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Deciding how to 'change big things quickly':

Pros and cons of different appraisal techniques to inform decision-making on low-carbon transformational policies

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Developed by the EEIST Consortium, this policy note examines several case studies derived from the experiences of Brazil, China, Europe, India and the UK with low carbon transformational policies in order to shed light on the importance of the tools used to guide decision-making.

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A. Background

In this policy paper, several case studies derived from the experiences of Brazil, China, Europe, India and the UK with low carbon transformational policies are analysed to shed light on the importance of the tools used to guide decision-making. The transition to a low-carbon economy is rapidly changing the environmental but also the economic landscape in which government policy unfolds. Governments around the world must, in this context, decide how to position themselves, where to focus their policy efforts and investment in order to benefit environmentally and economically from the transition to a low-carbon economy.

However, certain decision-making tools which are widely in use to assess the overall desirability of a certain policy action, such as Cost Benefit Analysis (**CBA**), cost-effectiveness and general equilibrium modelling, have significant limitations when the aim is to transform the economy or, in other words, to change big things quickly. This is because such techniques represent the economy as statistically predictable, imposing a status quo bias, and downplaying the crucial systems dynamics that, in reality, drive transformative change.

This policy note narrates four cases of highly successful technology programs. Their purpose is to illustrate key differences between the guidance that could be derived from CBA approaches and other approaches, such as the Risk-Opportunity Approach (**ROA**)[1] framework being developed by EEIST, which consider the economy as a complex system in constant change. We show that these successful technology decisions were made on considerations other than what the application of a CBA would have suggested. In other words, under a CBA representation, these major success stories would have appeared as not cost-effective and possibly not worthwhile, thus removing essential arguments in favour of their adoption. Yet, due to the diffusion and cost dynamics that have been empirically observed, as impacts of the policy strategy, the technologies have become cost-effective, indeed transformational. Suitable appraisal techniques capable of representing these dynamics are therefore urgently needed to inform decision-making on how to ‘change big things quickly’.

B. The rise of the UK offshore wind industry

The cost of generating electricity from offshore wind in the UK has fallen from around £170/MWh in 2008, to around £40/MWh for projects coming online in 2023.[2] In just over a decade offshore wind has evolved from an expensive, relatively immature technology, to one that is competitive with fossil fuel generation, and is soon likely to produce ‘negative’ subsidy. Costs are set to continue falling[3], cementing its economic attractiveness and future contribution to electricity generation, and producing the wider economic benefits that attends the growth of a substantial new industry with a global market. This outcome is largely the result of strong, well-targeted, and sustained policy support from the UK government. A review of

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[1] Sharpe, S. et al. Deciding how to decide Risk-opportunity analysis as a generalisation of cost-benefit analysis. (2020); Mercure, J.-F. et al. Risk-opportunity analysis for transformative policy design and appraisal. (2020). Available at www.eeist.co.uk/output.

[2] Jennings, T., Tipper, H. A., Daglish, J., Grubb, M. & Drummond, P. *Policy, innovation and cost reduction in UK offshore wind*. (2020).

[3] Farmer, J. D. & Lafond, F. How predictable is technological progress? *Res. Policy* (2016). doi:10.1016/j.respol.2015.11.001; Jennings, T., Tipper, H. A., Daglish, J., Grubb, M. & Drummond, P. *Policy, innovation and cost reduction in UK offshore wind*. (2020); Rechsteiner, R. German energy transition (Energiewende) and what politicians can learn for environmental and climate policy. *Clean Technol. Environ. policy* 1–38 (2020).

the evidence surrounding this success story has been published by the Carbon Trust and members of the EEIST consortium in a previous project[4], from which key elements are summarised below.

A key aspect of this success story is that **decisions that led to the creation of the policy framework targeting offshore wind technology were made on the basis of strategic considerations, and they may not have happened if analysis using standard Cost-Benefit Analysis (CBA) had determined decision-making**. Thanks to this policy, which offered effective financial support per MWh of electricity produced to renewables operators, offshore wind benefited from £140-£150 per MWh, which corresponds to a contribution of around £280/tCO_2e. By way of comparison, the carbon price used in cost-benefit exercises at the time, and the value of carbon emissions in UK policy appraisal, was £14/tCO_2e in the power sector and £59/tCO_2e in other sectors. This could have seemed disproportionately large and unsound value for money in CBA, especially if the financial contribution had been understood to be required indefinitely. And indeed, CBA would have suggested that other emissions reductions options existed at much lower prices, such as planting trees in tropical countries.

