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A road map to navigate the energy transition

Abstract

Energy transitions are complex processes that are difficult to characterize using a small number of features. Despite this, this study tries to provide a framework for the energy transition, pointing out that some long-run scenarios have a higher probability than others. The document is organized around four key propositions:

1) The energy transition is driven by policies rather than by technology improvements.
2) The energy transition disrupts liberalized electricity markets and undermines their economic foundation.
3) Given the current technologies and technological perspectives, the energy transition to renewable sources is going to be incomplete.
4) There is a change in consumer preferences for cleaner energy and this change demands new business models.

These four propositions lead to the following consequences:

a) The outcome in terms of electricity prices and energy production will depend on the policies applied. There are multiple possible polices and potentially multiple paths of energy transition.
b) A complete transition based on renewable energy may be technically possible, but politically difficult to manage in liberalized markets. These markets need a totally new design.
c) There is a change in consumers preferences towards decarbonized energy, creating new business opportunities and jeopardizing traditional business models.

Energy transitions are complex processes and it is not possible to make accurate predictions on this phenomenon, but, in our opinion, this study adds value to the current debate since it provides general guidelines for policymakers, energy companies and investors.

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Introduction

Energy transitions are a multidimensional, complex, non-linear, non-deterministic, and uncertain phenomenon and, therefore, they are difficult to characterize using a small number of features. They require a transformation of actors and their conduct, of markets, and a change in the existing regulations and policies (Sovacool and Geels, 2016). In this context, this study takes a limited view of the energy transition and defines it as the switch from an economic system dependent on specific energy sources and technologies to a different economic system, following Fouquet (2016). Historically, a new energy source or technology has displaced another because it can produce either cheaper services or services with superior attributes, such as being cleaner, easier or more flexible. Previous energy transitions have been the result of the development of a better technology or the emergence of a new source of energy with superior technological attributes, so the world shifted from biomass to coal, from coal to oil, and from oil to natural gas. From a purely economic perspective, a technology-driven transition has a positive impact on the supply, reducing the cost of the energy and increasing the quantity of energy delivered to the market, which is a positive supply shift.

The current energy transition is a simultaneous shift towards low-carbon energy sources and power. IRENA (2018a) provides a definition of the current energy transition as 'a pathway toward transformation of the global energy sector from fossil-based to zero-carbon by the second half of this century. […].' However, power is at the heart of this transformation for three reasons.

- First, most successful[1] clean technologies are power generation technologies such as solar, wind, geothermal and hydropower. Other renewable sources, like biomass and biofuels, are less promising from a technological or economic perspective, although they are playing a role in the energy transition.
- Second, policymakers are promoting the electrification of industries, transport and buildings to reduce carbon emissions and local pollution. In relation to this, the International Energy Agency (IEA) (2017) explains that low-carbon electricity is a prerequisite to reduce fossil fuel use and to mitigate CO_2 emissions, not only in power generation but across all the end-use sectors (industry, transport and buildings). The case of electric cars is a paradigmatic example of shift to electricity. In addition to this shift towards power, there is a rapid process of electrification[2] in emerging economies.
- Third, electricity markets are going through a deep technological transformation due to a technology revolution (OIES, 2018). Power systems are switching from centralized systems controlled by central operators, to decentralized systems with potentially millions of different small generators. The generation of electricity is moving away from predictability to intermittency and unpredictability. Operating costs, which are critical for fossil fuel power plants, are irrelevant for solar and wind generators. Storage emerges as a technology that will transform electricity markets, making it unnecessary to run an instantaneously balanced market.

In this context, energy companies are designing strategies to adapt to the new scenario. Oil companies in particular are looking for resilient strategies to deal with a 'fast transition', according to Fattouh et al. (2018). The adaptation to the new energy scenario is particularly evident among utilities, not only with substantial changes in their business models, but also with the emergence of new business models and actors (OIES, 2018). In this context of decarbonization of the energy mix and rapid process of electrification, we explore four key characteristics of the energy transition based on four different

[1] We define 'successful' in terms of penetration in the energy system, this is, the share of each source of energy in the energy mix.

