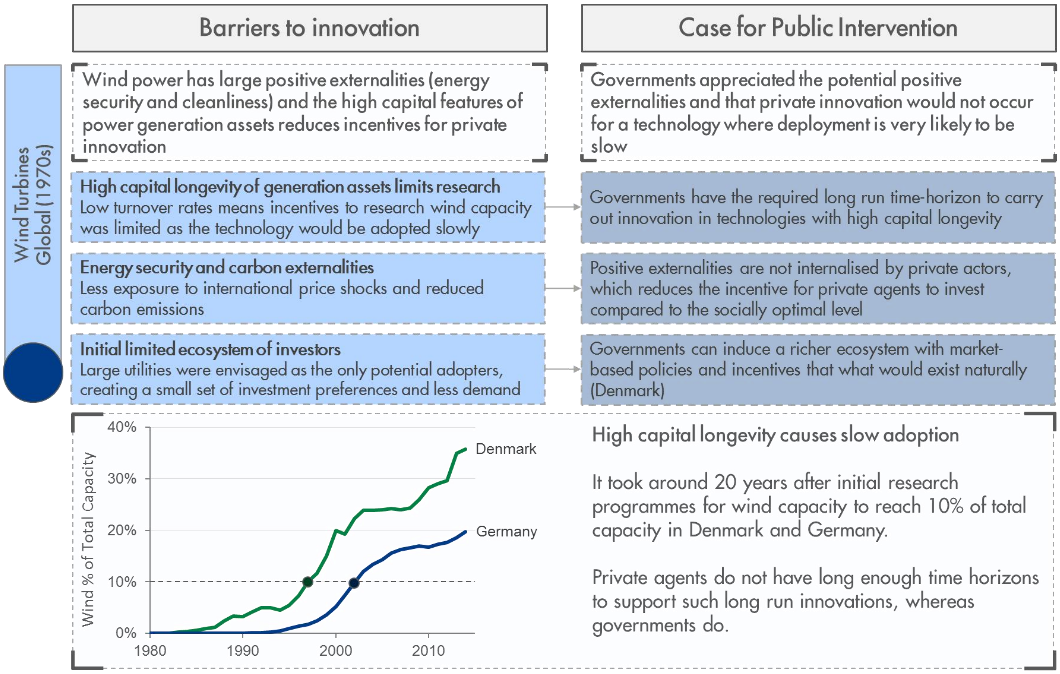
[2] In fact, competition on concepts can help stimulate rapid progress and cost reductions.

are all frictions that can result in socially beneficial innovations not reaching market deployment. It is in government's interests to help ease these frictions and deliver the best societal outcome possible.

ii. Capital characteristics

The second set of factors concern the inherent capital features of a technology, namely its capital intensity and capital longevity. The capital intensity of an asset is the capital cost of a minimum viable unit. This will tend to be low for modular technologies, such as solar PV cells, and higher for technologies that need to be deployed at scale, such as nuclear plants. High capital intensity means fewer chances to experiment and greater financial risk should the technology not perform. For technologies being deployed in niche markets, high capital intensity often requires a longer payback period, which is riskier as the technology may not perform for the length of the payback period. This can reduce demand, and without sufficient demand, an innovation will not be profitable even if it is successfully developed, in turn leading to less investment for innovation and slower innovation overall. Capital longevity is the useful lifetime of an asset and can also reduce innovation by causing lower turnover rates, creating fewer opportunities to learn by doing, and generating less demand for new capital assets.

Figure 3. **Energy generation assets are expensive and have long lifetimes, leading to generally slow take-up rates that reduces incentives for private investment**



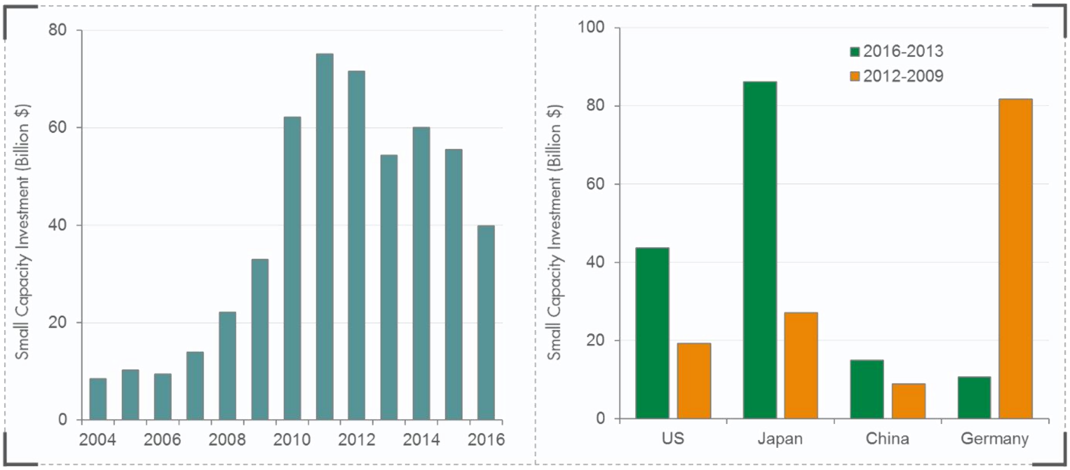
Source: *EIA, IEA, Neij & Andersen, 2012*

Energy generation technologies generally have high capital intensity and long capital longevity, limiting the potential for experimentation and slowing deployment rates. Government can provide support to overcome these barriers. The case study of wind turbine development in the 1970s, summarised in Figure 3, provides an example of this. In Germany, there was an emphasis on developing very large turbines, which had a high capital intensity, but improved economic potential. In Denmark, the government wished to accelerate innovation in wind turbines and actively supported the development of smaller turbines. These smaller turbines were less complex than the large German turbines and the capital cost was lower. This lower complexity and greater number of opportunities to experiment reduced the risks that demonstration turbines would fail and accelerated the learning rate, which led to Denmark's faster deployment of wind power, establishing the industry rapidly with the minimum viable product.

New technology and business models are altering the economics of assets. A key trend is digitalisation enabling some durable goods to be treated as consumables. Consumers currently purchase these assets as durable goods, incurring a fixed cost regardless of how much the asset is used. Digitalisation enables consumers to purchase use of the asset as a consumable good. Consumers only pay when they use the asset, like renting. This is enabled by digital tracking of usage and billing, which reduces the transaction costs of sharing an asset across many consumers. For example, through services such as Uber and Didi, consumers need only pay for car transport according to how much they use them, rather than paying the fixed costs of a car upfront. Mobike is an example of this in bicycles.

As energy end use assets are transformed from durable goods to consumables, there is a change in the underlying economics. For example, in terms of asset suppliers who either provide a platform connecting asset owners and consumers, such as Didi and Uber, or who are aggregators of demand that own and operate a fleet of assets, such as Mobike. In turn, these new business models create the opportunity for faster innovation. The transformation of durable goods into consumable goods is likely to increase utilisation rates, which will increase turnover of assets, effectively reducing capital longevity. Fleet management of assets is also likely to accelerate innovation as management companies are better prepared and capitalised to support more innovative technologies.