On a strategic basis, costs were expected to decline and the intention was partially to develop industry and industrial capabilities. And indeed, costs have gone down dramatically as a result of the policy, from over £200/MWh back in 2008 to around £120/MWh in 2015, going down steeply to £60/MWh in 2020 and a forecast between £30-£50/MWh for 2030. This is below the cost of gas electricity of between £60-£100/MWh. Suffice to say the policy support will not be needed much longer, and the UK is now in a much better position to export offshore wind technology, knowledge, and related services. **For EEIST, the learning to extract from this transformation concerns the observed technology dynamics and, specifically, the need for better decision-making tools capable of foreshadowing such transformational effects**. **This is precisely what EEIST is trying to achieve with the development of its Risk-Opportunity Assessment (ROA) framework**. Having such tools available to decision-making would enable policy-makers to make the case for such policies on more than political/strategic considerations and against misleading arguments derived from CBA analysis.

The policy initiative that made the transformation possible can be summarised as follows. To achieve its target of 10% of electricity generated from renewables by 2010, in 2002 the UK government introduced the Renewables Obligation (RO): a tradable green certificate mechanism providing subsidy in addition to the market price of electricity. As the RO was technology-neutral, it favoured the construction of mature, lowest-cost renewable technologies, such as onshore wind. In 2009 the government introduced technology ‘banding’; awarding more Renewable Energy Certificates (ROCs) to less mature technologies to encourage their development (with offshore wind receiving two ROCs per unit of generation, for 20 years following accreditation). At this point the RO had no cap on either budget or capacity, and the government held levers to ensure the price of ROCs remained stable. In 2008-09, three other key enabling policies and measures were introduced:

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[4] Jennings, T., Tipper, H. A., Daglish, J., Grubb, M. & Drummond, P. *Policy, innovation and cost reduction in UK offshore wind*. (2020).

- In June 2008, Round 3 of the Crown Estate ‘leasing rounds’ took place. The British Crown, which owns the seabed surrounding the UK up to 12 nautical miles, auctioned rights for seabed space sufficient for over 32GW of offshore wind capacity[5]. In doing so it also invested £80 of co-funding for developments, and a range of other actions to improve understanding of offshore wind development.
- In October 2008, the Offshore Wind Accelerator (OWA) was launched. The OWA was launched as a joint initiative between the government (via The Carbon Trust) and nine leading offshore wind developers to accelerate cost reduction (aiming for 10% by 2015) and technology reliability via RD&D, to feed into installations to be built under Crown Estate Round 3 leases. When launched the OWA was funded two-thirds by industry and one-third by the UK and Scottish governments.
- Following the EU’s Third Energy Package, which required electricity transmission and generation assets to have separate ownership, the UK regulator (Ofgem) began a new Offshore Transmission Owner (OFTO) regime, awarding transmission operator licences via competitive tendering. Although this did little to reduce transmission costs itself, the separation of assets allowed low-risk transmission infrastructure to receive much reduced cost of capital. As transmission assets comprise 10-20% of the cost of offshore wind farms in the UK, this produced substantial savings.

The stability, long-term security, and relative generosity of the subsidy provided by the RO allowed developers space to experiment, for the industry to form, core technical knowledge to grow, and ‘learning by doing’ to develop across the supply chain (including in the financial sector, which alongside the OFTO, allowed the cost of capital to fall). The absence of mechanisms to induce competition between developers also encouraged collaboration, supported by the OWA in particular.

In 2013 the RO was replaced by a Contracts-for-Difference (CfD) scheme, in which a certain volume of new renewable capacity is sought in ‘rounds’, to which eligible renewable generators applied received a fixed ‘strike price’ for 15 years of generation capacity. If the market price for electricity falls below the strike price, the government pays the difference. If the market price exceeds the strike price, the generator pays the government the difference. Contracts are awarded in two ‘pots’; one for mature technologies, and one for less mature technologies (including offshore wind). In 2014/15, the process became fully auction-based, with the lowest bids receiving contracts until the capacity available in each pot is satisfied (with all successful bidders receiving the same strike price, set at the level of the highest successful bid). In Round 1 in 2015, 1.2GW of offshore wind contracts were granted – 54% of supported capacity. Shortly afterwards support for solar PV and onshore wind was removed due to political opposition, with the majority of new CfD support to focus on less mature technologies, and particularly offshore wind. In Round 2 in 2017, 3.2GW of offshore wind represented 96% of all newly contracted capacity, and 93% of the total 4GW of contracted capacity in Round 3 in 2019. In 2019, the government and offshore wind industry agreed the Offshore Wind Sector Deal (OWSD), guaranteeing CfD action rounds every two years to achieve at least 30GW of deployment to 2030 (increased to 40GW in late 2020), along with measures such as local

