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Scale and innovation in the energy sector: a focus on photovoltaics and nuclear fission

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Abstract
Energy technologies have a tendency to become locked in. Mature technologies are favoured due to their accumulated experience and low costs, preventing the entry of new competitors into the market. Public policies support technological evolution in the energy sector through research, development, demonstration and market transformation initiatives. These programmes can reduce CO_2 emissions. Their scope, however, is limited by costs and therefore efficiency is critical. Based on a study of photovoltaics and nuclear fission, I show that the scale of an energy technology influences its responsiveness to policy interventions. Rapid innovation can be more effectively supported with limited funds for small scale technologies than for those restricted to the size of a large power plant. An energy infrastructure consisting of small scale technologies may more readily adapt to strict emissions regulations.

Keywords: scale, innovation, learning curves, energy, climate change

1. Introduction

Measures to rapidly stabilize CO_2 emissions are unpopular due to their anticipated negative effects on economic growth. An assumption here is that the energy technology sector is not able to adapt to ambitious regulations while continuing to supply affordable electricity and fuels. Regulations, such as those prompted by the Kyoto Protocol, are therefore lenient in the near-term. They must, however, become significantly more stringent if we are to meet CO_2 stabilization targets (at ∼450–550 ppm) expected to prevent the most damaging impacts of climate change. The potential for our energy infrastructure to evolve in response to regulations is limited by technological lock-in. Mature technologies have benefited from learning and cost reductions associated with experience and therefore have an advantage over new competitors. The lock-in of mature technologies can prevent both the market entry of new classes of energy technologies (e.g. photovoltaics, wind energy, geothermal energy) and that of new technologies within a class (e.g. thin-film photovoltaic cells).

Public policies are critical for supporting technological evolution in the energy sector, through supply-push programmes such as research, development and demonstration (RD&D) of new technologies, and demand-pull programmes such as emissions regulations. The scope and impact of such programmes is limited by their cost, borne by taxpayers or businesses (and eventually consumers). It is therefore important to make interventions as effective as possible. Several other studies have focused on the structure and effectiveness of such programmes [1, 2]. Here I study how the physical characteristics of scale and modularity of an energy technology affect its responsiveness to policy interventions. Photovoltaics is taken as an example of a small scale technology, where installations can range from ∼100 W to 100 MW; nuclear energy is examined as a representative of a large power-plant scale technology, where installed system sizes range from ∼300 MW to 1.5 GW. I briefly address several other small and large scale examples, and discuss the possibilities of constructing small scale, modular versions of existing large scale technologies. Scale is defined as the smallest installation possible, in units of watts. A modular unit is defined as one that even after modification does not alter the operation of the system within which it is installed. Of interest here is the scale of the smallest modular unit for generating electricity.

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2. Learning curves, innovation and lock-in

The costs of many technologies, including those in the energy sector, have been shown to decrease with increasing cumulative production [3–7]. This is attributed to a set of factors that fall into the following three general categories: increasing economies of scale in manufacturing or in an installed system, learning that results from the manufacturing, installation and operation of a technology, and technology changes that improve performance [8]. The latter two categories can be defined as innovation. The penultimate category is generally incremental. The last category can be incremental or radical. The decrease in cost with increasing adoption can be represented in an experience curve—a more generalized version of the learning curve for an individual firm—which can be as expansive as to cover an entire industry and cumulative production across the globe. An experience curve can be plotted for an aggregate of technologies, such as class of energy technologies (e.g. photovoltaics, wind energy, nuclear fission). Separate learning curves can be plotted for individual technologies within a class if there is limited learning spill-over between them [9].