Figure 4. **There has been a clear rise in small capacity investment since 2004 and 3 of the 4 major markets have continued to increase investment in more recent years**



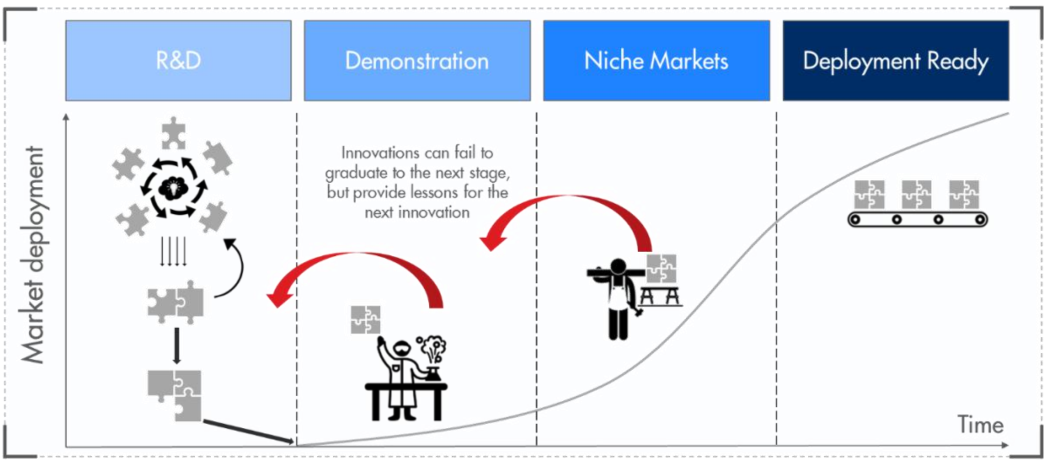
Note: *Small capacity is defined as roof-mounted solar PV cells with a total capacity of under 1MW*
Source: *Frankfurt School of Finance & Management & Bloomberg New Energy Finance, 2017*

Another key trend in energy has been a transition towards decentralised energy, where technologies have smaller unit sizes. Decentralised energy is broadly defined as small-scale generation that is produced close to where it will be consumed. This has become a major trend in the current energy transition, with households and towns installing electricity generation capacity. These installations have smaller minimum unit sizes that are cheaper to install, which makes generation assets accessible to an entire new, large category of agents. This is illustrated by the global increase in investment in small capacity solar installations in the last decade (see Figure 4). The lower capital intensity of decentralised energy, in turn, opens new demand avenues that increase adoption rates, creating the necessary signals for new innovation.

III. The innovation pathway

There are four stages of innovation that must be crossed for an innovation to be deployed to the general market (see Figure 5). Different actors are prevalent at each stage: universities are active in R&D whilst demonstration and niche markets are the purview of venture capitalists and equity markets. Once an innovation is deployment ready, all actors in the mass market become participants. The relevant types of support at each stage also vary. In the early stages, grant funding and favourable loans are most relevant. When a technology moves beyond demonstration, market creation policies, such as providing long-term incentives or supporting infrastructure, and public procurement become the more common options for intervention.

Figure 5. **The innovation pathway is made up of four stages – an fledging technology must pass through each to reach mass market**



Source: *Vivid Economics*

i. Challenges along the innovation pathway

The changing characteristics of each stage and fundamental market failures create challenges along the innovation process. The two main challenges that can hinder innovations are:

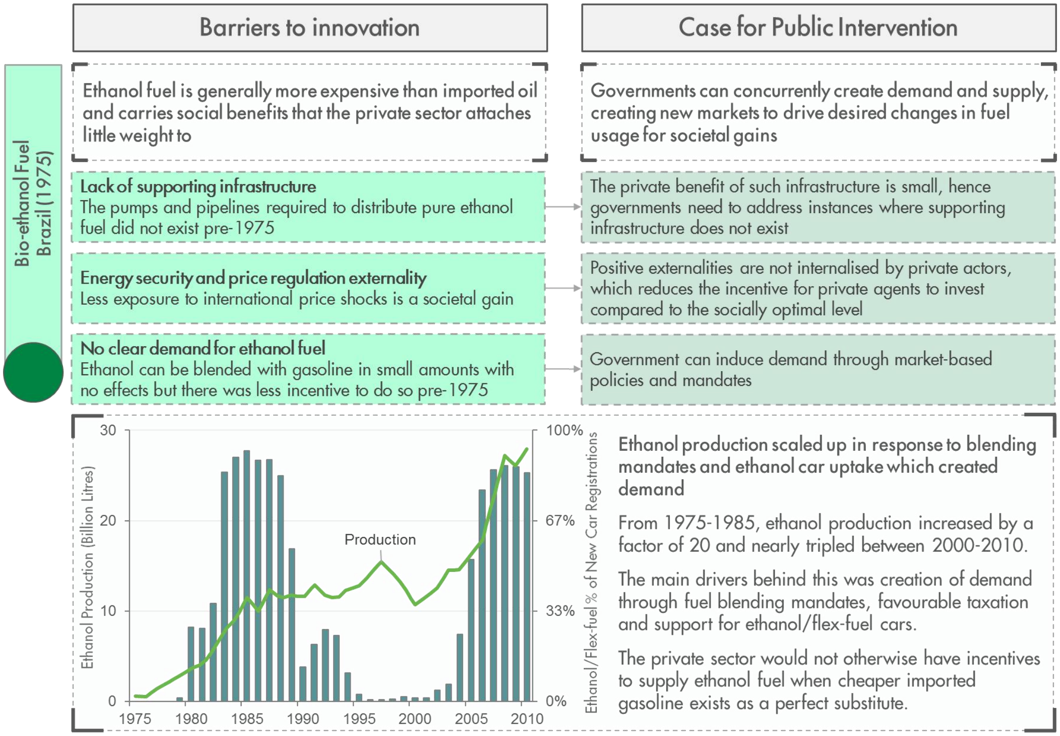
- misaligned incentives between actors across each stage of innovation; and
- changing capital requirements and risk as projects advance through the innovation pathway.

Misaligned incentives arise due to the differing goals of innovation funders, both private and public, at each stage. They can lead to technologies with positive externalities being under-supported and socially inefficient innovations surviving. Innovations are funded by the market based on the positive private value they provide, not the full public value of the innovation. For example, where positive spill overs and externalities exist and where the service an innovation provides cannot be monetised, private investment is likely to be limited regardless of the potential value of that innovation. Low carbon energy technologies suffer from positive externalities and spill overs and generally require government support along the innovation pathway.

Misaligned incentives can also lead to imitation, where near identical products are deployed to the market, which is wasteful for society but economically rational on a private basis. Imitation 'innovations' arise when competing products are not interoperable because they adhere to different standards or formats. This can be less efficient than having a common, interoperable system. For example, the competition between HD-DVD and Blu-ray players, where both offer higher quality video playback, but force consumers to buy discs that are only compatible with one technology. The diversity of electric vehicle plug formats is another example. However, should competing products be interoperable then imitation can lead to price competition that can spur faster innovation and benefit consumers – it is the creation of restricting or fragmented standards that is inefficient rather than imitation itself.

