Perspective

Spurring low-carbon electrosynthesis through energy and innovation policy

Tobias S. Schmidt¹,²,*

SUMMARY

Reaching the climate targets set in the Paris Agreement on climate change requires decarbonizing all parts of the global economy. The electrification of industry processes—and more specifically, electrosynthesis (ES)—is an important decarbonization mechanism. To tap into this mechanism’s potential and accelerate the decarbonization of these processes, I argue that public policy needs to perform two tasks. First, energy policy needs to enable the provision of CO₂ emissions-free baseload electricity. Second, innovation policy needs to accelerate cost reductions for ES. Here, I discuss why this is the case, what the challenges are, how policy makers can address them, and how political ambition can be increased.

INTRODUCTION

To avoid catastrophic global warming and comply with the goals set out in the Paris Agreement on climate change, all parts of the global economy need to be decarbonized (Mulugetta et al., 2014). Furthermore, hard-to-decarbonize sectors such as freight, steel production, and the chemical industry need to substantially reduce their emissions (Bataille et al., 2018). These sectors’ activities result in major energy- and process-related emissions (see Figure 1). Although efficiency gains and some process optimizations have already resulted in a reduced carbon footprint (per unit of output) and will continue to play an important role in the next years, a deep (or even full) decarbonization requires substantial technological change. In general, the most important mechanism for decarbonization is the electrification of processes that are currently based on fossil fuels (Schiffer and Manthiram, 2017; Williams et al., 2012). Of course, other decarbonization mechanisms, such as biofuels, synthetic fuels, or carbon capture and storage (CCS) exist and are likely to play an important role. However, they come with additional challenges, such as land availability issues (biofuels), high cost (synthetic fuels), and acceptance issues (CCS). Electrosynthesis (ES) is one decarbonization option within the electrification mechanism. It is particularly interesting for two reasons: On the one hand, ES can directly replace synthesis processes in chemical and industrial sectors that are currently based on fossil fuels (De Luna et al., 2019; Kingston et al., 2020; Yuan et al., 2019). For instance, in the iron & steel industry (the largest emitting industry sector, see Figure 1), the reduction of iron oxide (ore) to iron could be performed through (alkaline) iron electrolysis (Allanore et al., 2008). In the cement industry (the third largest industry sector in terms of emissions, see Figure 3), ES-based calcination could help reduce CO₂ emissions substantially (Ellis et al., 2020). On the other hand, water electrolysis (a specific type of ES) can be used to produce hydrogen, which can replace fossil resources as fuel or as a reactant in the chemical, steel, freight, and other sectors (Glenk and Reichelstein, 2019).

The global carbon budget is quickly expiring (Peters et al., 2013), and thus we must make decarbonization happen on the ground, and do so quickly. In theory, the technological solutions exist. However, given the large and long-term investments as well as the many market and system failures related to low-carbon innovation (Gillingham and Sweeney, 2010), technological change in these sectors happens rather slowly (Grubler et al., 2016). Therefore, policy intervention must accelerate low-carbon technological change and thus the decarbonization of these sectors (Roberts et al., 2018). Although most researchers agree that putting a price on carbon (e.g., thorough a tax on CO₂ emissions) is an important policy intervention, additional policy action is required (del Rio González, 2008; Lehmann and Söderholm, 2018; Schmidt and Sewerin, 2019). In the case of industry electrification and ES, two policy tasks are particularly important:

1) Securing the availability of carbon-free, low-cost baseload electricity
2) Accelerating innovation and cost reductions in ES technology

¹Energy Politics Group – Swiss Federal Institute of Technology, ETH Zurich, Haldeneggsteig 4, 8092 Zurich, Switzerland
²Institute of Science, Technology and Policy, ETH Zurich, Universitätsstrasse 41, 8092 Zurich, Switzerland
*Correspondence: tobiasschmidt@ethz.ch
https://doi.org/10.1016/j.isci.2021.102045
The first task relates to the electrification of industrial processes in general, whereas the second refers more specifically to ES. Below, I argue why these two tasks are essential and how policy makers can achieve them. I then discuss how the necessary policy ambition can be created.