[2] Universal access to electricity is one of the goals of the 2030 Agenda of Sustainable Development of the United Nations. However, according to the International Energy Agency (IEA) (2018), the number of people without access to electricity is 992 million, with Africa as the region with the lowest penetration of electricity. In this context, BP *Energy Outlook 2019* forecasts that electricity will represent 50% of primary energy consumption in 2040 versus 36% in 1990 and 43% in 2017.

economic dimensions: policy, markets, technologies and preferences. These four dimensions, which are collectively exhaustive and, to some extent, mutually exclusive, allow for the identification of a road map to navigate the energy transition. This road map is organized around four key propositions:

1) The energy transition is driven by policies rather than by technology improvements.
2) The energy transition disrupts liberalized electricity markets and undermines their economic foundation.
3) Given the current technologies and technological perspectives, the energy transition to renewable sources is going to be incomplete.
4) There is a change in consumer preferences for cleaner energy and this change demands new business models.

It is important to highlight that most of the ideas discussed in this document are not new. Our goal is not to develop a new approach to the energy transition or to provide innovative solutions. This study attempts to summarize different aspects of the energy transition and to present relevant conclusions in a structured and coherent manner. The objective of this road map is to provide an analytical framework for the energy transition, pointing out that some long-run scenarios have a significantly higher probability than others. However, as was mentioned before, energy transitions are complex processes and it is not possible to make accurate predictions on this phenomenon. This road map is, therefore, subject to criticisms and debate. However, it adds value to the current debate on the energy transition since it provides general guidelines for policymakers, energy companies and investors.

We want to clarify that this paper discusses the transition towards a decarbonized energy mix. There is sometimes some confusion between the transition to a decarbonized economy and the transition from fossil fuels to renewable energy. Currently, renewable energy is the main driver of the energy transition, but fossil fuels combined with carbon capture and storage (CCS) or nuclear energy are also a way to decarbonize the economy.

There are three main consequences following the four key propositions:

1) The outcome in terms of electricity prices and energy production will depend on the policies implemented, which vary between countries. Therefore, there are multiple potential paths of energy transition[3].
2) A complete transition based on renewable energy may be technically possible, but politically difficult to manage in liberalized markets. These markets need a totally new design. In addition, this issue raises the provocative question of whether public monopolies are better equipped to deal with energy transition in the power sector.
3) There is a change in consumers' preferences towards decarbonized energy, creating new business opportunities and jeopardizing traditional business models.

The following section describes the context of the transition, the next four sections discuss the key propositions, and the last section presents the conclusions.

[3] For the sake of illustration, France and Germany have had different approaches to decarbonization, although both share the same targets, which are set by the European Union. The German approach was based on renewables and the French one was based on nuclear power.

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The context: climate change forces a fast transition

Most of previous energy transitions have happened over long periods of time, as Fouquet (2010) points. However, the current energy transition needs to occur at an unprecedent fast pace[4], and it is focused on achieving one of the many attributes of energy in particular: carbon emissions. In the early 1990s the need to transition towards a decarbonized energy mix emerged for the first time. The Kyoto protocol, adopted in 1992, required industrialized countries to reduce greenhouse gas emissions and emerging economies to stabilize it at 1990 levels by the year 2000. Twenty-four years later, the Paris Agreement entered into force. This agreement was signed by 195 countries, signalling strong international political concerns on climate change. Since the Kyoto Protocol, governments have used a wide spectrum of different policy levers to shift the energy mix towards a decarbonized one. Despite the poor achievements in terms of carbon emissions[5], as a result of these policies there has been a sharp increase in renewable energy generation. Figure 1 shows the speed of the different energy transitions, the starting point being the year in which the technology reached a 1 per cent share of the energy mix. The speed of penetration of renewable energy has been similar to the one of nuclear energy. However, unlike nuclear energy, there is a wide consensus among energy institutions and industry that the renewable energy transition will continue at an unprecedented speed. According to diverse scenarios from different institutions, the share of renewables in 2040 will range between 12 per cent and 17 per cent of the total primary energy consumption[6], overtaking previous energy transitions.