Private incentives can sometimes prevent useful knowledge sharing, preventing potentially beneficial collaboration and slowing the overall pace of innovation. However, where network effects or synergies exist, this could lead to active collaboration between private agents. For example, where there is potential for private joint ventures to deliver winning innovations should all parties mutually benefit from collaboration, such as Panasonic collaborating with Intel in developing a new range of batteries for notebooks in 2005. There can also be active knowledge sharing if network benefits arise from an increased number of users of a product. This is the reason why Tesla and Toyota have both released patents for their electric and hydrogen car technologies. Only with a sufficient number of users will the essential enabling infrastructure for these types of cars be developed, i.e., it is in Tesla's and Toyota's current interests to develop the market by sharing their knowledge.

Figure 6. **Government intervention created a market for ethanol to deliver its associated positive externalities**



Source: *ANFAVEA, 2012; Meyer et al., 2012*

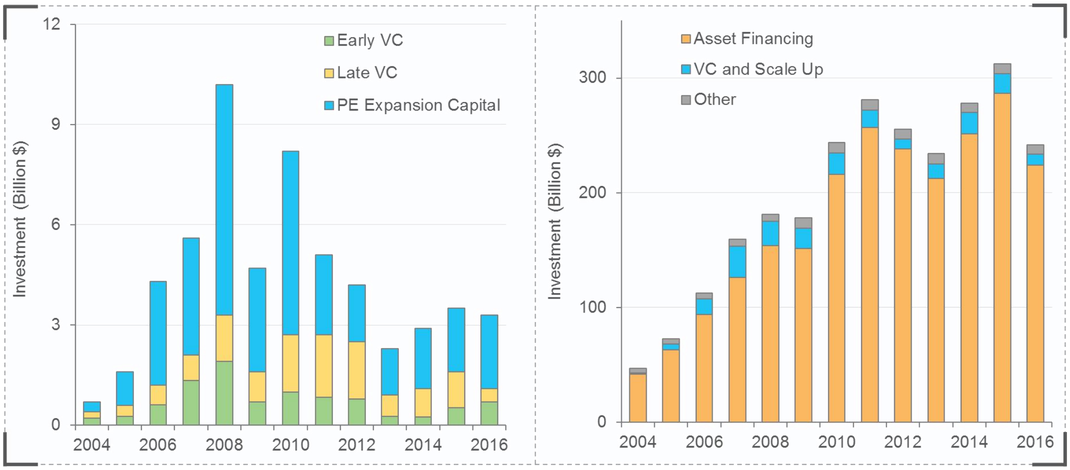
There is an important role for policy in addressing misaligned incentives, such as in the case of ethanol in Brazil (see Figure 6). Ethanol fuel was heavily supported in Brazil despite being costlier than imported oil. The cost of ethanol production was significantly higher than imported oil at the time the project began in 1975 and there was no existing demand for a gasoline-ethanol blend. With no market and no cost advantage, ethanol fuel investments would not have been made if left to the private sector alone. It was the government, who recognised the energy security benefits of domestically produced ethanol and the value of having a domestic market for the country's large sugar cane output and who promoted ethanol fuel based on its societal benefits. This was achieved by creating demand through ethanol-gasoline blending mandates, providing ethanol distribution infrastructure, and pivoting to supporting flexible fuel technology from commercial innovations.

Changing capital requirements are a consequence of the complexities of innovation. The various stages of innovation have their own risk and capital characteristics, with most individual investors rarely having the right preferences or capabilities to support an innovation along the entire pathway. Hence, there is a need for a diverse ecosystem of investors to provide the range of preferences and capabilities to adequately support each of the stages of innovation.

As technologies move along the innovation pathway, their capital requirements and the odds of success change markedly. The early stages of R&D and demonstration are characterised by high risk[3] but low capital requirements. As innovations move closer into niche market deployment, their odds of success and the level of capital support that they require increases. In the context of investment into renewables, the scale up of private equity investment has been greater than early or late venture capital funding, but both are relatively small compared to the cost of financing and deploying these assets at scale.

[3] i.e., it is highly uncertain at that stage if the innovation will make it to mass market.

Figure 7. **For renewables, VC funding comes at the earliest stage and is smaller than expansion funding which come later. Both are a small fraction of the cost of actually deploying assets**



Note: *Scale up funding includes PE expansion capital and public market funding*

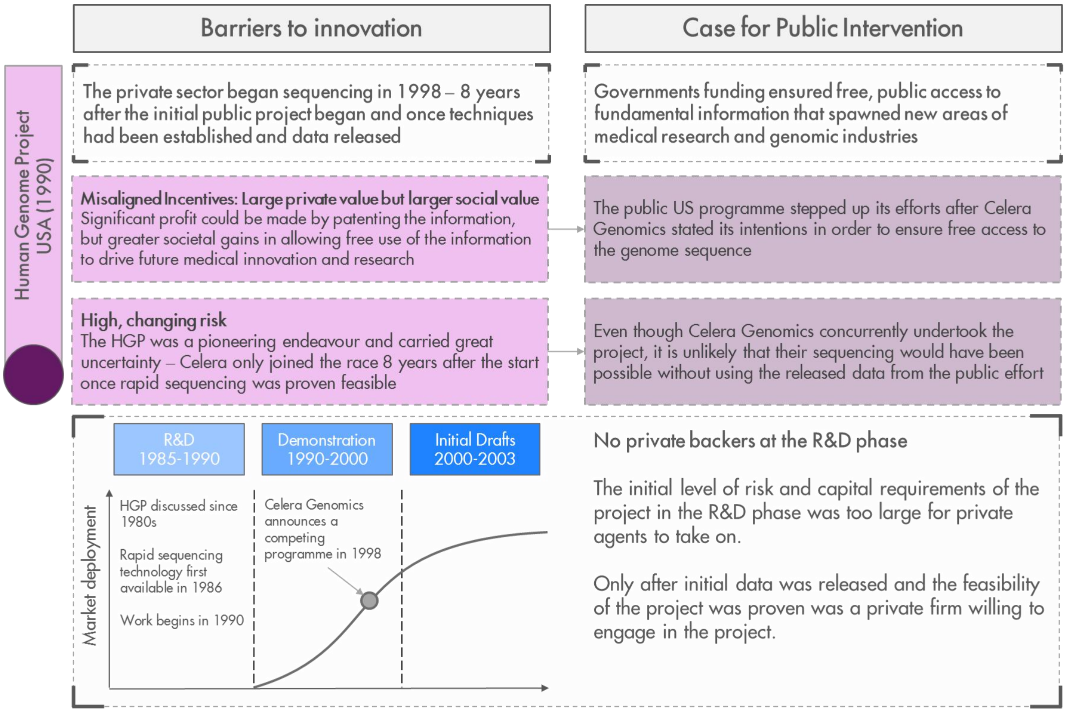
Source: *Frankfurt School of Finance & Management & Bloomberg New Energy Finance, 2017*

A large range of investors, with different risk preferences and capital availability, will help ensure adequate support for all stages of innovation. Having an ecosystem of investors with preferences that covers the diversity of potential characteristics within the stages is necessary to provide support across the innovation pathway. For example, if all investor preferences are towards low risk projects, there will be insufficient support for the early stages of innovation, which will in turn hinder the overall rate of innovation. Similarly, if all investors have low capital endowments and a preference for high risk projects, there will be inadequate support as innovations progress to later stages of niche markets and beyond.

Without an ecosystem of investors, good innovations can fail to progress and be left in the 'Valley of Death'. In a well-functioning innovation ecosystem, links between investors are strong and there is enough diversity of preferences that projects can be passed to different investors if required as they progress through the stages of innovation.