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[5] Sharpe, S. *et al. Deciding how to decide Risk-opportunity analysis as a generalisation of cost-benefit analysis*. (2020).

content requirements and an aim to treble the size of the UK offshore wind workforce (with supporting initiatives).

In contrast to the RO, the CfD mechanism held an explicit objective of reducing costs of the now-maturing technology through competition, encouraged by a target of achieving £100/MWh from offshore wind by 2020, as determined feasible by the UK's Offshore Wind Cost Reduction Taskforce in 2012. The CfDs, with the long-term commitments made in the OWSD, provided the industry with sufficient confidence to build on the developments made under the RO regime and invest in future growth and innovation. This generated economies of scale in local manufacturing capacity, the size of the turbines, and the number of turbines in a single project; investment in developing specialist support technologies (such as bespoke installation and maintenance vessels) and workforces and skills (both of which were previously repurposed from the oil and gas industry); and other improvements and efficiencies produced by continued learning-by-doing. The stable long-term support regime, coupled with increasing project size and accumulating experience also attracted a wider range of investors, further reducing finance costs.

Broadly, the cost reductions achieved have been the result of a combination of well-designed and context-appropriate 'technology-push' and 'demand-pull' policies, dominated first by the RO to encourage commercialisation, and then by the CfD to introduce competition once the technology was near maturity. But, throughout, these instruments were supported by both high-level, long-term commitments to the technology, and by more granular enabling measures to address specific barriers to development and diffusion[6].

CBA could not have foreseen the above storyline for the following reasons. It is generally not the case that learning-by-doing that results from increased technology roll-out is considered in the discounted expected costs calculated, nor the way in which lower costs attracts more roll-out in an overall positive feedback. This may be partly due to the substantial uncertainty over the size of the expected technology roll-out, which may be seen as obscuring the analysis, and partly due to the complexity involved in setting up such a strong positive feedback in models. Learning curves are also not generally included in energy system cost-optimisation models (such as UK-Times or MARKAL) since the inclusion of positive feedbacks prevents optimisation models from converging. Therefore, the possibility that offshore wind costs could decline dramatically was in all likelihood *specifically excluded* by the models available at the time. Meanwhile, it is also clear that after the fact, a decade later once costs have come down following these innovation dynamics, CBA could now tell a completely different story, since offshore wind is now at or near parity with other technologies.

The question for EEIST is therefore what decision-making tools could have guided a transformational policy decision that CBA could not. In a policy appraisal process using ROA and working closely with analysts using transition models that represent the co-evolution of costs, technology attractiveness and roll-out, a storyline consistent with the above could have been foreseen. The risks analysed could have included in the diverse ways in which a lack of uptake and volume could have materialised. Meanwhile, the opportunities analysis could have laid out the advantages, on indicators such as employment, innovation activity, skills, industrial capabilities and economic activity, of successfully developing an offshore wind industry.

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[6] Mercure, J.-F. *et al. Risk-opportunity analysis for transformative policy design and appraisal*. (2020).

C. Financing Brazil's wind energy

The UK case is but one example of how transformational policies can support the low-carbon transition and the need to develop appropriate tools for this type of decision-making processes. Wind power is also a success story in Brazil, in which the development bank has played a key role. This case study is drawn from Ferraz et al.[7]

The energy sector in Brazil has historically been dominated by hydroelectric power. In the early 2000s, Brazil was gripped by a drought, which led to an energy crisis as hydroelectricity production depends on water availability. This started the search for alternatives. In 2004, the government created two markets for energy investments: regulated auctions with a guaranteed demand on the one hand, and an unregulated regime of bilateral contracts.

The quasi-publicly financed Brazilian Development Bank (BNDES) plays a key role in the Brazilian economy: it covered 20% of Brazil's total investments between 2007 and 2015, with an emphasis on infrastructure.[8] Its goal is to finance investments that support development. In addition to its broad mission-driven remit, it also has the capacity to identify opportunities due to its broad network and qualified professionals.[9]

For wind energy, this opportunity for BNDES arrived with a combination of a favourable policy (auctions with a guaranteed long-term demand), a growing energy market, a decreasing demand for wind during the financial crisis elsewhere (so that suppliers had to find new markets), and technological progress which drove the round prices.