For the sake of illustration, the scenario shown in Figure 1 show the expected penetration of renewable energy based on BP (2019) Evolving Transition Scenario “which assumes that government policies, technology and social preferences continue to evolve in a manner and speed seen over the recent past”. This scenario, represented by a dotted line, is not consistent with the goal of the Paris Agreement. This path of renewable penetration is not sufficiently aggressive, since this is a positive scenario rather than normative scenario designed to achieve Paris Agreement targets. According to IPCC (2018), the current Nationally Determined Contributions are not ambitious enough and global warming will largely surpass 1.5 degrees pre-industrial levels. The same report suggests that carbon emissions must decrease above 90 per cent of the 2010 levels by 2050 to keep climate change compatible with a 1.5 degrees increase in global temperature. Other scenarios are less aggressive in terms of carbon emission reductions, but in general terms, there is a need for a massive reduction in carbon emission in the next 20–30 years[7] to keep climate change in line with the Paris Agreement targets[8]. The need to accelerate the transition is one of takeaways from the 2018 United Nations Climate Change Conference (COP24), according to the IEA[9], strengthening the role of policies in the current energy transition. There is also an implicit conclusion here. If the current energy transition is policy driven, it can also be derailed by the lack of policy.

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[4] The average duration of past energy transitions was 95 years (Fouquet, 2016). Fattouh et al. (2018) state that the current energy transition is taking place at a very fast pace.

[5] CO_2 emissions from fossil fuels combustion increased by almost 250% in 1992–2017 globally, according to BP (2018).

[6] Scenarios for IEA, *World Energy Outlook 2018*; BP, *Energy Outlook 2019 edition*; ExxonMobil, *2018 Outlook for Energy: A view to 2040*; and OPEC World Oil Outlook 2040.

[7] See for example, IEAs ‘Sustainable Development Scenario’, included in the *World Energy Outlook 2018*, BP ‘Low Carbon Scenario’ included in the *Energy Outlook 2019*, and Shell ‘Sky scenario’ (https://www.shell.com/energy-and-innovation/the-energy-future/scenarios/shell-scenario-sky.html).

[8] United Nations Climate Change (2019): ‘The Paris Agreement central aim is to strengthen the global response to the threat of climate change by keeping a global temperature rise this century well below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius’.

[9] IEA (2019). ‘Commentary: Five Key Takeaways from COP24 for Energy’, https://www.iea.org/newsroom/news/2019/january/five-key-takeaways-from-cop24-for-energy.html?utm_campaign=IEA%20newsletters&utm_source=SendGrid&utm_medium=Email

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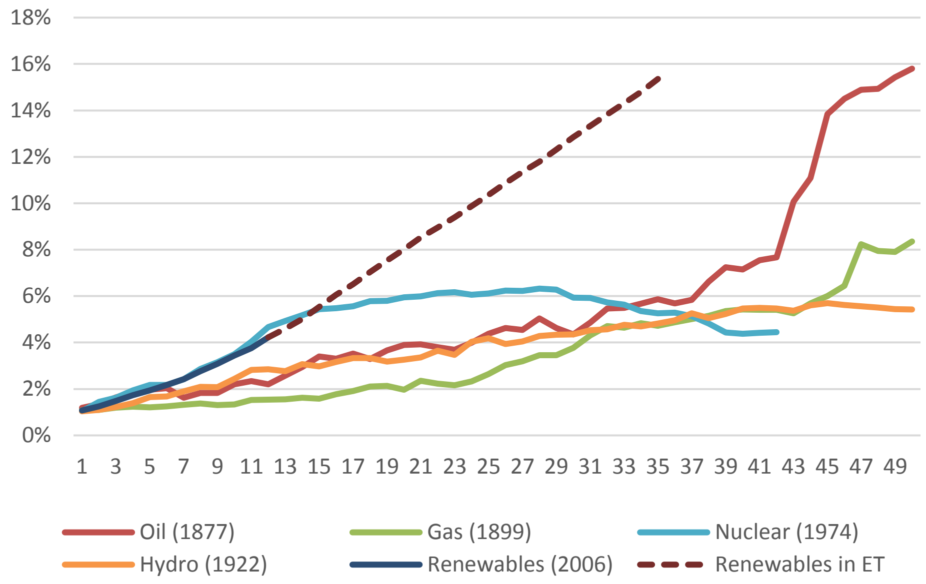
Figure 1: Speed of penetration of new fuels in the global energy system