Securing zero-carbon, low-cost baseload electricity for electrosynthesis

Decarbonizing our economy is a system of systems challenge, where different sub-systems (e.g., economic sectors) are linked not only through infrastructures but also through material and energy supply chains (Grubler et al., 2016). Hence, decarbonizing one sub-system is often not enough. In the case of electrifying industrial and chemical processes (including the production of hydrogen), the decarbonization effect will only be global and economy-wide if the input electricity is produced in a carbon emissions-free way. Hence, energy policy (particularly electricity policy) plays an important role in ES. Several emissions-free renewable electricity generation technologies (RETs; particularly solar photovoltaics and on-shore wind) have matured over the last few decades, making renewable generation cost-competitive with fossil fuel-based generation on a levelized cost basis (IRENA, 2020); however, three energy policy-related challenges remain that require policy action.

The first challenge is to manage the variability introduced by intermittent renewable sources (Ziegler et al., 2019). In simple terms, the sun does not always shine and the wind not always blow when electricity is in demand, requiring a massive increase in the electricity system’s flexibility (Sepulveda et al., 2018). In the chemical sector (and very likely in hydrogen production as well), synthesis processes are run in a continuous manner to increase output per invested dollar. Chemical plants are very capital intensive. For example, in Europe, the chemical industry’s average capital intensity is 21% higher than the capital intensity of the manufacturing industry (CEFIC, 2020). Consequently, continuous (baseload) zero-carbon electricity supply is quintessential to tap ES’s decarbonization potential. Short-term flexibility solutions such as battery storage have experienced and will continue to experience rapid cost declines (Beuse et al., 2020); however, balancing longer-term, particularly seasonal, fluctuations is still an issue (Zerrahn and Schill, 2017). In general, overcoming these seasonality issues seems to be possible, even in Europe, which has strong seasonality (Tröndle et al., 2020). Yet regions with lower degrees of seasonality (e.g., with high solar irradiation throughout the year, such as the Gulf region or the southern United States) might have a competitive advantage (IEA, 2019). Should the resulting electricity cost differences be very large, a relocation of the chemical industry to these regions might occur. This would have major economic implications, as the chemical industry creates millions of jobs and contributes billions of dollars to economic output (measured in GDP). Although the regions that currently have strong chemical industries might suffer, such relocations might accelerate the transition of newly attractive regions away from fossil fuels, which is often the dominant income source (at least in the Gulf region and parts of the United States). From a policy perspective, these regions could use their geographical advantage and foster the construction of energy systems that are able to provide CO₂ emissions-free baseload power. Vice versa, regions with large chemical sectors but seasonality need to increase their ambitions in managing seasonality despite decarbonizing their electricity systems. One potential mechanism for this is hydrogen (Kober et al., 2019; Parra et al., 2014), and another is improved electricity grids with larger geographical reach (Haller et al., 2012). Finally, leveraging political stability and thus low-financing costs is an option, which leads to the next challenge.

Figure 1. Greenhouse gas emissions of the 10 largest emitting industry sectors
Adapted from Rissman et al., 2020.
This second challenge is that renewable electricity is only competitive with fossil fuel-based electricity if financing renewable energy projects can be done at a low cost (Egli et al., 2018; Hirth and Steckel, 2016). Other than fossil fuel-based power plants, whose levelized costs are dominated by the cost of fuel, RET projects are very capital-intensive, requiring major up-front financing (Figure 2A and Schmidt, 2014). Figure 2B demonstrates how increased financing costs result in much higher levelized costs of electricity for photovoltaic projects (the same is true for wind). A policy recommendation is therefore to design policies that enable low-cost financing by allowing independent power producers, by adopting (or continuing) renewable energy auctions, and by avoiding policy volatility/reversal, which increases financial risk (Egli, 2020; Schmidt et al., 2019).