In the first phase of finance in the early 2000s, wind energy projects were most exclusively done via the regulated market. BNDES used its financial instruments to stimulate industrial development: materials needed to be bought from local suppliers. Initially 60% of material had to be sourced locally in line with investments in other sectors, independent of the complexity of the technology. A policy tailored to the wind sector was implemented in 2009 and sophisticated in 2012. Calls were sent depending on the level of technological complexity, said middle range component and high-technology devices would also be stimulated.

As a result of the financial policies, the Brazilian wind industry grew significantly over the last two decades. The stipulation of local sourcing has meant that a regional decentralisation of industry took place to some manufacturing plants in the north-east and south, instead of only in São Paulo.

Under a traditional cost benefit or other static equilibrium analysis, the modelling would have supported the case for cheaper hydroelectric dams in favour of wind in the early stages of development. Furthermore, a marginal analysis would have shown that importing technology is cheaper than producing it locally. This would have missed the opportunity to stimulate the local economy and build a secure supply chain. **The intervention of BNDES relied, as in the case of offshore wind development in the UK, on a wider set of considerations beyond those that CBA could offer.** Firstly, it is well documented that BNDES, which operates on a

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[7] Ferraz, J. C., Ramos, L. & Plattek, B. *Innovations in development finance and conditioning factors: BNDES and the fostering of sustainability-related industries in Brazil*. (2021).

[8] Carreras, M. Investigating the Role of BNDES as a Tool to Transmit Countercyclical Policy Decisions: Evidence from 2002-2016. (2020).

[9] Carreras, M. Investigating the Role of BNDES as a Tool to Transmit Countercyclical Policy Decisions: Evidence from 2002-2016. (2020); Mazzucato, M. & Penna, C. C. R. Beyond market failures: The market creating and shaping roles of state investment banks. *J. Econ. Policy Reform* **19**, 305–326 (2016).

portfolio basis, has in general been successful at picking winners and avoiding picking losers in terms of projects financed.[10] Secondly, developing a domestic industry often makes technology less costly eventually in comparison to imports, while it supports a positive contribution to the trade balance. There are many reasons why this may appear preferable to policy stakeholders in comparison to what equilibrium or cost-benefit analyses could have generated in terms of recommendations. In effect, the structure of the economy and industry has been altered in a permanent way for as long as these new capabilities remain.

D. The *Energiewende* in Germany and China's rise to global leadership in photovoltaics

The late 20th century feed-in-tariff (FiT) in Germany of the *Energiewende* ('energy transition' in English), and the influence it had globally, especially in China, is an important example of how a policy triggered a series of positive feedbacks that led to a rapid decline in the cost of photovoltaics (PVs) globally and thus expedited the transition to a post-carbon society. It did this despite serious criticism at the time from mainstream economists.[11] The resilience of the policy to these criticisms has roots in its broad set of motivations and the political discourses at the time around nuclear energy. These allowed consideration of a wider set of risks and opportunities than a traditional cost-benefit analysis would include.

The anti-nuclear movement in Germany started around the 1970s when local initiatives organised protests against plans to build nuclear power stations. After the accident at the U.S. nuclear power plant Three Mile Island in 1979, around 200,000 people took to the streets in Hannover and Bonn, demonstrating against the use of nuclear power. The nuclear catastrophe in Chernobyl in April 1986 further strengthened the anti-nuclear sentiment. Most German politicians began to state that nuclear was only a "transient" technology and after 1989 no new commercial nuclear power stations were built.

When the Social Democrats and the Green Party won the elections in 1998, the government of Gerhard Schroeder then reached what became known as the "nuclear consensus" with the big utilities. They agreed to limit the lifespan of nuclear power stations to 32 years. The plan allocated each plant an amount of electricity that it could produce before it had to be shut down. In 1998, renewables in Germany provided 284 PJ of primary energy demand, 5% of the total electricity demand.[12]

The 2000 Renewable Energy Sources Act included a FiT in support of renewable energy. The German government, declaring climate protection as a key policy issue, announced a carbon dioxide reduction target by the year 2005 compared to 1990 by 25%. It is during the mid-2000s that the German FiT program spread quickly to other countries in Europe and beyond.[13] As more countries adopted the then profitable FiT model, the ensuing expenditure on renewables jump-started a period of significant increases in demand for PVs, led to manufacturers adding

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[10] Carreras, M. Investigating the Role of BNDES as a Tool to Transmit Countercyclical Policy Decisions: Evidence from 2002-2016. (2020).