Increasingly, the dynamic costs of a technology are used as input into predictive energy planning models that estimate the costs and benefits over time of adopting different energy portfolios [10, 11]. One parameter of interest is the learning rate, which refers to the percentage decrease in cost resulting from a doubling of cumulative production. This value can be derived from empirical data, which for many technologies follows a power law (equation (1) below), and can be used to project future decreases in cost and the total cumulative investment required to reach a certain cost (equation (2) below), for example the point at which the electricity generated is competitive with coal-based generation [6]. The lower the starting costs and the greater the slope, the lower the total investment. This investment estimate can include private RD&D expenditures, which may be partly recovered through market transformation initiatives. Public spending on RD&D will often not be reflected in this figure unless it is awarded directly to companies. Public RD&D can, however, significantly affect the learning rate, and various researchers have used a two-factor learning curve to study the effect of RD&D spending on the learning rate, in addition to the effect of increases in cumulative production [12, 13]. In many cases the magnitude of the RD&D spending is significantly less than the total investment estimated by equation (2).

$$c_t = c_0 \left(\frac{n_t}{n_0} \right)^{\alpha}. \tag{1}$$

The learning rate, $1 - 2^{\alpha}$, is the reduction in cost with doubling cumulative production, n_0 is the initial cumulative production, n_t is the cumulative production at time t, and c_t is the cost at time t.

$$C = \frac{c_0}{\alpha + 1} \left(\frac{n_t^{\alpha+1} - n_0^{\alpha+1}}{n_0^{\alpha}} \right). \tag{2}$$

The total cost, C, of reaching c_t is found by taking the integral of the experience curve from n_0 to n_t.

The concept of technology lock-in due to increasing returns, in this context, is based on the idea that as the market for a technology grows the costs decrease and any new competitor (either a new class or new technology within a class) will have difficulty gaining a share of the market, especially when the learning gains with increasing adoption are large. These learning gains are a function of the increase in cumulative production and the learning rate (equation (1)) [14]. This phenomenon limits radical innovation. While investing in a technology allows it to progress along its experience curve and therefore encourages incremental innovation, new and possibly better technologies cannot initially compete, even if they would ultimately achieve lower costs and better performance. Radical innovation can be represented by an experience curve for an aggregate of technologies, for example a class of energy technologies, where new, superior versions are able to enter the market and grow (figure 1). The more radical the innovation allowed, the steeper the curve, and the lower the total investment required to reach cost-competitiveness. (This is true in most cases even when RD&D spending is fully accounted for.) The discussion of learning and experience curves up to this point has dealt with cost reductions. Other types of performance improvement could be shown in a learning curve, where the performance parameter is plotted along the y-axis.

Policy-makers can deal with the problem of lock-in by subsidizing the development of new energy technologies that have a desired quality, such as being less carbon intensive than mature technologies [15]. Typically, technology classes are granted support in the form of supply-push programmes (RD&D) and demand-pull programmes (market transformation) [2, 16].

It is difficult for policy-makers to determine which new classes of energy technologies to support due to uncertainty about their ultimate performance and adoption—this is the classic problem of trying to pick a winner in advance [15]—and it can be even more difficult to pick the best technology within a particular class. Using public policy to create diversity in technology options is important, however, since within each class there may emerge a number of competitors over time with vastly different potentials for eventual high performance and growth (figure 1).

3. Nuclear fission

In the early stages of the nuclear power reactor market three primary technological options emerged—light water, heavy water and gas graphite reactors [17]. These differ in the coolant material used to transfer heat from the reactor core, and the material used as a moderator to control the energy level of the neutrons in the reactor core. For light water reactors the coolant and moderator are both water. For heavy water reactors the coolant and moderator are heavy water. Gas graphite reactors employ a gas such as helium or carbon dioxide as the coolant and graphite as the moderator. While demonstration and commercial reactors were built for each of these three technologies—the first reactor to be connected to the electrical grid was a gas graphite reactor at Calder Hall in the UK in

