LEARNING FOR DECARBONISATION:

START EARLY, CONCENTRATE ON PROMISING TECHNOLOGIES, EXPLOIT REGIONAL STRENGTH AND WORK WITH YOUR NATIONAL SYSTEM

Objective: The Policy Brief makes the case that national decarbonisation strategies should put a special emphasis on the benefits of learning. Accordingly, countries should start early to deploy and develop low-carbon technologies, concentrate on promising technologies, exploit individual regional strength and bear in mind the opportunities and constraints of the national innovation system.

SUMMARY

Early investments to foster learning reduces decarbonisation costs in the long term. In addition, early investments into decarbonisation technologies also offer economic opportunities for individual countries to develop new low-carbon technologies and sectors. Learning is not only a result of R&D, but also of 'learning by doing' effects that can follow from increased deployment. Learning rate estimations show clearly an advantage of available low-carbon technologies over mature "brown" technologies when it comes to electric power generation. We also find that almost every country has some potential to specialise in a particular low-carbon technology and could benefit from doing so. Specialisation is necessary, especially for small countries, as specialisation in all low-carbon technologies at the same time is not feasible. Finally, we find that an existing strong sector can fail to develop new technologies (electric vehicles in Italy), but also massive industrial expansions do not automatically yield the latest technology (PV in China). In the end, right policy choices and implementations are crucial to foster learning as well as to the creation of a local industry.

POLICY BRIEF

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This brief compiles research from Deliverable D3.3 as well as modelling work performed under WP3. All this work involves the following institutions: Bruegel, UOXF, TU, ENEA, UCT, IDDRI and COPPE. This brief has been coordinated by Georg Zachmann and Alexander Roth at Bruegel.

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Introduction

A crucial factor for successful decarbonisation is the development of technology which entails, both, increasing the efficiency of already available technologies in addition to the development of new technologies. An example of improving efficiency is batteries for electric cars: better technology that engenders cost reductions and mass market adoption could pave one significant pathway to decarbonise the transport sector. Carbon-neutral aeroplanes are an example of a technology yet to be developed (or at least brought to market). Future air mobility would have to be reduced dramatically in order to comply with the global decarbonisation pathway without a major breakthrough in decarbonising aviation, unless other technological breakthroughs in the field of negative emissions are invented. Thus, the improvement and development of low-carbon technologies is a key requirement to stay on the "well below 2°C" / "1.5°C" pathway to decarbonisation.

These two examples illustrate the double character of technology development in the context of decarbonisation: decarbonisation is not achievable without it, followed by drastic changes in the economic system. In addition, technology development opens up new economic opportunities. Regions specialising early in low-carbon technologies can develop new industries, create jobs and reap innovation benefits.

Climate policies, such as carbon taxes and emission standards, are in place to discourage carbon intensive business behaviour. These policies increase the cost of "brown industries" that currently rely on emitting activities. Increased costs on carbon emissions – that trigger down the value chain – may create competitive disadvantage to countries with less stringent climate policies. As a result, political actors either try to delay aggressive climate policies or seek compensation for the most visible "losers". Hence there are, political boundaries that impose limits on whether measures to discourage carbon emissions can be implemented.

Policies to promote low carbon technologies, such as fiscal incentives for deployment and innovation in low carbon technologies allow policy makers to highlight that decarbonisation is also an economic opportunity. The global aim - development of competitive low carbon technologies in order to allow global decarbonisation; and the national aim – development of a competitive edge in some low carbon technology segment, are not inconsistent. In both cases incentivising learning is essential for fostering low carbon industries but learning needs time. Innovation and its benefits are uncertain, which is why innovation policy needs long commitment and foresight to support skills development in strategic areas.

Against that backdrop, this policy paper aims to guide policy makers and practitioners by presenting the latest data and evidence in the field of learning and decarbonisation. The report is based on research done for the COP21 RIPPLES project. First, we will present to the importance of learning, after which we focus on time and spatial aspects of learning, before finally presenting policy options.