A third, location-dependent, challenge relates to the timing of providing the supply of low-carbon base-load electricity, including grid infrastructure upgrades. Large chemical plants relying on ES would require much stronger integration into the high-voltage electricity grid. Note that the electrification of other sectors, such as transport, rather rely on extensions of the medium- to low-voltage distribution grids (Dyke et al., 2010). Similarly, if hydrogen is supposed to replace fossil fuels and reactants, it would be necessary to build a hydrogen gas grid or upgrading existing gas grids. Electricity and gas grid extension and upgrade projects have very long lead times (for planning and construction) (Qiu et al., 2015). For example, in Europe, the average time to receive a building permit for a new high-voltage electricity grid line is 7 years, with more than a quarter of projects requiring more than 14 years (Battaglini and Lilliestam, 2010). Thus, electricity planners should already be considering potential demand from ES. The need for long-term planning is exacerbated as public acceptance issues can further delay electricity infrastructure projects (Tobiasson and Jamasb, 2016). In other words, a major coordination problem between the sectors and the underlying (policy) incentives exists—a classic problem when changing a complex system of systems. To address this issue, setting ambitious yet realistic long-term targets is an important policy strategy (Foxon and Pearson, 2008; Schmidt et al., 2012). These targets can facilitate coordination between the various players and sectors involved, including ES users, electricity producers and distributors, technology providers, and financiers. Relying on markets alone seems problematic, given (1) the non-arms-length relationships needed to transform large and complex socio-technical systems (Nelson and Winter, 1982) and (2) the time constants involved—markets are a powerful short-term optimization tool, but they typically fail to provide long-term guidance (Mazzucato, 2015; Rodrik, 2004). These targets can also help in policy makers’ second task: accelerating innovation and deploying ES.

Accelerating ES innovation and cost reduction

While little research on the role of policy in ES innovation exists, one can draw a great deal of insight from the ongoing—and relatively advanced (Markard, 2018)—transition in the electricity sector, which is also characterized by large-scale, long-term investments into largely complex technologies (Verbong and Geels, 2007). In recent years, researchers have uncovered the factors underlying RETs’ cost declines. One crucial factor is the effect of policies supporting the research and development (R&D), demonstration, and deployment of RET (Kaviak et al., 2018; Nemet, 2019; Taylor, 2008; Trancik et al., 2015). R&D policies create an increased variance in the knowledge base; demonstration and deployment support policies enable learning by doing,
learning by using, and learning by interacting among actors along the value chain (Gallagher et al., 2012; Malhotra et al., 2019). In other words, and as shown in Figure 3, technological advancement profits from knowledge feedbacks from experiences made with the technology in demonstration projects, during manufacturing, and during use (Malerba, 1992). Combined with economies of scale and reduced margins caused by increased competition (Papineau, 2006), these learning effects explain “experience curves,” which describe the empirical observation that technologies’ specific cost (e.g., per kWh output) decreases with the technology’s cumulative deployment (Ferioli et al., 2009). Interestingly, these effects extend beyond the investment cost (Duffy et al., 2020)—they have been studied within the context of projects’ engineering, procurement, and construction costs (Nemet et al., 2020; Strupeit and Neij, 2017), operation and maintenance costs (Steffen et al., 2020), and even financing costs (Egli et al., 2018).

Inducing ES innovation and cost reductions would likely require a similar mix of policy instruments, as this has been proved to be effective in RETs. Yet not all technologies, even within sectors producing the same output (e.g., electricity), are equal (Huenteler et al., 2016b; Malhotra et al., 2019). Some RETs have experienced dramatic cost declines (particularly photovoltaics), whereas other RETs (such as biomass or geothermal plants) have seen very little cost reduction (IRENA, 2020; Rubin et al., 2015). In a recent paper, (Malhotra and Schmidt, 2020) argue that higher global experience rates can be observed for technologies, which (1) have relatively low technological design complexity (McNerney et al., 2011), typically allowing mass-manufacturing, and (2) require few adjustments if transferred to new contexts (Figure 4). An extreme case is solar photovoltaic modules, which have limited design complexity (Huenteler et al., 2016b) and can be used in almost all contexts without adjustments (Haelg et al., 2018). Consequently, the observed experience rate of these modules is about 22% (i.e., modules’ cost in USD/Watt decline by 22% per doubling of their deployed capacity). In contrast, biomass plants, which are highly complex in design and whose core components (boiler, feeding system, etc.) need to be adjusted to new contexts with different biomass specifications (Binz et al., 2017), only show an average experience rate of 9% (all statistics taken from Malhotra and Schmidt, 2020).