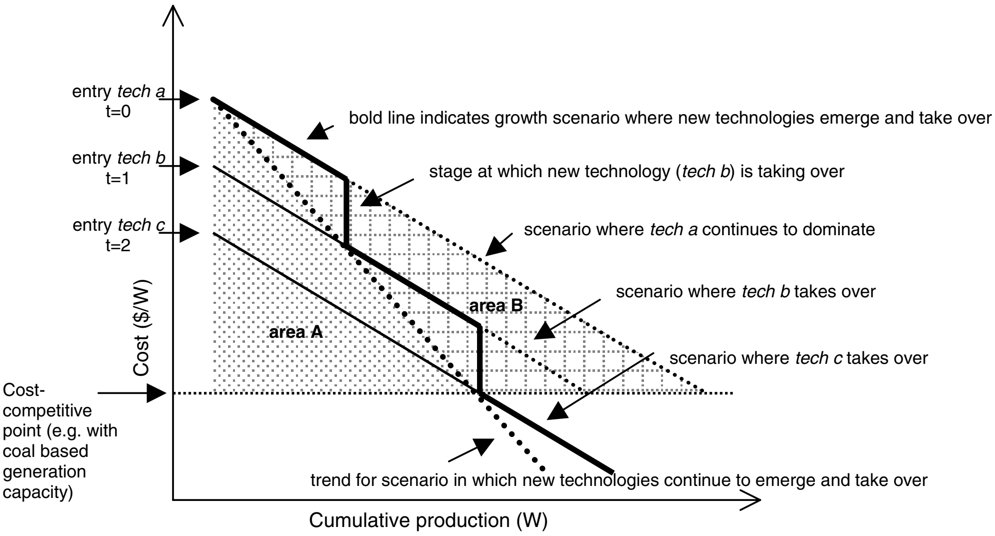

Figure 1. Schematic of experience curves on a log–log plot for a class of technologies (*techs a,b,c*), showing incremental (scenario where *tech a* continues to dominate) and radical (scenario in which new technologies continue to emerge and take over) innovation leading to cost reduction. This figure illustrates the effect of innovation on the slope and the total investment to reach a cost-competitive point. The first technology to enter the market at time $t = 0$ is *tech a*. At $t = 1$, *tech b* enters, followed by *tech c* at $t = 2$. If *tech a* has progressed far enough along its experience curve, then *tech b* may not be competitive with it initially, and must reach a competitive point before it can take over the market (vertical section of bold line). In the case where new technologies continue to emerge and take over (bold solid line), the resulting trend in cost reduction (bold dotted line) follows a power law. Other assumptions about the timing of entry of new technologies could result in cost reduction trends with other functional forms. The scenarios affect the total investment required to reach a cost-competitive point. For example, if *tech a* continues to dominate, the total investment = area A + area B. In the scenario where new technologies continue to emerge and take over (bold dotted line), the total investment is approximated by area A. Small changes in the slope of the experience curve can have a dramatic effect on the total investment required to reach a cost-competitive point. For example, in the case of photovoltaics, a 5% difference in the learning rate (from 25% to 20%) can lead to a 25 billion US dollar difference in the prediction of the total investment required to reach a cost-competitive point. These values are also very sensitive to the assumed starting costs [6].

1956—the light water reactors fairly rapidly began to dominate the market. By the mid 1980s light water reactors controlled over 70% of the market in terms of reactor numbers [17], and they continue to dominate today with about 80% of the market in terms of reactor numbers and 90% in terms of installed capacity (figure 2) [18]. This happened despite doubts expressed by a variety of stakeholders throughout the early years of the industry about whether this was the best technology in its class [17].

The historical events associated with the dominance of the light water reactor have been convincingly characterized by Cowan, as a combination of the early adoption by the US navy in the 1940s for its propulsion programme, the subsequent desire for quick construction of a nuclear generating station (after the explosion of the Soviet nuclear bomb in 1949), and subsidies given to light water reactors by the US government in an attempt to support the dominance of this technology worldwide [17]. The dynamic increasing returns in this market appear to have been significant, causing the first technology to gain adoption to have a great advantage over other technologies attempting to enter the market, regardless of their merits. The purpose of this paper is not to determine which technology is superior, but rather to understand factors governing whether a new, superior technology would be able to grow. It appears from historical data that competitors to light water reactors were fairly quickly closed out of the global market.

A few factors can explain why the increasing returns would be large in the nuclear power industry, and why the sector was sensitive to the historical events outlined above. Much of the learning-by-doing and associated decreases in costs happens in the process of building reactors, and in optimizing the operation of the reactor [17, 19]. A second type of learning involves developing the ability to better predict the cost of electricity generated by a reactor; much of this learning also takes place during construction and operation [19]. Learning of these two kinds happens through the building and operation of demonstration and commercial scale plants, and gives an advantage to the first reactor technologies to be built [17, 19]. A demonstration reactor is costly due to its large scale—today estimates for new ‘Generation IV’ reactors range from approximately 0.5 to several billion USD [20, 21], and projects are estimated to require at least 6 years [20]. Significant changes to the reactor design must be tested in a demonstration plant, thus the size of the modular unit is that of the reactor. A full-scale commercial reactor is even more costly than a demonstration plant. Due to these high costs, there are limited opportunities for subsidized demonstration and early commercial scale plants. Once light water reactors gained a small lead it became difficult for the other technologies to catch up.