Learning can significantly reduce decarbonisation cost

Over the last decade, the costs of solar PV modules and wind turbines have declined rapidly due to the exploitation of economies of scale, "learning by doing" effects and increased R&D expenditures.[1] Particularly, learning is an enabling factor in enhancing technology diffusion and the success of decarbonisation. As argued by Peruzzi et al. (2014) learning can be sped up by upfront and parallel investments into public R&D in clean technologies. This section explores the implication of learning rates for the decarbonisation cost of different low-carbon technologies. It uses the POLES model, which addresses learning as an endogenous phenomenon.

The crucial question is how accelerated or reduced learning rates impact the long-term deployment of low-carbon technologies and consequently the cost of transition. For this question, we analyse results from sensitivity simulations carried out with the POLES model.[2] We essentially test, how the costs of decarbonisation change, when policies enacted increase or decrease the speed of learning by 50% compared to the reference scenario (2DS[3]). Learning thereby is defined as the reduction in technology cost due to its deployment. That is, if the global capacity of wind turbines is doubled, the 2DS scenario expects the cost of wind turbines to decrease by 40% in 2050 compared to the current value – while in the "fast learning" scenario they would decrease by 70% and in the "slow learning" scenario only by 30%.

"Fast learning" lowers the deployment cost and increases the competitiveness of corresponding technologies. "Slow learning" prevents the deployment of green technologies and increases the duration of the transition. The impact of different learning rates is marginal at the beginning of the period, but then accelerates between 2030 and 2050. At the end of the period wind represents 51% and solar PV 12% of global electricity generation in the "fast learning" scenario. By 2050, wind technologies will approach their potential limits and will feature only low additional cost reductions, while solar technologies continue to increase their role (see **Figure 1**).

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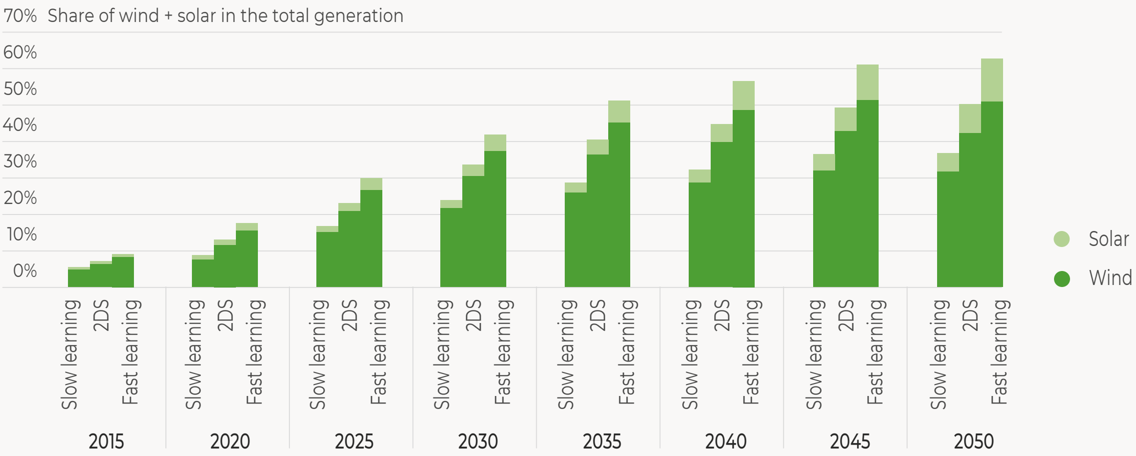
[1] This section is mainly based on work conducted by Silvana Mima from Université Grenoble Alpes.

[2] We assume that average learning rate of four different renewable energy technologies (on-shore wind power, off-shore wind power, photovoltaics and concentrated solar power) vary from -/+50 % of those in the RIPPLES 2DS scenario. Comparing these two sensitivity scenarios with climate policy 2DS scenario reduce considerably the complexity of the analysis. These sensitivity cases are solved for scenarios with the following abbreviated labels: Fast learning and Slow learning.

[3] 2DS is the COP21 RIPPLES reference scenario for achieving the target of the Paris Agreement to contain global warming to below 2°C above preindustrial levels.