Source: Source: BP (2019)

Proposition 1: the current energy transition is policy driven

Policy is the main difference between the current energy transition and past energy transitions. The current energy transition is mostly policy driven, conducted by policies rather than by cost competitiveness[10]. This does not imply that technology is not playing a significant role in the transition, but it is not the main driver of the shift in energy sources that has taken place since mid-1990s. Governments have used a variety of policy tools to try to decarbonize the energy mix, regardless the cost of the clean technologies. These policies can be described, from a pure economic perspective, as supply shocks to the production of electricity. Polices that directly stimulate the deployment of renewable technology (feed-in tariffs, feed-in premiums, production tax credits, investment tax credits, green certificates, renewable portfolio standards) or favour the technology progress of renewable energy (financial support for R&D) are a positive supply shock. These policies favour a decline of electricity prices in energy-only markets and an increase in power generation. On the other hand, polices aimed at directly reducing carbon emissions (carbon taxes and cap-and-trade systems) are a negative supply shock since they tend to reduce power generation from coal, natural gas and oil plants and to increase the price of electricity. Power markets are under the effects of both types of policies all around the world.

To add additional uncertainty to the final impact on electricity markets, it is important to specify how these policies are financed. If these policies are financed directly by electricity consumers or ratepayers, there is a direct negative impact on demand. For example, in some Europeans countries the cost of these polices is financed by a tax added on top of the wholesale electricity market. This tax increases the price of electricity to consumers and reduces potential demand for electricity due to a substitution effect. These policies can also be financed by taxpayers and, in this case, there is no direct impact on

[10] See Atalla et al. (2017) to compare with the transition from coal to gas in the USA, Germany and United Kingdom in the 1990s.

the demand of electricity, that is, there is no substitution effect. In both policies there is also a negative income effect.

Policies leading to electrification of industry, buildings or transport, as electric vehicle policies, are a positive demand shock in the electricity market. These policies can have a positive or a negative impact on fossil fuels, depending on the power generation mix and the relative technical efficiency of the power plants, the internal combustion engine of the car, and the electric motor. For example, in a country with a power generation fleet based on natural gas and coal, a policy to promote electric vehicles is a negative demand shock for oil and a positive demand shock for electricity and, therefore, for natural gas and coal.

Finally, subject to no rebound effects, energy efficiency programs can be described as negative demand shocks as they tend to depress the consumption of all types of energy, including power.