The Human Genome Project (HGP) illustrates both the changing capital requirements and risk of a project as it develops – private interest emerged after the project was proven viable, with the potential for a "winner take all" outcome. The project was the first successful attempt to describe human genetics. The level of funding for the HGP increased over time as the project advanced. In 1988, $54 million was provided but this increased to $290 million in 1992. In the final two years of the project, average yearly funding stood at $550 million, ten times the initial level in 1988. The level of risk associated with the project was initially high, but once the technology was proven, the private sector started to innovate. A private firm, Celera Genomics, announced their intention to concurrently decode the genome in 1998, 8 years after the HGP first begun. By this time data had been released and the feasibility of the project proven. The lower risk attracted private investment that was not available during the initial, higher risk phase of the project (see Figure 8 for more detail).

Figure 8. **The HGP was a first of its kind project – private backers only emerged after proof of concept was established**



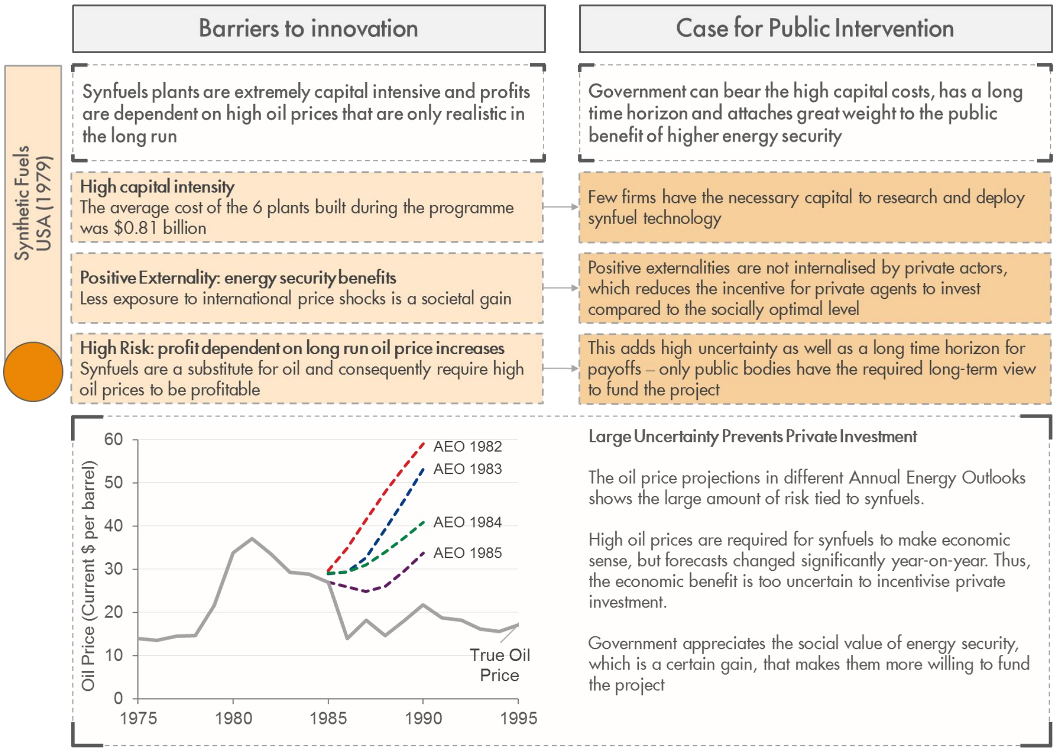
Source: *ITIF, 2014; Tripp & Grueber, 2011; Waterston, Lander, & Sulston, 2002*

IV. Risk and reward along the innovation pathway

Increasing capital requirements and increasing risk are both undesirable from the point of view of an investor. Hence, for a certain level of risk and capital investment, an appropriate level of expected return is required. Should this level of expected return be available, then an investor can theoretically be found for a project. Issues arise if a project does not meet that level of return: in such cases the payoff of the project is insufficient relative to both its capital requirement and risk and would not be funded in a competitive market environment.

Synthetic fuels in the US had highly uncertain returns, due to large risks and high capital costs, which together inhibited private investment. The capital costs of synthetic fuel plants are large: approaching a billion dollars in the US during the 1980s, with costs of more modern plants nearly ten times that. The expected private return of a synthetic fuel plant is inherently tied to the expected future oil price, as the two goods are near perfect substitutes. Given the volatility of oil prices and the generally poor accuracy of price forecasts, synthetic fuels carry a degree of risk that when coupled with the high level of capital at stake is unattractive for private investors. Policy makers have longer time horizons over which price fluctuations can be averaged, lowering risk to an extent. They are also able to internalise potential energy security considerations, should synthetic fuels reduce oil imports. For example, energy security considerations played a significant role in US government support for a large-scale synthetic fuel project, as described in Figure 9.

Figure 9. **The private payoff of synthetic fuels was unpredictable, preventing private investment**



Source: *Anadon, Nemet, & Schock, 2012; EIA, 2005*

The inherent complexity of innovation means it involves uncertainties that cannot be forecast ex ante: innovations can quickly lose support if shocks shift the key parameters of investment. Even good technologies can get into trouble due to unforeseeable shocks. For example, a shock to the price of an essential commodity may necessitate additional short-term funding or alter the perceived risk of a project. Difficulties arise due to the complexity of distinguishing between what is a temporary shock and what is not. For example, in the early 1980s, oil prices were consistently forecast to rise – through the 1990s and beyond. However, the price dips of the 1980s were not a short-term shock, but the beginning of a 20-

year period of low prices – after 1982 oil did not reach a yearly average of $30 per barrel again until 2004.

Distinguishing between structural changes and temporary shocks is difficult and can lead to inefficient innovation investment. A new state of the world may merit abandoning a previously 'good' innovation, whereas additional funding may be merited to tide over temporary shocks. Reducing support prematurely can lead to missed opportunities in the long-term but can save resources in the short-term, whereas providing support for too long can lead to wasted resources. For example, within commodity-exposed sectors, funding may be reduced or stopped as result of shocks that lead to a lack of available capital for new investment. Providing support through such episodes can help preserve projects that still have long term value but creates the risk of 'slow failure' where funds are wasted on an innovation that is now unviable in the long-term. This is a friction for which there is no simple solution. It requires dynamic innovation policy focusing not just on the end outcome, but also on the efficiency of the innovation process and is responsive to new developments.

Finally, it is worth bearing in mind that choosing to invest in innovation is more than investors matching their funding abilities and preferences over risk and return to projects. The prevailing investment culture also has a role to play in how risk and reward along the innovation pathway are perceived. For example, without precedents for technology investment, there is unlikely to be sufficient funding for innovation. For a rich innovation investment ecosystem to exist there needs to be a desire to support the technologies of the future and innovate for innovation’s sake. Without this culture in place, investors and funds alone will be inadequate to support a large innovation market. Innovation policy can help create this culture, as can private sector seed funding or large companies acquiring start-ups and giving entrepreneurs the space to take risks.

V. Innovation policy

The role of a government or public body is to minimise the challenges of misaligned incentives and changing capital requirements of innovation via monetary and non-monetary interventions. Governments have a range of policy options available to them to address these challenges and improve the social outcomes of innovation, from monetary interventions to compensate for a limited ecosystem of investors or misaligned incentives preventing socially beneficial projects being invested in to non-monetary interventions to foster a culture of innovation investment, ensure strong links between agents in the ecosystem, or provide market support.