Figure 1. Role of wind and solar in the total world generation



Source: POLES, COP21 RIPPLES

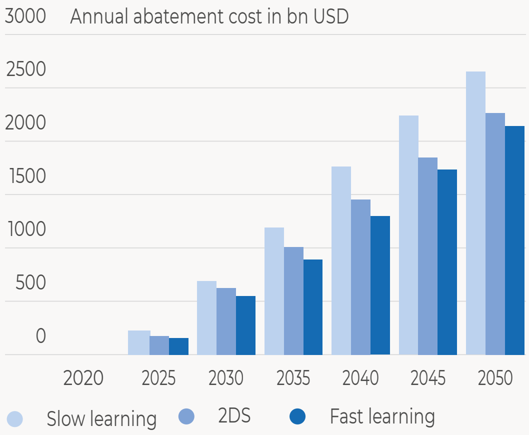
The costs of the decarbonisation of the energy system increase in the long run, particularly in the "slow learning" scenario (**Figure 2**) and only begin to stabilise in 2050. In the "fast learning" scenario the decarbonisation cost will be about 19% lower than in the 2DS decarbonisation scenario. In the "slow learning" scenario the decarbonisation cost will be 17% higher. Thus, the current uncertain future learning rates of only two technologies can have a very substantial impact on the overall cost of decarbonisation.

Learning itself does not only depend on the learning rate, but also on the decarbonisation scenario. Scenarios are explored on a standard mitigation policy compatible with the Paris targets and cover a wide variety of cost patterns compatible with any reasonable cost futures. An early and fast deployment of technologies, for example, generates much more and early learning.

Using model insights, we show that the learning process, which is integrated in all technologies but with varying intensity particularly for new and renewable energy technologies, has a crucial role in limiting the costs of mitigation policies in the very long run. Thanks to learning effects, ambitious stabilisation targets (2DS) can be met with lower cost increases for the energy sector.

Figure 2. Annual abatement cost of decarbonisation scenarios

with different learning rates for wind and solar PV



Source: POLES, COP21 RIPPLES

Early investments and the predictability of technological change

The effects of technological change are so ubiquitous in modern societies that they often are hard to appreciate.[4] Radically new technologies appear and displace older ones; incremental but sustained innovation in existing technologies makes them cheaper and more convenient; and new uses are discovered over time. As a result, predicting technological progress to help policy design is a very difficult problem. However, recent work has shown that for many technologies, performance-adjusted real costs decline at an approximately constant rate for several decades. A well-known example of such a trend is Moore's law, which broadly predicted that the cost of semiconductors would halve every 18-24 months. An important point, however, is that the rate of these cost reductions varies greatly between technologies. The impressive technological progress rate in semiconductors contrasts with much slower rates in other products, for instance minerals and other commodities.

Once a technology-specific rate of improvement has been calculated, it can be used to make quantitative, empirically validated forecasts, where a range of likely technology cost values are given as a function of the forecast horizon. This approach does not explain why technological progress occurs, it simply gives future cost ranges based on limited past observations of a technology's rate of progress and its volatility. In contrast, a large literature has focused on explaining these trends using "experience": instead of being based on the passing of , cost forecasts are made based on the accumulation of , i.e. cumulative effort expended on the activity, such as cumulative production, cumulative electricity generated, cumulative investment etc. Research has shown that, because production and experience both tend to grow exponentially, forecasts made based on time alone are approximately as good as those made conditional on experience. This means that under business-as-usual scenarios, simple time series can be used to forecast tech-

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[4] This section is mainly based on work conducted by Rupert Way from Oxford University.

nological progress. However, when attempting to forecast future technological performance in "alternative" scenarios (i.e. business-as-usual), experience curves are more reliable.