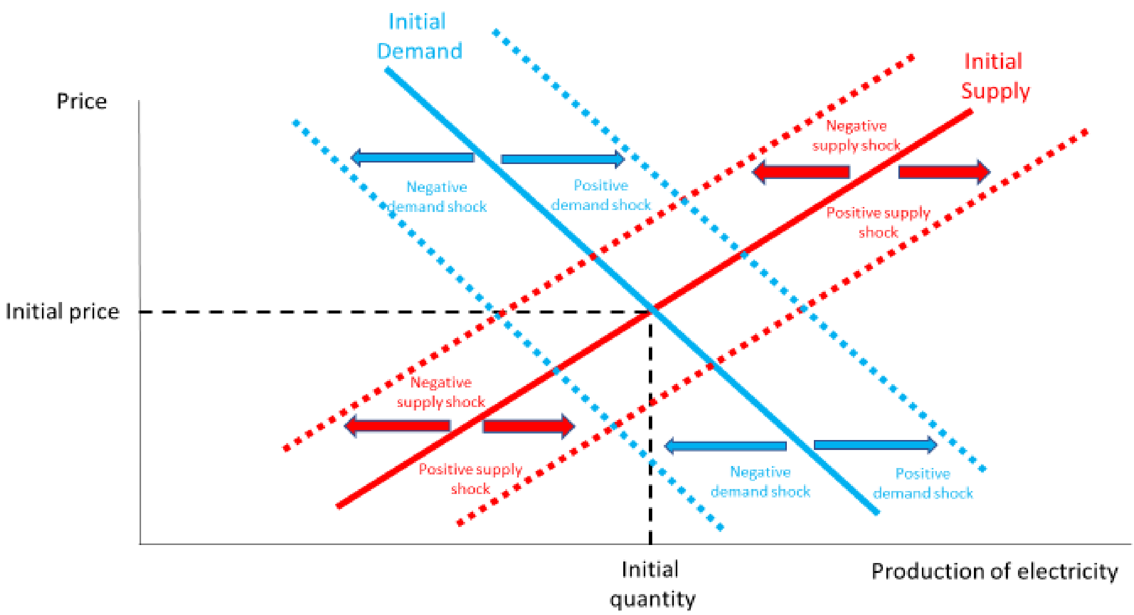
As mentioned previously, the main driver of the energy transition is not technology but policy. A technology-driven transition has a positive impact on supply, reducing the cost of the energy and increasing the quantity produced. However, the outcome of a policy-driven transition is not clear in terms of energy generated and costs. As we have explained in the previous paragraphs, electricity markets face simultaneously positive and negative supply and demand shocks. The outcome of the energy transition will depend on the relative intensity of each policy stimulus. Table 1 summarizes the impacts on electricity in terms of energy-only markets. For the sake of completeness, Figure 2 shows the shifts of the supply and demand curves under different policies in the power markets.

Table 1: Impacts of policies on energy-only electricity markets

		Supply-side policies	
		Promoting renewable energy (Positive supply shock)	Curbing fossil fuel consumptions (Negative supply shock)
Demand-side policies	Policies costs are paid by electricity ratepayers (Negative demand shock)	Price (–) Production **(?)**	Price **(?)** Production **(–)**
	Energy efficiency (Negative demand shock)	Price **(–)** Production **(?)**	Price **(?)** Production **(–)**
	Policies costs are paid by taxpayers (No impact on demand)	Price **(–)** Production **(+)**	Price **(+)** Production **(–)**
	Policies to promote electricity consumption (Positive demand shock)	Price **(?)** Production **(+)**	Price **(+)** Production **(?)**

(+) Increase.
(–) Decrease
(?) Inconclusive. It is possible an increase and a decrease.

Figure 2: Shifts of the supply and demand curves under different policies



Source: authors

The outcome in terms of wholesale electricity prices and production of current energy transition is not determined. It might be the case that similar countries which are transitioning in parallel towards a decarbonized energy mix, but with different polices, diverge in terms of prices, total electricity generated and the energy mix.

Polices have been the main driver for deployment of renewable technologies since the mid-1990s and have had a significant positive impact on the cost of this technologies[11]. There has been a huge decline in the cost of renewables energies. The price of the solar modules in the USA has decreased by 94 per cent[12] (from 4.25 dollars per watt to 0.24) since 1992. In the case on onshore wind, investment cost has declined by around 40 per cent in the same period, according to Bloomberg New Energy Finance (2018). There is a consensus that renewable technologies are heading towards cost competitiveness, measured in terms of the levelized cost of electricity[13] (LCOE), and they will not need additional financial support to compete with fossil fuel technologies in the future. Figure 3 illustrates this point by comparing the expected LCOE (an estimation for expected total average cost per MWh generated) of different technologies. This might suggest that policies will no longer be needed to complete the energy transition. However, climate change and the need to decarbonize the energy mix in record time is an anchor for policies[14].