4. Photovoltaics

In a photovoltaic (PV) system, a module is combined with balance of system (BOS) components, including a support

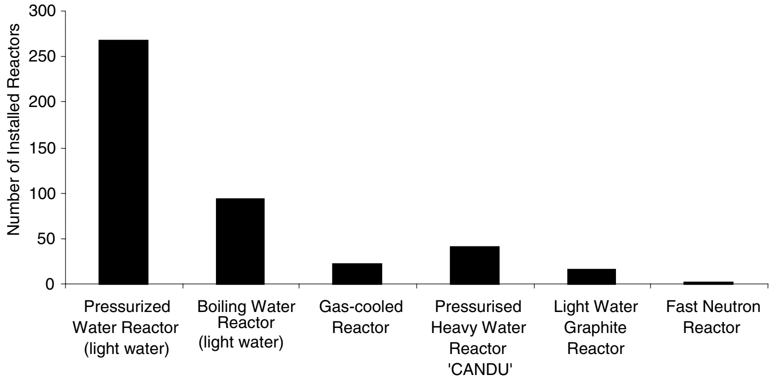

Figure 2. Global nuclear power plants in commercial operation, 2006. Light water reactors account for 82% of the total number of installed reactors, and 88% of the total installed capacity. The total installed capacity of all nuclear fission reactors in 2006 is ~370 GW [18].

Table 1. Cumulative production and annual growth rates by technology. TF = thin-film; a-Si = amorphous silicon; x-Si = crystalline silicon; CdTe = cadmium telluride [22].

PV technology	Cumulative production 2004	Production growth in 2004
CdTe (TF)	20 MWp	132%
a-Si (TF)	310 MWp	53%
x-Si	3482 MWp	50%
All PV	3820 MWp	53%
x-Si percentage of total	91%	—

structure, a current collection system and an inverter, to generate electricity. The module is the most high-tech and capital-intensive component of a PV system. A system can be built with a single module or many modules, and range in capacity from ~100 W to ~100 MW. In the PV sector, there are several module technology competitors that operate based on different scientific principles. The dominant module technologies can be divided into the categories crystalline silicon (x-Si) and thin-film (TF). There is likely to be limited learning spill-over between these categories [9]. The most common PV technology today is crystalline silicon, followed by several thin-film technologies, including amorphous silicon (a-Si), polycrystalline cadmium telluride (CdTe) and polycrystalline copper indium diselenide ($CuInSe_2$ alloys, or CIS) (table 1).

Based on its large market share, crystalline silicon does appear to have benefited from increasing returns [8]. However, new thin-film technologies have been growing in recent years. CdTe, for example, grew 132% in 2004 (table 1), and a CdTe manufacturer, First Solar, successfully bid for a 100 MW project in Germany [23, 24]. One factor that may have contributed to the early success of crystalline silicon was the possibility for PV manufacturing firms to purchase unwanted silicon from the semiconductor industry, rather than having to process their own silicon. The recent growth in TF systems roughly coincides with a shortage in silicon for PV modules from the semiconductor industry, due to increasing demand for PV systems. Even if this is taken as a complete explanation for the increase in TF systems, it is notable that this market-ready alternative existed and was ready to grow so rapidly.

Similar to the case of nuclear energy, the first PV module technology to be installed in an operating PV system will have an advantage over other competing technologies as it will have progressed some distance along its experience curve [8]. The PV technology that gains the largest market early on will benefit from economies of scale in module manufacturing, learning in manufacturing and installation, and the ability to accurately predict installed system costs. The longer the dominance persists, the harder it will be for new technologies to compete.