The causes of cost reductions are varied and numerous, but in general they result from the gradual accumulation of knowledge and expertise at various stages of the production process (science, R&D, manufacturing, commerce, organisation). Undoubtedly, innovation is a complex process and also sometimes occurs independently of experience, but broadly speaking, applying more effort is likely to lead to more progress. In addition, advances are cumulative: once a useful skill or technique has been learned, it becomes adopted widely by the production system and is not easily forgotten. Thus, learning is largely a purposeful and one-way process in which the total stock of knowledge keeps growing and grows faster the more effort is made. The experience curve concept is a simple way to model this process: more effort invested helps reduce costs faster, although with some degree of uncertainty.

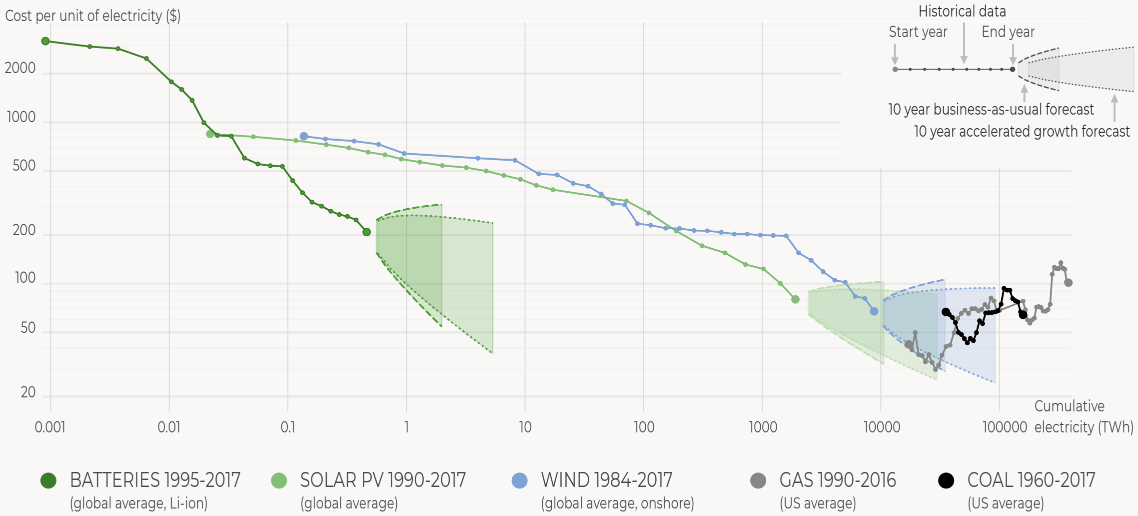
Importantly, not all technologies respond to effort in the same way. The manufacturing of solar photovoltaic panels, for instance, appears to have a fairly high "learning rate": more effort translates into significant cost reductions. For other technologies, such as biomass electricity, it takes much more effort to achieve similar cost reductions. In a few cases, it is not clear that more effort translates into lower costs at all; in nuclear energy the cost trend is upwards. This happens because industry, government and consumers not only learn how to perform various tasks more efficiently, they also learn more about risks associated with technologies, which can lead to new safety standards, regulations and changes in public opinion (for good or ill).

Our analysis of experience curves for a range of technologies suggests that early investments in low-carbon energy technologies are very appealing. These technologies tend to have high learning rates, and their deployment is still very limited, so that a bit more effort is likely to translate into significant cost reductions. While they are already competitive in good locations, accelerating progress along the experience curve can make these technologies affordable in more and more locations in the short to medium run, depending on local conditions and broader energy systems considerations.

Figure 3 shows how probabilistic cost forecasts for solar, wind and battery technologies are affected by following a low-growth path ("business-as-usual", 10% annual growth) versus a high-growth path ("accelerated growth", 30% annual growth). After 10 years median cost forecasts are 57$/MWh for solar, 55$/MWh for wind and 129$/kWh for batteries

Figure 3. Experience curves for selected energy technologies

with 10-year forecasts (95% confidence intervals) in two scenarios



For solar, wind, gas and coal, "cumulative electricity" refers to global electricity generation; for batteries it refers to global electricity storage capacity produced. For solar, wind, gas and coal, cost is Levelized Cost Of Electricity, 2017$/MWh; for batteries it is cost per unit of electricity storage capacity, 2017$/kWh. Data: IEA, EIA, BNEF, BP, Lazard, Schilling & Esmundo 2009, Wiser et al. 2016, Schmidt et al. 2017, McNerney et al. 2011, Colpier & Cornland 2002.