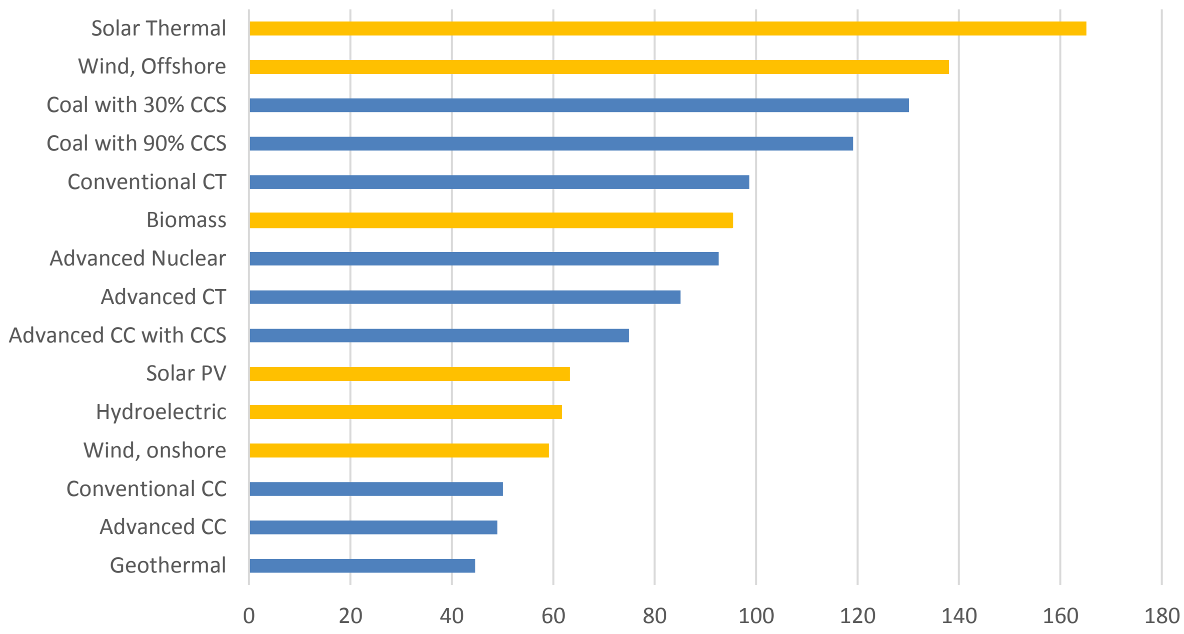
[11] Learning-by-doing or economies of scales back the idea of a negative relationship between production and marginal cost of production. IRENA (2018b) estimates the learning curves for the different renewable technologies, finding that wind has a learning curve around 7–12% and solar PV around 18–22%. This means that every time installed capacity doubles, the average cost declines by 7–12% in the case of wind and by 18–22% in the case of solar PV.

[12] IEA (2006) and Bloomberg New Energy Finance (2018)

[13] The LCOE allows the cost comparison of different technologies of unequal lifespans, project size, capital cost, risk, return, and capacities.

[14] For example, Jerry Brown, Governor of California, signed into law on 10 September 2018 a bill mandating that renewable and zero-carbon sources should supply all the state's retail electricity by 2045. In June 2019, the House of Commons passed legislation to commit the UK to net-zero carbon emissions by the year 2050.