Unlike a nuclear fission reactor, however, a PV module is a small scale, modular unit—major differences in the module type do not significantly change the requirements for the other components of the system. For PV systems, much of the learning and associated reductions in system cost happen at the stage of manufacturing a PV module. Because of their small scale the demonstration of multiple new module types in small PV systems can be done with limited financial resources. This means that advances can be made in the two main types of learning outlined for nuclear energy—learning by doing and learning about the cost of electricity generated—at relatively low cost. In contrast, as noted earlier, much of the learning and associated cost reduction of a new nuclear fission reactor occurs during the construction of a much larger scale and more expensive demonstration plant.

5. Comparison of technologies

The financial resources required to support the stages of development of a new technology are compared in table 2 for PV and nuclear fission. There is a much higher cost associated with building a single nuclear fission demonstration or commercial unit. Note that the total spending of International Energy Agency (IEA) countries on PV RD&D from 1992 to 2003 peaked in 2000 at approximately 320 million (2004) USD [25]. In comparison, as noted above, the cost of building a single new demonstration nuclear plant is estimated at 0.5 to several billion USD [20]. Table 2 demonstrates that, with a given budget for RD&D, it is possible to support a greater diversity of options for small scale technologies. Similarly, one could envision the possibility of supporting early market

Table 2. Stages of innovation in nuclear and solar energy technology sectors and associated differences in the magnitude of funding required.

Innovation stage	Nuclear fission	Photovoltaics
Research and development (R&D)[a]	Global spending in 2000 on RD&D (including demonstration costs) 3.5 billion (2004) USD [25]	Global spending in 2000 on RD&D (including demonstration costs) 320 million (2004) USD [25]
Demonstration	Generation IV projects ∼1–4 billion USD [20]	Wide range from ∼kW to MW and ∼5000 to 5 million USD
Commercial scale deployment	Costs vary depending on plant size—values >1 billion USD [20]	Wide range from ∼kW to MW and ∼5000 to 5 million USD [23]

[a] R&D projects can be pursued at a variety of scales for both of these technology classes. Note, however, the difference in the magnitude of funding for PV and nuclear energy.

entry for a variety of new small scale technologies, through mechanisms such as small guaranteed markets or prizes. These measures could allow new technologies to reach a market entry point and progress some way along their experience curves. The importance of this for the slope of the aggregate experience curve for a class of technologies was shown in figure 1.

RD&D and market growth (or cumulative production) have been shown to be critical for allowing a technology to make progress along its experience curve [13]. The slope of the curve, which in turn affects the total investment required to reach a certain cost point, reflects a rate of innovation and sensitivity to RD&D and market growth. A simple comparison of learning rates for nuclear fission and photovoltaics is interesting. Whereas the learning rate for PV is estimated at approximately 20% [22, 26], the learning rate for nuclear fission is less than zero, i.e. capacity costs have been increasing with growing cumulative production [27–29]. These learning rates are based on global data for PV and US data for nuclear fission. The increase in capacity costs for nuclear fission is at least partially due to increasing safety regulations, and it has been argued that this should be corrected for in the experience curves. For the purpose of this paper, however, such increases in costs are instructive since they reveal a difficulty in adapting to externally imposed constraints.

A more detailed look at the effect of RD&D on learning is also revealing, since the initial creation of diversity in technologies is primarily done at this stage. Using a two-factor learning curve, researchers have shown a sensitivity of PV to RD&D, finding a ‘learning by searching’ rate of ∼14% [13]. The learning by doing rate estimated in the same study was ∼18%. (A similar analysis for nuclear fission would not show responsiveness to RD&D due to the positive slope of its learning curve.) In addition, a simple comparison between time series data of RD&D and experience curves for these technologies suggests that PV has been more responsive to RD&D than nuclear fission. Figure 3 shows the large decreases in costs in the PV sector (globally) since 1975. The slight increase in costs of nuclear fission capacity is also shown in figure 3 (based on US data). The much higher magnitude of RD&D spending for nuclear fission as compared to PV is shown as well. The data suggest that, in terms of cost reduction, PV was more prone to innovation than nuclear fission. While the differences in RD&D expenditures and cost curves are striking, it is difficult to determine definitively the extent to which these historical trends were influenced by technology scale. Nonetheless, scale could influence innovation rates in future, if the ability to create diversity for small scale technologies is explicitly supported.