Source: POLES, COP21 RIPPLES

in the low-growth case and 47$/MWh, 48$/MWh, 94$/kWh (respectively) in the accelerated case. Importantly though, the 95% confidence intervals are also narrower in the accelerated scenario.

As well as the direct benefits of cost reductions, early support is useful for at least two other reasons. First, lower costs allow innovators to explore new areas of the technology landscape, opening up previously-inaccessible applications and leading to positive feedback. For example, recent cost reductions in solar PV and batteries are creating new possibilities for peer-to-peer energy trading, vehicle-to-grid applications, and even replacing new-build gas power stations. Second, increasing early stage experience generates valuable new data about the experience curve for a particular technology, allowing more accurate forecasts of its likely future prospects, based on its own unique learning system.

Determining which technologies will benefit most from early support depends on both the slope of experience curves and how much progress has already been made. Progress is much easier for young technologies. Each new kWh generated by a solar panel, or used to power an electric vehicle, reflects a much larger contribution to relative experience than one generated by a gas power station. The latter involves simply repeating many well-known, already highly optimised steps, while the former involves building new systems, innovating, implementing new processes etc., and at each stage there are new opportunities for optimisation and efficiency increases.

Another key point is that there are opportunity costs in investing in high-carbon technologies. Because many energy technologies are substitutable, continuing to invest in high-carbon technologies means not investing in renewable energy technologies, and therefore directly learning and innovating towards a low-cost, clean energy system. In contrast to young technologies (solar, wind, batteries, electric vehicles etc.), technologies that have already accumulated vast amounts of experience (coal, oil, gas, nuclear, hydro) are not likely to experience significant progress in future.

Finally, each of these technologies relies on other technologies, and is useful for other technologies. This means that investing in certain technologies provides higher overall system-level benefits than investing in others. This is a topic of current research, but early results have suggested that clean energy technologies provide higher system benefits than “brown” technologies.

In summary, global experience in solar, wind, batteries and the network of related hi-tech, low-carbon technologies is currently very small, and policies that increase experience in these technologies are likely to contribute to lowering their average costs equivalent fossil fuel energy costs in the long-run, due to the one-way accumulation of knowledge. The speed at which these lower costs can be accessed depends on the timing and the scale of support. The faster experience is increased, the greater the chance of achieving lower costs sooner.

Specialisation is crucial

As argued above, timing and technology choice is crucial for the development of low-carbon technologies.[5] As the development of technologies takes time, early investment decisions have long-lasting impacts. Similarly, learning has an important spatial dimension as countries (and even regions) differ in their preconditions to specialise in certain technologies.

Following the theory of revealed comparative advantage, every country has a set of technologies it can relatively specialise in. A country’s strength in a technology can be measured by its success of exporting and patenting in that technology. Larger countries tend to export and patent more, but, the relative export/patent strength of a country in each technology reveals information about the underlying comparative advantages of the country in the individual technologies. For example, if one of two otherwise similar countries exports ten times as many solar panels than wind turbines, while another one exports ten times as many wind turbines as solar panels, the first one appears to exhibit a comparative advantage in solar panels while the second one in wind turbines.

To address this size-effect we assess a country’s relative strength in a technology with two measures: revealed comparative advantage based on gross exports (RCA) and the revealed technological advantage based on patenting numbers (RTA). The revealed advantage in a technology of a country is defined by a fraction of two shares. For the RCA, the technology’s share of export on total exports of that

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[5] This section is mainly based on work conducted by Alexander Roth and Georg Zachmann from Bruegel. Research assistance from Enrico Bergamini is gratefully acknowledged.

country is divided by the global export share that the technology exhibits worldwide (sum of worldwide export of that technology divided by the sum of all worldwide exports). The same methodology is used to calculate the RTA using patents counts instead of gross exports.[6] We focus on a choice of fourteen low-carbon technologies[7] and 46 countries[8].