Although a more detailed study on both factors is lacking for ES—and differences between different ES processes exist—a recent analysis focusing on power-to-product based on electrolysis (Kober et al., 2019) revealed that ES plants have a medium level of design complexity (with only a few parts that are mass-manufactured). To the best of my knowledge, no analysis characterizing the need for adjustments if ES is introduced in new contexts exists. However, the literature on innovation in the chemical sector (e.g., Murmann, 2003) has shown that large shares of tacit knowledge remain with the technology user; hence, it is important to incentivize continuous inter-sectoral learning between technology users and producers (Malhotra et al., 2019; Stephan et al., 2017). To this end, stable and local demand is important (Schmidt and Huenteler, 2016). Policy makers who incentivize stable home markets and cross-sectoral collaboration for ES are likely able to capture first-mover advantages, as entry barriers for complex technologies increase quickly (Surana et al., 2020). This is because the knowledge that is gained through these

---

**Figure 3. Learning feedbacks from experience gained with a technology (source: author)**
processes is often tacit, can only be gained through experience with the product and its manufacturing, and is hard to transfer (Quitzow et al., 2017; Schmidt and Huenteler, 2016).

Two innovation-related challenges remain. The first relates to finance. Given the very long lead times of complex industrial technologies such as ES, the venture capital (VC) model typically does not work. VCs expect much shorter lead times and higher potential upsides, as evidenced in energy technologies where VC money is mostly limited to small-scale hardware solutions and software but excludes large hardware solutions (Bumpus and Comello, 2017; Gaddy et al., 2017; Rai et al., 2015). In such situations, innovation is typically financed by large incumbent players either through in-house corporate R&D or through strategic venture investments, yet these players might be locked into their existing technology (due to sunk cost as well as capability and expectation biases toward existing practices) (Geels, 2012). In other words, new ventures developing radically new technology might face massive capital constraints (Polzin et al., 2018). This reality is termed the “first valley of death” of innovation (Karltorp, 2016) and can be located around the two left-hand boxes in Figure 3. To address this capital market failure, new sources of early-stage risk-seeking capital are required (Deleidi et al., 2020). One possible source is public (“green”) investment banks, such as the European Investment Bank (Geddes et al., 2018).

Even if the “first valley of death” can be overcome, many innovations fail because they do not receive enough downstream capital in the early deployment phase. Infrastructure and industry investors are typically risk-averse and therefore shy away from financing new technologies. This prevents innovation from entering the market, a phenomenon termed the “second valley of death” (Karltorp, 2016); this can be located around the two right-hand boxes in Figure 3. In the energy sector, public banks have played an important role in bridging this gap (Geddes et al., 2018), which is particularly important if projects are financed within project finance structures (i.e., off-balance sheets), as these projects depend on banks (or other financial intermediaries), which are particularly risk-averse (Steffen, 2018). Project finance might be relevant for ES used to produce fuels (e.g., hydrogen via electrolysis) because long-term supply contracts with fixed prices (comparable to power purchase agreements in the electricity sector) are conceivable for such commodities. However, public banks might be less important regarding the application of ES in the chemical industry. Here, providing policy incentives—be it sticks (e.g., in the form of a carbon price) or be it carrots (e.g., in the form of subsidies)—for the chemical industry is more important.