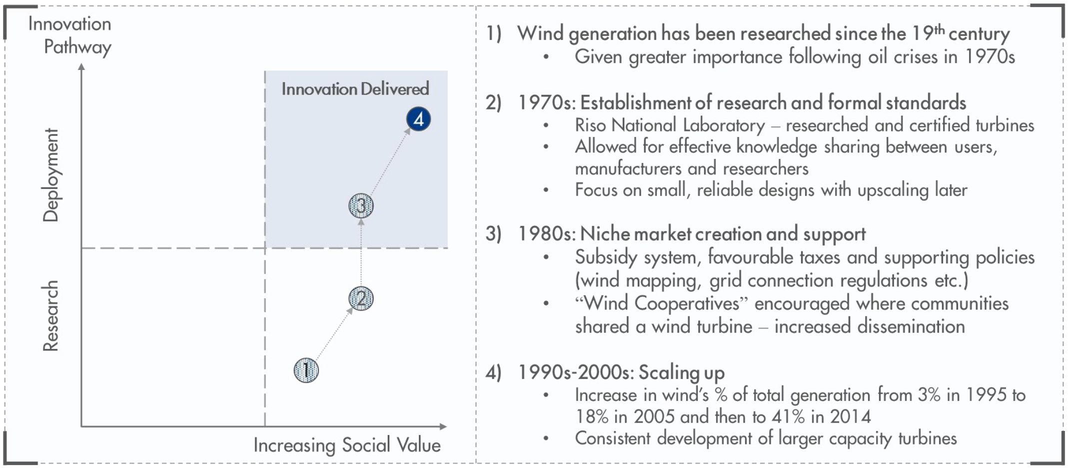
While inefficiencies within the innovation process create a role for public intervention, what defines 'success' or 'failure' of such interventions is less so. Innovation is an experimental process: whilst discovering viable technologies is a key aspect of innovation, there is inherent unpredictability and uncertainty in which technologies are going to ‘win’, and hence should be supported. There are also indirect spill overs and learnings that arise even when technologies do not reach the general market, which are valuable nonetheless. Consequently, defining success purely on the widespread use of a new technology will not create the optimal environment for successful innovation.

Innovation policy should not be judged solely upon the final success of specific technologies. Instead, policy should support projects based on expectations of high social value[4] and be responsive as more information becomes available over time and the expected value of the project changes. Whilst producing winning technologies is the ideal outcome, stopping projects in good time when it becomes apparent that they are no longer beneficial is also desirable. Hence, exploring the dynamic path of innovation as well as the final outcome is key to effective innovation policy.

How policy support changes in response to unexpected circumstances is a key part of successful interventions, and actions taken in response to changing circumstances and shocks carry more weight rather than the final outcome. Figure 10 and Figure 11 illustrate two contrasting pathways. Wind power was developed in several countries during the 1970s, with different policy approaches at different stages resulting in diverging outcomes. Germany chose to focus heavily on R&D in large-scale turbines whilst Denmark adopted a more holistic programme of support that ultimately proved more successful. Germany then showed flexibility by later adopting many aspects of the Danish programme and achieving large-scale wind deployment despite initial setbacks.

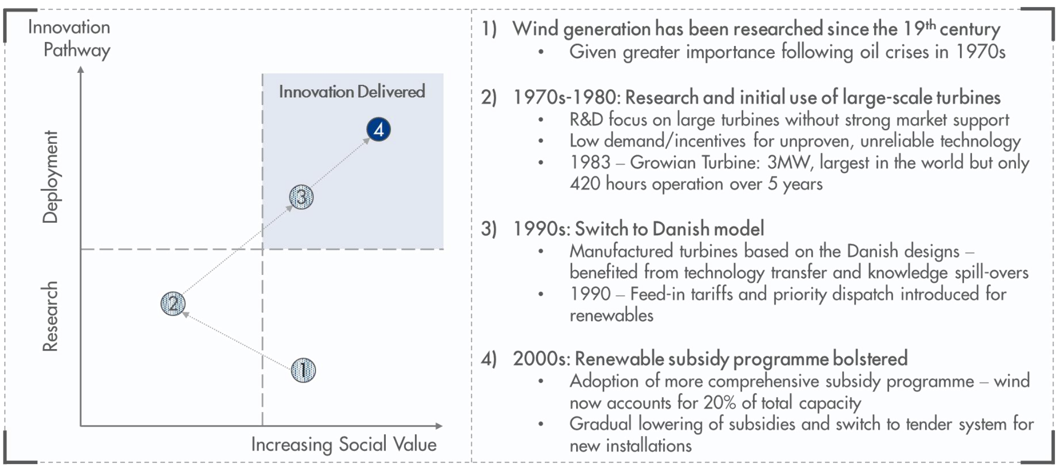
[4] Social value is defined as the total benefit to society, both directly and indirectly via externalities, normalised by the project cost. High social value innovations generally create a new or improved service or have significant positive externalities.

Figure 10. **Denmark successfully delivered innovation in wind power by focusing on reliability and supporting niche markets**



Source: *Irena-GWEC, 2013a; Neij & Andersen, 2012; IEA, 2016*

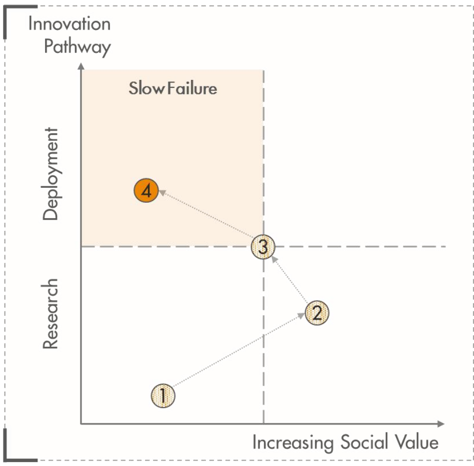
Figure 11. **Germany's initial efforts to produce large-scale turbines were unsuccessful, but a shift in policy eventually led to a successful deployment of wind capacity**



Source: *Irena-GWEC, 2013b; Neij & Andersen, 2012; EIA, 2014*

Dynamic innovation policies along the innovation pathway will help ensure that the appropriate market signals at each stage are not drowned out. Maintaining an appropriate level of exposure to competition at each stage of innovation is important to make full use of market signals in guiding policy decisions. As innovations become more developed, increasingly exposing them to market conditions can provide useful signals on the expected future social value of the innovation. Providing overly-generous budgets or limited exposure to competing technologies in the later stages of the innovation pathway can prevent the viability of a technology from being tested, and policy decisions on whether to continue support or not more difficult.