Current export specialisation

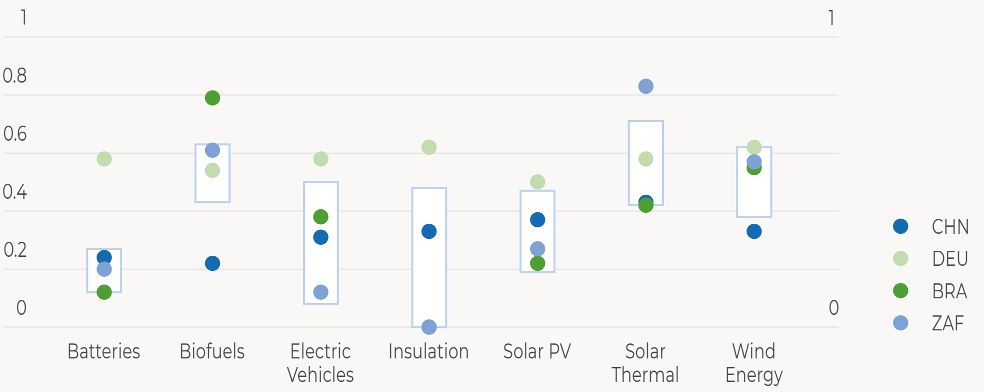
Almost all countries are specialised in exporting at least one of the 14 low carbon technologies. In fact, only three countries (Australia, Norway and Malta) are not specialised (RCA<0.5) in exporting any of the low-carbon product categories. However, 28 countries do not export at all in at least one of the 14 product categories. Larger countries exhibit average specialisations in most of the categories, while smaller countries have more pronounced strengths and weaknesses. Currently, the countries that have the most low-carbon products with export advantage are France, Germany, Bulgaria, Hungary, and Poland. Nevertheless, as depicted in **Figure 4**, for almost every country there exists a low carbon technology it is particularly highly specialised in, and another one it is particularly unspecialised in.

Certain low-carbon products show a pattern of strong concentration in few countries, such as nuclear power within Canada, Czech Republic, France, Germany, Japan, Netherlands, Russia, and Sweden having above average export specialisation. Other products, such as efficient heating and cooling, efficient combustion technologies, and insulation products are much more widespread over many countries. That has most likely to do with the technological complexity involved in producing these products. While the production of products for nuclear power plants involves in itself a lot of sophisticated technologies, thus the entry barrier for companies is high, other low-carbon technologies allow easier access for newcomers and thus a wider spread over several countries.

Current patenting specialisation

Of the total 46 countries, 32, mainly smaller countries, have an RTA of exactly zero in at least one of the low-carbon technologies as no patent activity is recorded in that particular technology group for the covered time period. Overall, we see that large countries (for instance Germany, France, US, China, Japan) exhibit average specialisation in most technology groups whereas many smaller countries specialise only in a few technologies.

Figure 4. Export specialisation of four countries in seven low carbon technologies (RCA)



Note: the blue bar shows the range of countries that is not among the 25% most and 25% least specialised is this technology.

Source: Bruegel, COP21 RIPPLES

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[6] We standardise both measures to make sure they are between 0 (not specialised) and 1 (only country that is active at this technology). Thereby 0.5 is the level, at which a country is as specialised in a certain technology, as the average country.

[7] The technology selection consists of batteries, biofuels, efficient combustion, electric vehicles, energy management, heating and cooling, hydropower, insulation, lighting, nuclear, rail, solar PV, solar thermal and wind.

[8] Countries are all G20 and EU28 countries as well as Iceland, Norway, Switzerland and Israel.

In **Figure 5**, the selected sample illustrates that most countries are, both, particularly specialised in one and particularly unspecialised in another technology. In many cases these patent specialisations coincide with export specialisations (e.g., biofuels for Brazil or wind for Germany) – but notably in the case of China, patent specialisation for solar PV and wind lacks behind export specialisation[9].