This brings me to the second innovation-related challenge: the level of policy intervention. In the case of new technologies, there is debate about the extent to which “picking winners” should be performed by markets or policy makers, i.e., whether policies should be “technology-agnostic” or “technology-specific” (del Río González, 2008; Gawel et al., 2017; Sandén and Azar, 2005; Schmidt et al., 2016). Given the
importance of learning by doing and using (see above) and that the resulting knowledge cannot be fully appropriated by those who invested in creating it (representing a positive externality), technology-specific instruments can increase the long-term efficiency of policy intervention (Lehmann and Söderholm, 2018; Van Benthem and Gillingham, 2008). In the electricity sector, policies tailored to incentivize the deployment of photovoltaics and wind since the early 2000s were essential in driving the technology down its experience curve (Hoppmann et al., 2014; Huenteler et al., 2016a; Nemet, 2019). A similar approach is conceivable for commodities produced using ES (such as fuels or steel), as processes are very much standardized and often independent from other processes. In the specialty chemical or pharmaceutical industries, however, ES has to be integrated into (sub-) sector- and application-specific processes, which might look very different from application to application. In other words, a wind turbine looks more or less similar from one wind farm to the next, whereas an ES process for commodities will look similar between firms. However, in specialty product industries, ES in Firm A might look quite different from ES in Firm B (because of cross- or within-sector differences). Taking it to the extreme, ES might be a viable option for Firm A, whereas Firm B might have to take another decarbonization route (such as CCS or biofuels). Hence, providing technology- or design-specific incentives is inappropriate—incentives targeting technology fields (i.e., not technology-specific but also not entirely agnostic) are more appropriate. Examples of this are sub-sector-specific emissions standards or subsidies. Importantly, how to incentivize ES may also differ between commodity versus specialty industries. In commodity industries, such as steel, cement, or synthetic polymers (Blanco and Modestino, 2019) changes in processes are typically made on the basis of unit cost, whereas in specialty industries, such as pharmaceuticals, new reactivity is key for adopting new processes (Kawamata and Baran, 2020; Tanbouza et al., 2020). Consequently, policy measures affecting production cost might be more relevant for commodity industries compared with specialty industries, which might be better incentivized by interdisciplinary research, crossing the boundaries of energy and chemical sciences (Kawamata and Baran, 2020).

Creating policy ambition and stickiness

While the previous sections provided recommendations for policy measures, it is equally important to consider how to create policy ambition and thereby make such measures politically feasible. In this regard, research on climate and energy politics related to transitions can provide important insights. One important finding is that framing green technologies as an economic opportunity is a more promising strategy than framing them as a way to limit the burden of climate change mitigation (Meckling et al., 2015; Schmidt and Sewerin, 2017), meaning that a race toward ES between the world’s economies could be kick-started. Such a race can currently be observed in the field of electric vehicles, where European policy makers are showing very high ambition to compete with East Asian (particularly Chinese) players (Beuse et al., 2018). Interestingly, the European Union and the German government are also starting to establish industrial strategies around “green” hydrogen (i.e., hydrogen produced with renewable electricity-powered electrolysis). This strategy is also an integral part of the German COVID-19 stimulus package. Similarly, China shows ambition to produce low-cost “green” hydrogen.

Another insight from the literature on the energy transition is that policies aiming to incentivize socio-technical transitions need to be “sticky” (i.e., they should not be dismantled quickly) (Jordan and Matt, 2014). Transitions in infrastructure and industrial sectors take decades—hence, policy durability is required. To make policies sticky, policy feedback research has established that it is important to trigger positive and avoid early negative political feedback on policy measures (Cashore and Howlett, 2007; Jacobs and Weaver, 2015). Hence, positive policy incentives (i.e., “carrots,” such as subsidies) should be used in the early periods. Only later—once industry advocacy around ES has been established, creating jobs and thus becoming equipped with a certain political power—should negative incentives (“sticks,” such as emissions standards) be introduced. Indeed, political coalitions around certain technologies can be changed over time due to positive feedback from technological innovation (Schmid et al., 2019). A “ratcheting-up” logic along a political self-propagating pathway is much more promising than introducing “sticks” right away (Meckling et al., 2017; Pahle et al., 2018).

CONCLUSIONS AND FUTURE RESEARCH

In this perspective, I have argued that policy makers have two major tasks if they want to spur ES and make use of its decarbonization potential. First, policy makers need to ensure the availability of low-cost, zero-carbon baseload electricity—a classic energy policy task. Second, they need to accelerate innovation and cost reductions in ES—a classic innovation policy task. Importantly, these two policy fields need
coordinate with one another. It is only if ES innovation and cost reductions are realized that large-scale market uptake will follow.