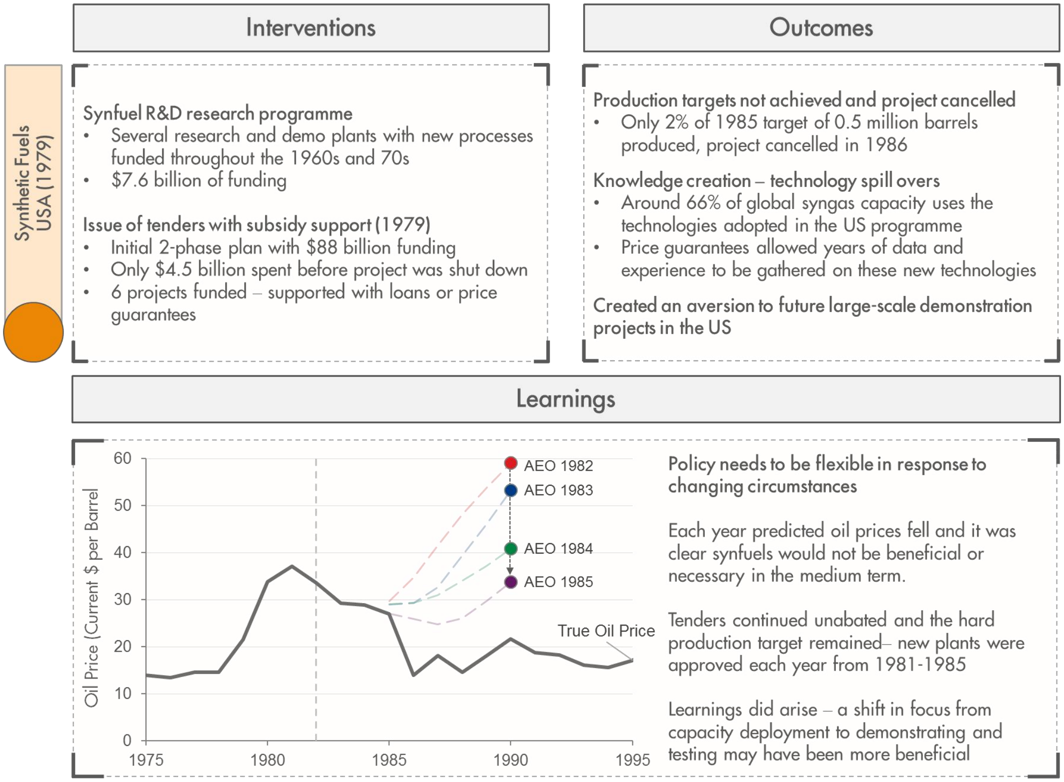
Figure 12. **Synthetic fuels in the US ended as a slow failure due to rigid production targets and a lack of flexibility to changing circumstances**



1) 1925 -1956: Synfuel research first conducted
   - Pilot plants shut down in 1950s due to high costs
2) 1970s: Oil Crisis, research into synfuel production technologies
   - Brent spot price rises from $14 to $37 from 1978-1981
   - EIA predicts trend to continue ($60 by 1990s), making synfuels viable for the future
3) 1980 -1985: Synfuel production target set, 6 contracts awarded
   - President Carter criticised for lack of response to oil crisis – potential nudge to implement large-scale project
   - 500,000 barrels per day target by 1987 – no consideration for oil prices in this target
   - Oil prices peaked in 1980, fell each year after but tenders still consistently issued – lack of flexibility
4) 1986: Oil price crash and termination of the project
   - Oil fell to $14 in 1986
   - Less than 2% of 500,000 barrel target produced
   - Total expenditure of $4.5 billion (2010$)

Source: *Anadon et al., 2012; Deutch & Lester, 2004*

Figure 13. **The targets of the Synthetic Fuels Corporation never changed despite changing circumstances – a different approach may have led to the programme being better received**



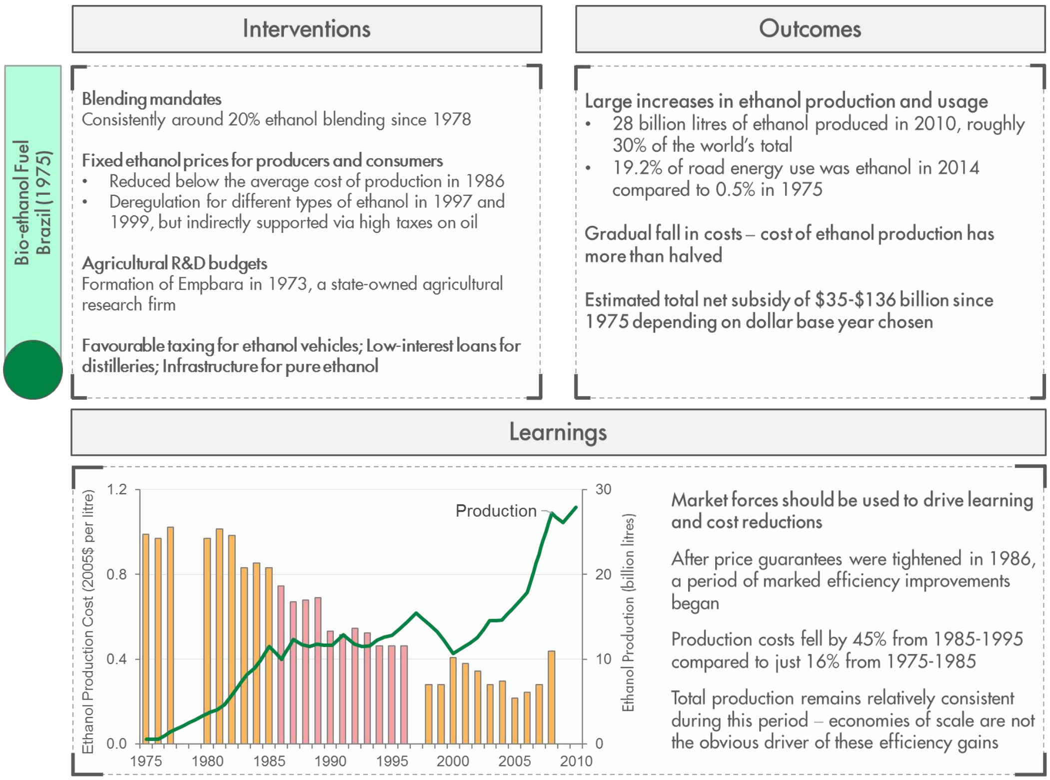
Source: Anadon, Nemet, & Schock, 2012; EIA, 2005; Deutch & Lester, 2004

The deployment of synthetic fuel capacity in the US illustrates the issues that can arise when policies are rigid and not updated with new information. By not responding to sharply declining oil prices, the US synthetic fuels project committed itself to developing capacity that would no longer be viable in the intended time frame, rather than shifting focus to developing alternative technologies that could be more valuable within in the new context (see Figure 12 and Figure 13).

However, trade-offs exist for government 'picking winners' versus allowing market forces to determine innovation. Market forces have many positive aspects, such as forcing private agents to bear risk, implementing market discipline and incentives to improve efficiency as well as potentially reducing information asymmetry. Governments providing direct monetary support run the risk of supporting a 'winner' and not exposing it to the right level of competition as it progresses through the stages of innovation. This not only limits incentives for efficiency improvements but can also mask signals indicating when an innovation is not providing significant value above existing or other innovative solutions.