Potential specialisation

Using trade and patent data, we can not only calculate the current comparative advantage of each country in a certain technology, but we can also try to estimate a country's potential. We base our analysis on systematic evidence originating from the regional growth literature triggered by Hidalgo et al. (2007), which found that countries diversify into industries that are closely related to current exports. Similarly, we infer a county's potential trade and innovation strength by assessing the strength in closely related technologies.

Overall, the strength of exporting and patenting in low carbon technologies, as well as the strength of the same countries in nearby technologies exports and patents paints a relatively consistent picture. This indicates that there are strong geographic specialisation trends in low carbon technologies, which countries should try to exploit and not (unneeded) try to counteract.

Technology and Industrial policy for low carbon technology: Juggling political commitment, skills development and finance

Different countries have different potential to develop different low carbon technologies.[10] Thereby, preconditions such as the deployment potential, technology proximity to existing technological strength, technology potential and access to export markets can inform choices about which technological developments a country might want to politically support.

In four case studies (Brazil, South Africa, China and Italy) we find that the main challenge in designing low-carbon industrial and technology policy is to tilt the incumbent domestic system to allow for effectively supporting these emerging sectors. Both in the low-carbon transport sector and in the renewables electricity sector, countries with strong

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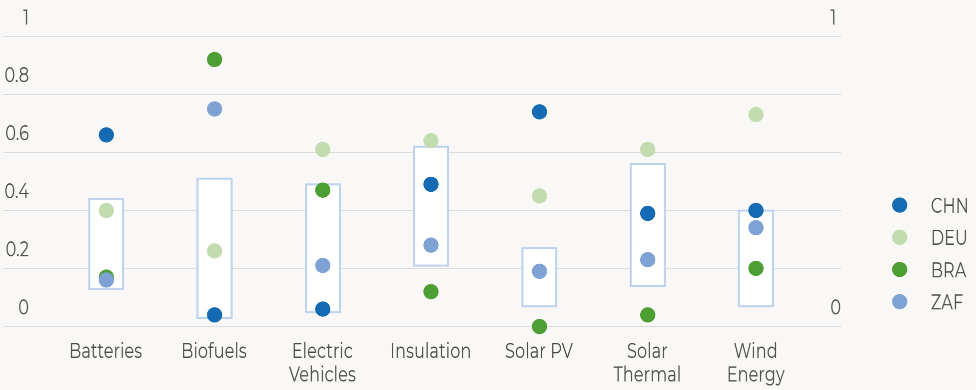
[9] The correlation of RTA and RCA was about 40%.

[10] This section is mainly based on work conducted by Britta Rennkamp from Cape Town University. With input from several project partners (ENEA, Tsinghua, COPPE).

Figure 5. Patent specialisation of four countries in seven low carbon technologies (RTA)



Note: the blue bar shows the range of countries that is not among the 25% most and 25% least specialised is this technology.

Source: Bruegel, COP21 RIPPLES

potential in low-carbon technologies also feature strong incumbent rivals. Examples are the Italian car industry, the South African concentrated solar power (CSP) sector and the Brazilian wind power sector. At the same time, there is competition and growing domestic demand for skills, which need to be built up in long term efforts and require strategic support of a larger supporting innovation system. Sustained domestic funding and international investments are essential to sustain skills development and the evolution of technological capability. Yet, sustaining a financial basis for low-carbon technology diffusion has proven very difficult for middle income countries with constrained public funds and 'bumpy' investment climates.

The comparative case study of local content requirements in the Brazilian and South African wind energy programmes has revealed once again the contested incentives that aim at enhancing technological and industrial development, while simultaneously posing trade barriers. The Brazilian programme has created jobs in manufacturing, installation, operation and maintenance while achieving highly competitive energy prices through a competitive auction system. The South African government has attracted significant investment in the wind sector but has not yet stabilised the renewable energy programme to create a reliable investment climate. Requiring compliance with local content requirements from international investors comes with the commitment to support of the industry and its investors, as the Brazilian case demonstrates. The Brazilian wind energy industry could build on an existing base in a combination of committed investors and an aviation industry in combination with a clear financial incentive to compliance and penalising non-compliance. The South African case has demonstrated that the lack of support of the industry in combination with lacking political commitment to a renewable energy programme has created significant trade-offs between quality, timelines, skills development and ability to comply with industrial development.