[11] GCEE. *The energy transition (energiewende): shifting towards a global climate policy*. (2016).

[12] IPCC. Chapter 3: Social, Economic and Ethical Concepts and Methods. in *Climate Change 2014: Working Group III: Mitigation of Climate Change* (Cambridge University Press, 2014); See the factsheet "Germany's energy consumption and power mix in charts" at https://www.cleanenergywire.org/factsheets/germanys-energy-consumption-and-power-mix-charts

[13] Schmalensee, R. Evaluating policies to increase the generation of electricity from renewable sources. (2011).

more and more capacity. Investors in the second half of that decade, seeing a stable investment, began funding multi-megawatt (utility scale) fabrication plants. By the end of the decade new manufacturers, specifically from China but also other low-cost manufacturing regions, had entered the market with aggressive pricing strategies that were supported by healthy manufacturing subsidies. It is at this point where PVs selling prices fell dramatically, halving in less than two years, with concurrent rapid increases in production.

The FiT, which initially created prices many times higher than the market price, was strongly criticised by neo-liberal economists in Germany.[14] These criticisms revolved around multiple issues: from the environmental and innovation goals themselves, to the mode of intervention (pejoratively classed as 'subsidies' by critics), to not pursuing alternatives such as insulating homes, or simply allowing the European emissions trading system to achieve the same goals. It was also felt that the policy was too focussed on national targets, and a more internationalist approach was needed.[15]

Nonetheless, the energy policies of the German government have continued on a similar vein since with public support despite an increase in energy prices. In March 2015, an opinion poll showed that a large majority (81 percent) of the German population were still in favour of the government's decision to exit nuclear power. Between 2000 and 2013, global investment in new power plants went mainly into renewables (57 percent), followed by fossil fuels (40 percent), while only three percent of investment was spent on nuclear energy.[16]

Following the success of the German Energiewende and corresponding feed-in-tariff policies in scaling up the solar PV market, China expanded state support for the production of solar panels and associated components and equipment, rapidly becoming the world's largest panel producer and exporter. The implementation of the policy has had consequences including trade disputes concerning China's ability to supply solar panels at prices with which most other producers are unable to compete with, and alleged flooding of global markets with cheap supply. Nevertheless, China has maintained its position as the leading panel manufacturer and has made a major contribution to the decline in solar PV manufacturing and assembly costs.[17] The policy has also been associated with domestic solar PV deployment through direct financial contributions and feed-in-tariffs. While these funds have repeatedly been depleted and initial curtailment rates were high due to overbuilding, the design and implementation of solar support policies are a key milestone in China's relationship with renewable energy and an important determinant of the renewable energy landscape today.

This case-study is **noteworthy because it shows how a feed-in-tariff policy in Germany, with broad motivations and helped by anti-nuclear sentiment, was able to set in train a complex set of reinforcing feedbacks, in Germany and beyond, contributing to the low costs of PVs today, a pillar for climate mitigation globally**. It is clear from the criticism of neoclassical economists, discussed above, that this policy would likely not have been adopted

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[14] Rechsteiner, R. German energy transition (Energiewende) and what politicians can learn for environmental and climate policy. *Clean Technol. Environ. policy* 1–38 (2020); GCEE. *The energy transition (energiewende): shifting towards a global climate policy*. (2016).

[15] GCEE. *The energy transition (energiewende): shifting towards a global climate policy*. (2016).

[16] See the factsheet "Germany's energy consumption and power mix in charts" at https://www.cleanenergywire.org/factsheets/germanys-energy-consumption-and-power-mix-charts

[17] Yu, H. J. J., Popiolek, N. & Geoffron, P. Solar photovoltaic energy policy and globalization: A multiperspective approach with case studies of Germany, Japan, and China. *Prog. Photovoltaics Res. Appl.* (2016). doi:10.1002/pip.2560.

had it been appraised by traditional techniques. However, that solar panels are available at low cost in Germany now completely hinges on the above chain of events. Its impact on the cost-effectiveness of power sector emissions reductions is significant and global, while still seen as inefficient in conventional economic thinking. Solar PV is set to become an important part of the new normal in energy systems.