The efficiency of ethanol production in Brazil increased sharply once subsidies were reduced, demonstrating the benefits of market forces and the potential consequences of 'picking winners'. As described in Figure 14, ethanol fuel in Brazil was supported for its ability to improve energy security and provide demand for domestic sugarcane production. It was never intended to be a cheaper alternative to gasoline when the project first came into being in 1975, but predictions of future high oil prices led to sustained generous subsidies and a belief that ethanol would become competitive naturally over time. After economic difficulties in 1985 and the oil price crash in 1986, guaranteed prices for ethanol were reduced, causing ethanol production to fall for the first time since the programme began. It was only following this reduction in guaranteed prices that ethanol production efficiency began to increase rapidly and consistently. From 1985-1995, production costs fell by 45% and average costs over that period were nearly 40% lower than for 1975-1985. Efficiency gains were obtained throughout the entire supply chain, from improving agricultural yields to larger distilling units and use of waste by-products for heat and energy. This potential for improvement was likely present in the 1970s, but did not arise due to overly-protective government policies.

Figure 14. **A reduction of subsidies led to increases in the efficiency of ethanol production in Brazil**



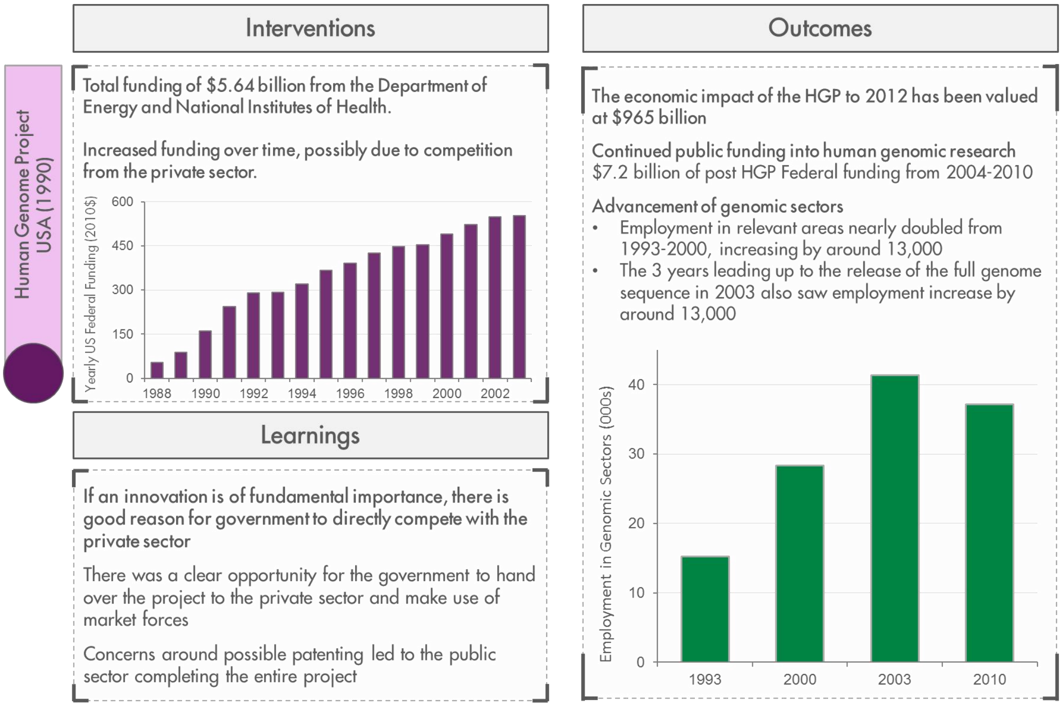
Source: *Goldemberg, 2007; Meyer et al., 2012; IEA, 2016*

i. Monetary interventions

One of the avenues of innovation policy is to provide direct monetary support. The innovation pathway can be an entirely private ecosystem where funding decisions are decided solely by market forces. However, given that frictions and inefficiencies exist, there is scope for appropriate government action to create a net gain for society. This action can be in the form of funding assistance, where the government enters the innovation market as a funder of primary R&D, as an investor, or non-direct assistance to help improve the investment ecosystem and create long-term incentives for investment.

Doing so can ensure that socially beneficial innovations receive funding when externalities and spill overs reduce incentives for investment. Technologies that primarily provide public benefits are unlikely to receive material private funding due to misaligned incentives (and the need for the project to be privately profitable to justify funding). Therefore, a role for government exists in identifying which innovations can deliver desirable social gains and ensuring that they receive the required funding.

Figure 15. **The HGP received heavy federal funding and was not passed to the private sector despite opportunities to do so**



Source: *ITIF, 2014; Tripp & Grueber, 2011; Waterston et al., 2002*

Moreover, there is a case for direct public investment in innovations that are too valuable to be owned as private property. As described in Figure 15, the Human Genome Project (HGP) received $5.6 billion of funding from the U.S. National Institute of Health and the Department of Energy from 1988-2003. In 1998, a private company entered the race with the intention of patenting genes. Instead of handing the project over and relying on market forces, the HGP continued. By continuing to support the HGP and directly competing with the private sector, the data was made open access and has driven rapid development in genomic sectors, drug development, and new avenues for further federal research. The direct and indirect positive economic impact of the HPG to 2012 has been estimated at nearly $965 billion, far outweighing its cost.

Governments can also provide indirect monetary support. They can grant private innovators exclusive access to revenue streams, as an alternative to direct government financing. These revenue streams can create additional profit opportunities. For example, patents grant a time-limited monopoly for an innovation, which has been used effectively in pharmaceutical development. In sectors with regulated prices, such as electricity networks, price formulas can be adjusted to incentivise innovation. In highly competitive sectors, innovation is either necessary to maintain existing margins, in which case the private sector delivers innovation, or margins are so thin that innovation is not rewarded. In the latter case, government can support innovation by offering to buy a new product at a higher than normal price if the new product meets innovative specifications. Finally, the use of public procurement to reward innovation has been an effective tool to support innovation in, for example, improving energy efficiency of the government estate.

ii. Non-monetary interventions

There are other effective non-monetary interventions to support innovation beyond directly funding projects, such as developing the ecosystem of investors.