Other large scale systems may also be prone to lock-in. These include technologies such as steam cycle power plants that are made from a complex set of interdependent components, where significant changes to the design create economic and technical risks that cannot be fully evaluated until the plant is built, and are therefore often unpopular with owners [30, 31]. Significant learning by doing and learning about the cost of electricity generated happens during installation and operation of full scale plants, as opposed to during manufacturing of modules and demonstration of small scale systems. In contrast, a wind turbine is an example of small scale, modular technology that can be demonstrated at a small scale. The wind turbine has evolved considerably, in terms of materials and design [32].

Neij compared the learning rates of several small and large scale technologies [33]. The average learning rate for a group of ‘modular’ technologies, including electronics and consumer durables, was 20%. The average learning rate for a group of ‘large plant’ technologies, including coal burning and nuclear reactor units, was a negative value. The group termed ‘small scale plants’, including gas turbines, steam turbines and integrated gasification combined cycle, had an average learning rate of 10%.

The scale of the smallest modular generating unit is only one characteristic of a technology that affects lock-in. Other important drivers are whether the technology is benefiting from the development of another technology. Examples of this, mentioned earlier, include light water reactors that were initially developed for submarines, and silicon based solar cells that use unwanted material from the semiconductor industry. Industries with more stringent safety regulations, such as the nuclear fission industry, are also more likely to experience lock-in because it is costly to evaluate a new option. Consumer preference for a known technology can also encourage lock-in. The scale of a technology does, however, affect the likelihood of being able to avoid lock-in due to the above reasons (except perhaps safety regulations, see below), through directed policy interventions to develop and demonstrate alternatives.

It may be possible to develop small scale, modular versions of today’s power plants, including nuclear fission reactors. There are several smaller scale fission reactors being

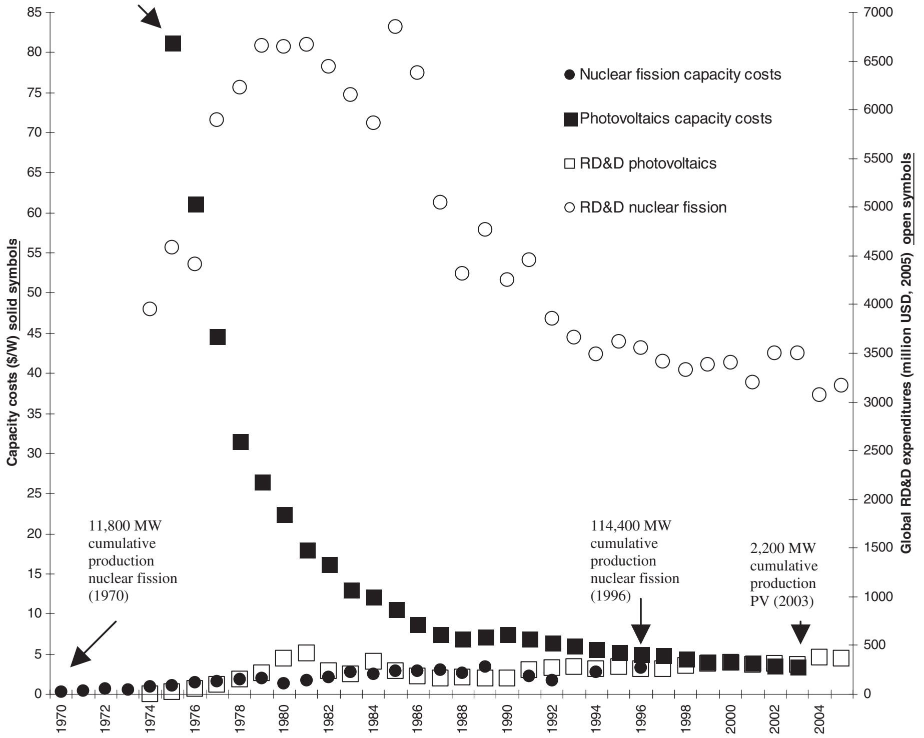

Figure 3. Empirical time series data of RD&D spending for IEA countries (open symbols) [25], and capacity costs (solid symbols) associated with increasing cumulative production of nuclear fission and PV [26–29]. RD&D spending for nuclear fission is of a much higher magnitude that that for PV. Significant cost reductions have been achieved for PV, while nuclear fission costs have increased over the time period. Capacity costs for nuclear fission are based on US data. The PV cost data are global. The capacity costs for PV are assumed to be \$/Wp (USD per watt peak), referring to the capacity of the system under full solar radiation at 1000 W m^{-2}. For the years 1974–1991, RD&D estimates are incomplete as they do not include expenditures for all countries [25]. This does not change the trends reported here. Further details can be provided on request.