Policy makers can learn from what has worked and what has not worked well in the still ongoing (but more advanced) transition of the electricity sector. One important insight is that innovation patterns of individual technologies—even if they produce the same good—can differ dramatically. Policy makers therefore need to be “technology-smart” (Beuse et al., 2018) and design instruments accounting for these differences. Future research should support policy makers by improving our understanding of the innovation patterns and the relevance of the different learning mechanisms along the value chain. Similarly, policy makers must understand the importance of different applications of ES. In some use sectors (e.g., specialty chemistry or pharmaceuticals), the processes are very tailored to individual products, and thus the need to adjust ES technology to existing processes may be high, making standardized policy instruments with a high technology specificity less suitable. In other applications (e.g., hydrogen production or commodity chemicals), this is not the case, and technology-specific policy (including support through public investment banks) may be an effective option. Importantly, technology-smart policy design increases future policy ambition by creating positive feedback (e.g., through creating jobs) and avoiding negative feedback (e.g., through losing jobs). Future research should analyze these differences in more detail and propose policy options for sectors in which technology adjustment to the use case is high; these options should also entail “carrots” to avoid negative feedback from these sectors. This research is needed to better understand the political dynamics within ES-related sectors.

To conclude, the electrification of industry processes—and more specifically, ES—is a promising approach for the direct or indirect decarbonization of several hard-to-decarbonize sectors. To tap into its potential, policy makers need to become active and be supported by interdisciplinary research examining technological innovation, the economics governing investment decisions in these sectors, and the politics driving (or curbing) policy ambition and design.

ACKNOWLEDGMENTS
The author would like to thank the members of ETH Zurich’s Energy Politics Group for very helpful comments on an earlier draft. He also greatly acknowledges the reviewers’ comments and the support by the editor Dr. Muzzio.

AUTHOR CONTRIBUTIONS
All tasks were performed by T.S.S.

DECLARATION OF INTERESTS
The author declares no competing interests.

REFERENCES
Allanore, A., Lavelaine, H., Valentin, G., Birat, J., P., and Lapicque, F. (2008). Iron metal production by bulk electrolysis of iron ore particles in aqueous media. J. Electrochem. Soc. 155, E125.

Bataillé, C., Åhman, M., Neuhoff, K., Nilsson, L.J., Schledick, M., Lechtenböhmer, S., Solano-Rodriguez, B., Denis-Ryan, A., Stiebert, S., Wasman, H., et al. (2018). A review of technology and policy deep decarbonization pathway options for making energy-intensive industry production consistent with the Paris Agreement. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2018.03.107.

Battaglini, A., and Lilliestam, J. (2010). On Transmission Grid Governance (Berlin).

Beuse, M., Schmidt, T.S., and Wood, V. (2018). A technology-smart battery policy strategy for Europe. Science 361, 1075–1077.

Beuse, M., Steffen, B., and Schmidt, T. S. (2020). Projecting the competition between energy-storage technologies in the electricity sector. Joule, 2162–2184.

Binz, C., Gosens, J., Hansen, T., and Hansen, U.E. (2017). Toward technology-sensitive catching-up policies: insights from renewable energy in China. World Dev. 96, 418–437.

Blanco, D.E., and Modestino, M.A. (2019). Organic electrosynthesis for sustainable chemical manufacturing. Trends Chem. https://doi.org/10.1016/j.trechm.2019.01.001.

Bumpus, A., and Comello, S. (2017). Emerging clean energy technology investment trends. Nat. Clim. Chang. https://doi.org/10.1038/nclimate3306.

Cashore, B., and Howlett, M. (2007). Punctuating the climate change regime? Understanding thermostatic policy dynamics in pacific northwest forestry. Am. J. Pol. Sci. 51, 532–551.

CEFIC (2020). 2020 Facts & Figures of the European Chemical Industry.

De Luna, P., Hahn, C., Higgins, D., Jaffer, S.A., Jaramillo, T.F., and Sargent, E.H. (2019). What would it take for renewably powered electrosynthesis to displace petrochemical processes? Science 364, eaav3506.

del Río González, P. (2008). Policy implications of potential conflicts between short-term and long-term efficiency in CO2 emissions abatement. Ecol. Econ. 65, 292–303.

Deledi, M., Mazzucato, M., and Semeniuk, G. (2020). Neither crowding in nor out: public direct investment mobilising private investment into renewable electricity projects. Energy Policy 140, 111195.