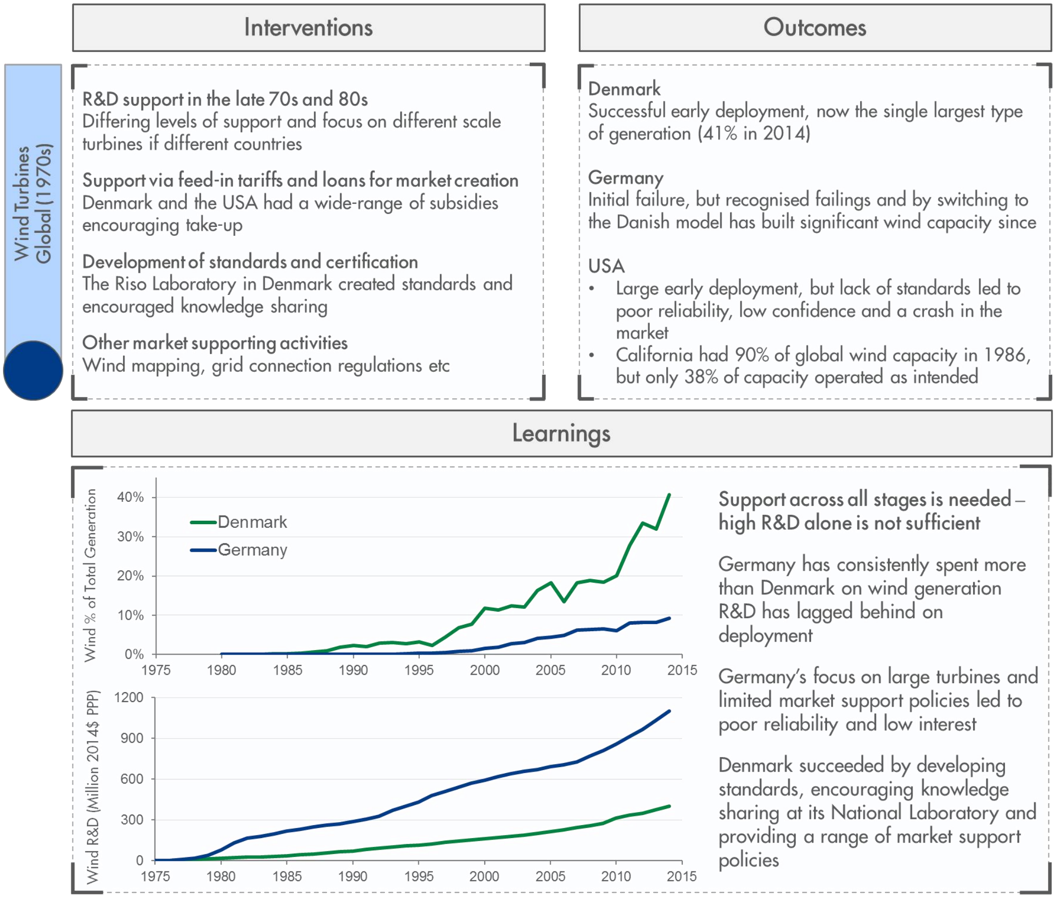
Cultivating a culture of innovation investment and encouraging more agents to participate will facilitate better matching of projects with investors – both in finding investors to take on projects initially and in handing over projects between stages. This helps to resolve the friction of changing capital requirements and risk across stages of the innovation pathway.

Better links amongst agents will help mitigate issues of information asymmetry between investors and make it easier for an innovation to be passed to a more suitable party as it progresses along the innovation pathway. Strong links between agents are also vital for owners of different technologies to collaborate and possibly cluster their assets to form a superior product to induce large-scale change. Strong links can also encourage collaboration across sectors, leading to spill overs where a technology is applied and used in ways that go beyond the original intent of the innovation. Both clustering and spill overs have the potential to increase the avenues of use for an innovation, leading to larger impacts from the technology and increased incentives for innovation.

Developing such an ecosystem of investors can be achieved through institutions that set standards and collect research to encourage knowledge sharing and collaboration between agents. Reliability is a vital factor for new technologies to have successful niche deployments that then lead to upscaling. The collapse of the heat pump market in Europe in the 1980s due to reliability issues and the initial small deployment of wind capacity in Germany during the same time show that a loss of confidence can severely hinder these budding markets. Establishing non-profit institutions to develop standards can help mitigate against such potential losses of confidence.

The contrast between the Danish and German experiences with wind turbine research and deployment shows the importance of an ecosystem approach to innovation and the impact of non-monetary interventions. The Riso National Laboratory in Denmark was tasked with developing a certification process for wind turbines, as well as testing and performing R&D activities. Their role allowed them to coordinate interactions between agents in industry, policy, and research as well as providing technical assistance to manufacturers when required. Denmark also provided strong market support policies, encouraging the adoption of wind power by a wide range of agents. In contrast, Germany had a heavy R&D focus in the 1980s without proper consideration of reliability and other measures of support for the initial deployment phase of wind power. The impact is illustrated in Figure 16, where Denmark's adoption and use of wind power has far outpaced Germany's despite a far smaller R&D spend.

Figure 16. **The comparison of Demark and Germany shows the need for non-monetary intervention**



Source: *Neij & Andersen, 2012; IEA, 2016; IEA, 2015*

References

Anadon, L. D., Nemet, G., & Schock, B. (2012). *The US Synthetic Fuels Corporation: Policy Consistency, Flexibility, and the Long-Term Consequences of Perceived Failures*. Retrieved from http://www.iiasa.ac.at/web/home/research/researchPrograms/TransitionstoNewTechnologies/15_Anadon_US_Synfuels_WEB.pdf

ANFAVEA. (2012). *Brazilian Automotive Industry Yearbook*. Retrieved from http://www.anfavea.com.br/estatisticas.html

C-Net. (2009). Loudcloud: Early light on cloud computing. Retrieved from https://www.cnet.com/uk/news/loudcloud-early-light-on-cloud-computing/

Deutch, J. M., & Lester, R. K. (2004). *Making technology work: applications in energy and the environment*. Cambridge University Press.

EIA. (2005). *Annual Energy Outlook Evaluation 2005*. Retrieved from https://www.eia.gov/outlooks/archive/aeo05/evaluations/

Frankfurt School of Finance & Management, & Bloomberg New Energy Finance. (2017). *Global Trends in Renewable Energy Investment 2017*. Retrieved from http://fs-unep-centre.org/sites/default/files/publications/globaltrendsinrenewableenergyinvestment2017.pdf

Goldemberg, J. (2007). Ethanol for a Sustainable Energy Future. *Science*, *315*.

IEA. (2015). IEA Energy Technology RD&D Statistics. http://doi.org/10.1787/enetech-data-en

IEA. (2016). *IEA World Energy Balances*.

Irena-GWEC. (2013a). 30 Years of Policies for Wind Energy: Lessons from Denmark. Retrieved from https://irena.org/DocumentDownloads/Publications/GWEC_Denmark.pdf

Irena-GWEC. (2013b). *30 Years of Policies for Wind Energy: Lessons from Germany*. Retrieved from https://www.irena.org/DocumentDownloads/Publications/GWEC_Germany.pdf

ITIF. (2014). *Federally Supported Innovations: 22 Examples of Major Technology Advances That Stem From Federal Research Support*. Retrieved from http://www2.itif.org/2014-federally-supported-innovations.pdf

Meyer, D., Mytelka, L., Press, R., Dall'Oglio, E., de Sousa Jr., P., & Grubler, A. (2012). *Brazilian Ethanol: Unpacking a Success Story of Energy Technology Innovation*.

Retrieved from http://www.iiasa.ac.at/web/home/research/researchPrograms/TransitionstoNewTechnologies/13_Meyer_Brazil_Ethanol_WEB.pdf

Neij, L., & Andersen, P. D. (2012). *A Comparative Assessment of Wind Turbine Innovation and Diffusion Policies*. Retrieved from http://www.iiasa.ac.at/web/home/research/researchPrograms/TransitionstoNewTechnologies/11_Neij_Wind_Power_WEB.pdf

The New York Times. (2009). U.S. Drops Research Into Fuel Cells for Cars. Retrieved from http://www.nytimes.com/2009/05/08/science/earth/08energy.html?mcubz=1

Tripp, S., & Grueber, M. (2011). *Economic Impact of the Human Genome Project*. Retrieved from https://www.battelle.org/docs/default-source/misc/battelle-2011-misc-economic-impact-human-genome-project.pdf?sfvrsn=6

US Energy Information Administration. (2014). Electricity Capacity. Retrieved from http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm

Waterston, R., Lander, E., & Sulston, J. (2002). *On the sequencing of the human genome*. Retrieved from http://www.pnas.org/content/99/6/3712.full