Technology leadership and local value-added needs more than low production cost

The case study about the Chinese PV sector shows that large gaps remain between Chinese PV technology and the most advanced technology at the international level, despite the advantage of scale, in markets within and without China. China's recent explosive growth in installed capacity of renewable energy was accompanied by an increasing demand for professional skills, which are not available from the Chinese innovation and training system. Most of the technology gaps are not only in design and manufacturing within the PV industry, but more importantly can be found in the upstream industry of material and basic industry. Similar to the experience in South Africa and Brazil, the Chinese renewable energy sector, intensive in technology and capital, requires a wide array of skills besides investment. The renewable energy industry struggles with a lack of skills in design, manufacturing, installation, commissioning and operational management. The lack of skills meets a tough environment for finance. Despite the growth of supporting industries in recent years, the relatively small capital size as well as substantial difficulties in loan financing have restricted the sustainable development of renewable energy enterprises in China.

The challenge of finance and skills also became evident in the case study of CSP technologies in South Africa and electric vehicles in Italy. These case studies also demonstrated the importance of the global technological and financial dynamics and their impacts on the ability for low carbon technology to evolve. The South African CSP programme is part of a larger renewable energy programme, which focuses on funding renewable energy projects via competitive bidding. The case of CSP is different from the wind and PV projects under the project, as it centres around a largely internationally funded innovation system, with a research centre on CSP at its core. As a result, South Africa is developing a comparative advantage in three CSP-related technologies, namely heliostats, air-cooled condensers and packed (rock) bed thermal energy storage. These developments are largely due to steady investments over the last decades, largely from public funds but also with increasing private sector participation. South Africa has recently made large investments in the deployment of utility scale CSP in South Africa. This has yet to drive CSP innovation. Improved strategic stability in the utility scale CSP programme and clearer commitment to the programme could improve this situation. Further evolution of the three technologies have a favourable chance of success in global supply chains, if the funding continues.

The case study about the Italian car industry attempts to understand its slow development of electric vehicle manufacturing compared to its competitors in Asia and Europe. Italy has a competitive automotive industry to start from, but the competitive advantages in innovating in internal combustion engines may become obsolete and disappear. Countering risks such as job and industry losses require to strengthen first the research base and the training (and re-training) of the workforce so that it is ready and capable to respond to private investment, as well as to support some of the most competitive national enterprises. To be a significant player in crucial areas such as battery manufacturing, large investments would be required.

In sum, strategic support of low carbon technology development needs to meet with political commitment. Skills development requires long term educational strategies in support of innovation systems for renewable and alternative energy technology.

Conclusion

This policy briefs argues that early investments to foster learning reduces decarbonisation costs in the long term. In addition, early investments into decarbonisation technologies also offer economic opportunities for individual countries to develop new low-carbon technologies and sectors. Learning is not only a result of R&D, but also of 'learning by doing' effects that can follow from increased deployment. Learning rate estimations show clearly an advantage of available low-carbon technologies over mature "brown" technologies when it comes to electric power generation. We also find that almost every country has some potential to specialise in a particular low-carbon technology and could benefit from doing so. Specialisation is necessary, especially for small countries, as specialisation in all low-carbon technologies at the same time is not feasible. Finally, we find that an existing strong sector can fail to develop new technologies (electric vehicles in Italy), but also massive industrial expansions do not automatically yield the latest technology (PV in China). In the end, right policy choices and implementations (see local content requirements for wind energy in Brazil and South Africa) are crucial to foster learning as well as to the creation of a local industry.

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The COP21 RIPPLES project

"COP21: Results and Implications for Pathways and Policies for Low Emissions European Societies" aims to analyse the transformations in the energy systems, and in the wider economy, that are required in order to implement the Paris Agreement (NDCs), and investigate what steps are needed to attain deeper, more ambitious decarbonisation targets, as well as the socio-economic consequences that this transition will trigger.

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