While such long and complex chains of events, with its phenomenal reduction in costs and replication in different countries, cannot be predicted even by techniques based on complexity economics, the latter at least allows for this scenario to remain within the possible futures, to be ‘in the cards’, rather than excluded from the ‘deck’ as in CBA-based approaches. The ROA approach allows for this type of outcomes to be explored because of its ability to incorporate analyses from dynamical models which can capture the powerful feedbacks described above. These larger scale opportunities, beyond individual countries, are worth considering in low carbon transformational policies, particularly for the potential for mutually beneficial cooperative strategies between countries. The case study thus gives us a real sense of the breadth of risks and opportunities, from opportunities such as sparking innovation and reduced costs, to risks such as industries moving abroad, and incumbents resisting change.

E. LED lighting in India

India is experiencing a rapid transition in its lighting market towards light emitting diode (LED) technology. Between 2014 and 2018, annual sales of LED bulbs increased more than 130 times to over 650 million, as seen in Figure 1, and is estimated to have saved some 30 TWh electricity to date (approx. 10% of UK’s annual electricity demand).[18] On the face of it, this has been an extremely successful low-energy transition. However, there have been issues and criticism of the narrow focus of policy.[19]

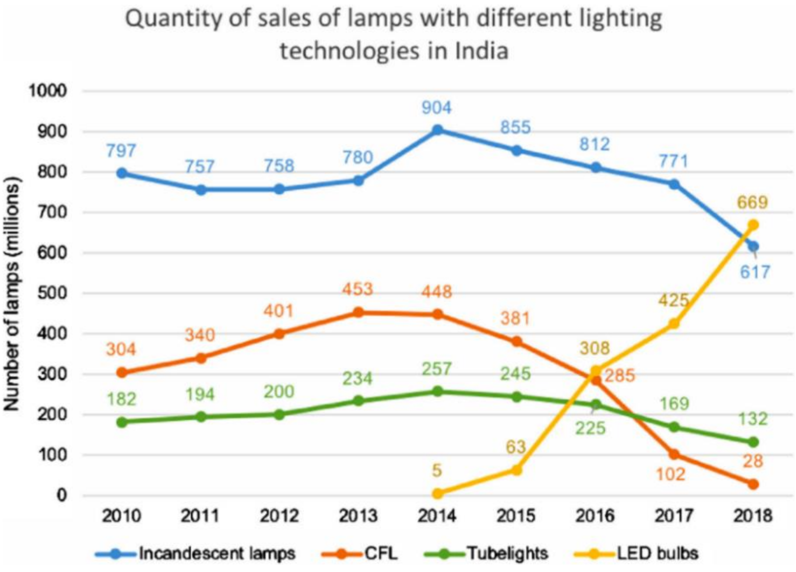

Figure 1: Quantity of sales of lamps with different technologies in India[20]

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[18] Kamat, A. S., Khosla, R. & Narayanamurti, V. Illuminating homes with LEDs in India: Rapid market creation towards low-carbon technology transition in a developing country. *Energy Res. Soc. Sci.* **66**, 101488 (2020).

[19] Kamat, A. S., Khosla, R. & Narayanamurti, V. Illuminating homes with LEDs in India: Rapid market creation towards low-carbon technology transition in a developing country. *Energy Res. Soc. Sci.* **66**, 101488 (2020).

[20] Kamat, A. S., Khosla, R. & Narayanamurti, V. Illuminating homes with LEDs in India: Rapid market creation towards low-carbon technology transition in a developing country. *Energy Res. Soc. Sci.* **66**, 101488 (2020); ELCOMA. Lighting Industry Data 2018–2019. (2019).

Though there are many LED-related policies in India, the real policy effort primarily acted on generating demand for LED lighting. Policy appears to have missed opportunities on the supply-side, which has created a situation in which the high demand for, and lower costs of, LED lighting have not gone hand-in-hand with important plans to enhance domestic technological competencies.

Rapid adoption of new technologies is often difficult for developing countries because their technological capabilities, infrastructure systems, and institutions can be underdeveloped. This means that diffusion of technologies has tended to cost more and happen comparatively late, after the technological development (and all the benefits for producing nations), has taken place elsewhere.[21] This can mean that developing countries are less able to reap the benefits of these transitions, are unable to define transitions that make the most sense, and thereby create the most value for them. The transition to LED lighting in India appears to highlight this issue and the challenges of developing policy that accelerates transitions whilst promoting in-country capabilities.