proposed (∼30–350 MW) [34], for which it may be possible to design policies to support rapid innovation. One concern is that the barriers to innovation may still be considerable due to the (medium rather than small) size of the proposed reactors. Another challenge is that the smaller size of a reactor can be a disadvantage in terms of licensing regulations, which require a license for each unit at a site [35]. If the manufactured and installed unit is modular, however, it may be possible to regulate the manufacturing plant rather than the installed generation unit. This would require stringent safety controls at the stage of manufacturing and assembly.

If technologies are small scale and modular it is possible to design policies that discourage lock-in of an inferior version, such as one with high carbon intensity or high cost. For example supply-push programmes funding RD&D can support multiple technologies at once. This is much more expensive to do for large scale technologies (table 2). Supply-push programmes allow private actors to assess a new technology and market related risks and decide whether to invest in it and perhaps forward price for a period of time in order to gain market entry. Because it is easier to create and evaluate a diversity of options, small scale technologies may be better able to respond to environmental policies such as CO_2 emissions regulations, allowing the adoption of more stringent regulations without the risks of an economy-wide downturn. Such technologies may provide a competitive advantage to private actors facing regulations.

6. Innovation and climate change

There are a variety of needs for innovation associated with current technology options. In the PV sector, for example, decreasing costs is critical if this technology is to contribute in a significant way to the global energy mix. In a recent study I showed that the entry and rapid growth of new technologies could both dramatically decrease the subsidy required to reach a cost that is competitive with coal based generation, by 60–70 billion USD, and make photovoltaics competitive much sooner than would be expected if crystalline silicon continues to dominate [9]. This is demonstrated by modelling cost reductions in PV systems for scenarios with different rates of growth for crystalline silicon and thin-film technologies.

There are innovation needs in the nuclear energy sector as well. If the nuclear industry is to grow significantly in coming years, given the uncertainties in resource availability and concerns about proliferation of nuclear weapons, there will be a number of technological hurdles to clear [36]. With existing technologies, it is estimated that meeting twice the global electricity consumption (in 2001) would exhaust the assured terrestrial uranium supply in a few years [36]. Extracting uranium from the oceans could supply plants for 2000 years—and breeder reactors for longer than that. These are both processes (and technologies) that are still in development. Concerns about the proliferation of nuclear weapons may limit nuclear power to specific regions of the world, unless a proliferation-safe fuel cycle can be developed, and this geographical limitation may make nuclear seem a less attractive option for capping global emissions. For these reasons innovation will be very important for nuclear energy, and lock-in a potential barrier to the ultimate success of the industry as a whole, if the first-mover technology is one that is constrained by resource availability, high costs or proliferation concerns. It will be difficult to pick the technology that offers the best solution to each of these problems at the outset; it would be preferable to support a technology class that can evolve considerably over time as the constraints become clearer. Designing policies to allow entry of new superior technologies as they emerge would be facilitated by a focus on small scale modules.

Avoiding lock-in to encourage innovation can be critical in reducing the costs of clean technologies, decreasing the carbon content of already inexpensive technologies, or achieving other performance enhancements. Since we do not currently have a sufficient set of clean, cost-competitive energy conversion technologies to meet emission targets over the coming century, innovation (and invention) is critical for mitigating climate change.

7. Conclusions

Preventing the most damaging impacts of climate change [1] requires substantial growth in the contribution of clean energy technologies to the global energy mix. Innovation is critical for reducing costs of clean technologies, and reducing the carbon content of inexpensive technologies. Policy interventions can subsidize a variety of new classes of energy technologies, until they reach a cost point where they can grow on their own. Other measures, such as emissions regulations, transform the market to drive the adoption of clean technologies. These policies are important for creating diversity, discouraging lock-in and allowing new, superior technologies to grow. Small scale and modular technologies are likely to be more responsive to these measures and prone to the rapid innovation needed to mitigate climate change.

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