India has had mixed success in advancing its technology innovation capabilities, it does not spend as much on R&D as other nations, nor has it specifically targeted LED lighting as an area to focus on in its investments in R&D and manufacturing. This may have led to some missed opportunities in the transition to LED lighting. To unpack this, it is important to understand what has driven this transition.

There have been multiple drivers, but primarily these have come from the government's ambitious policy program on the demand side, and the supply-side push from China, with its huge production capacity and low costs. India has created a wide variety of LED-related policies since the mid-2000s, including R&D funding programs, technical standards, and subsidies for LED lights. However, one policy has dominated all others, the 'Unnat Jyoti by Affordable LEDs for All' (UJALA) program. It was created in 2014 and targeted the residential sector, facilitating the purchase of LED lights at reduced costs by aggregating demand through multiple public sector utility companies. It also directly supported distribution of bulbs to households. The savings of buying in bulk were partially transferred to individual consumers and households. The program was complemented by successful marketing campaigns and strong political ownership and engagement, although there were significant concerns around how the program bypassed local retailers in the supply chain.

The focus of policy on creating demand for LED lighting has been successful, but lack of focus on other aspects of the transition (i.e., production, wider skills and capabilities) has meant India's own ability to meet this demand itself has been undermined.[22] There have been developments in the supply-side ecosystem in India; however, concerns about the adherence to quality standards have emerged as the technical capabilities to underpin testing and meet control guidelines are not always in place. The success of aggregating demand in lowering prices has also meant that many domestic manufacturers struggle to supply at those costs without cutting corners on quality.

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[21] Kamat, A. S., Khosla, R. & Narayanamurti, V. Illuminating homes with LEDs in India: Rapid market creation towards low-carbon technology transition in a developing country. *Energy Res. Soc. Sci.* **66**, 101488 (2020).

[22] Kamat, A. S., Khosla, R. & Narayanamurti, V. Illuminating homes with LEDs in India: Rapid market creation towards low-carbon technology transition in a developing country. *Energy Res. Soc. Sci.* **66**, 101488 (2020).

While the policy focus on demand may make sense on their own from a CBA standpoint, because demand is met by cheap foreign products, they have clearly had knock-on effects and created missed opportunities that this type of analysis cannot easily identify. In this context, a ROA approach would have shone a light on the potential supply-side risks but also opportunities of creating additional demand for the domestic industry. The policy contrasts with the case of Brazilian wind energy, for which a local industry was built. **The case study highlights the importance of taking a holistic view to explore the alignment of technology supply push with demand pull policy,**[23] **which can allow policy design and appraisal on both climate and development grounds. This is vital in developing countries where there is limited support for climate and energy policies that do not strongly support economic development and growth**. The ROA approach could improve the chances of identifying development-friendly climate policy in developing countries.

F. Conclusion

Predicting technological change and the success of low-carbon policy is challenging, in parts due to the success partly depending on the commitment of governments to their innovation policy, in parts due to the complex dynamics involved. However, it is observed that standard economic policy analysis reveals a marked status quo bias, in which costs are overemphasised, and benefits of innovation underestimated. This stems from the fact that policy analysis makes very limited use of available information in the form of cost and benefit quantifications of well-known elements, while innovation by definition creates developments and processes that are *a priori* unknown or uncertain. Despite this, it is observed empirically that technological progress follows clear and reproducible self-reinforcing dynamics, in which deployment reduces costs and develops industrial capabilities, which allows and incentivises further deployment. For that reason, standard policy appraisal of technology deployment policies has a tendency for systematic negative bias. This bias is hindering progress in the formation of low-carbon policy.

The case studies shown in this note suggest that technology evolution is complex and not predictable in a way that satisfies criteria to be used in standard policy analysis, as it is characterised by large uncertainty and complex dynamics. The case studies also tell a story of high degree of adaptiveness in policy-making. However, those dynamics are not impossible to predict given the right theory of systems evolution and a flexibility of policy frameworks that responds to the evolution of technology. And indeed, the use of a Risk-Opportunity Analysis framework could be much more successful than standard policy analysis at guiding adaptive policy formation that could successfully tackle the challenges of low-carbon transition.

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[23] Grubb, M. *Planetary Economics*. *Planetary Economics* (2014). doi:10.4324/9781315857688.

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