Figure 3: Estimated levelized cost of electricity for new generation resources entering service in 2022 (2017 $/MWh)



Source: Source: US EIA, 2018

It is important to highlight that the LCOE is a proxy for total generation costs, not for operating costs. LCOE compares the total cost of new generation facilities. Solar and wind technology are cheaper, in terms of LCOE, than coal or natural gas in many parts of the world. However, this does not automatically imply that new renewable power plants are cheaper than existing fossil fuel power plants. For existing power plants, the capital expenditure is a sunk cost. In other words, to displace existing thermal power plants from the current generation mix, the LCOE of renewables has to be lower than the operating cost of those thermal plants. This reinforces the idea that policies are still needed to accelerate the transition to a decarbonized mix.

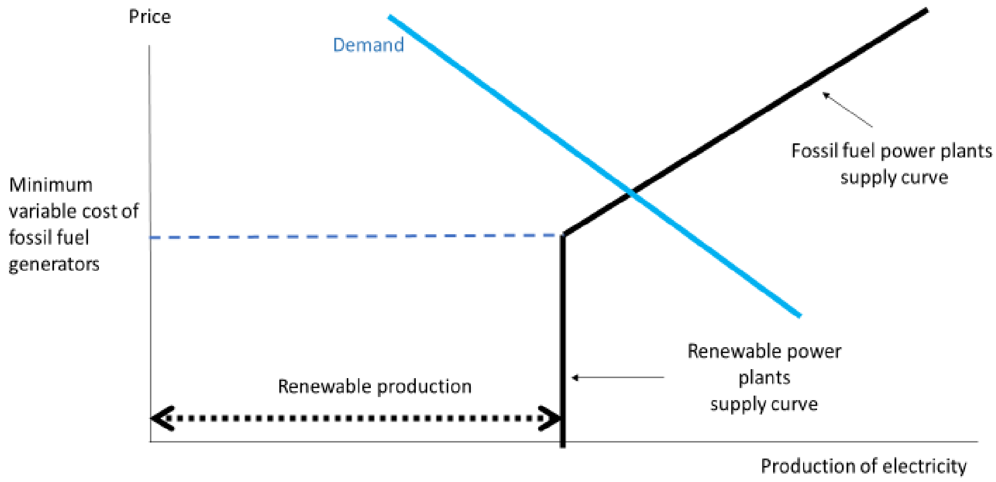
Proposition 2: the energy transition disrupts liberalized electricity markets and undermines their economic foundations

Many production technologies in the twenty-first century are increasingly characterized by situations where marginal costs are almost zero and the entire production cost is effectively a fixed cost. Renewable energies are almost zero marginal cost technologies[15] and, because of this characteristic, they are difficult to integrate into traditional markets designed for textbook supply and demand curves.

The short-term supply curve of the electricity market is the combination of two different types of technologies: renewable technologies with zero marginal cost, and fossil fuel generators with positive marginal cost of production, mainly reflecting the cost of the fuel. This combination results in a kink in the supply curve, as it is shown in Figure 4.

[15] For the sake of simplicity, we are going to assume that the marginal cost of renewables is zero.

Figure 4: Supply curve for electricity in the short term



Source: authors

For a low renewable penetration, which is when the demand for electricity is significantly larger than renewable production at any moment, the price of electricity is determined by the marginal cost of a fossil fuel technology (see Figure 4). As the penetration of renewables increases, the price of electricity tends to decrease. When renewable generation is very large compared with the demand, the price converges to zero. In addition to this, the intermittency and unpredictability of renewable generation lead to volatility of prices. These two facts are well known and studied. Browne et al. (2015), Clo et al. (2015), Dillig et al. (2016), Azofra et al. (2015) and Ballester and Furio (2015), among many others, discuss the impact of renewables on electricity prices of European markets where the penetration of renewable technologies is significant. In the long run and under market conditions, the average price of electricity must be higher than the average total cost of production of any technology to guarantee the deployment of new power capacity.

So, we can define three theoretical stages in the energy transition, as shown in Figure 5.

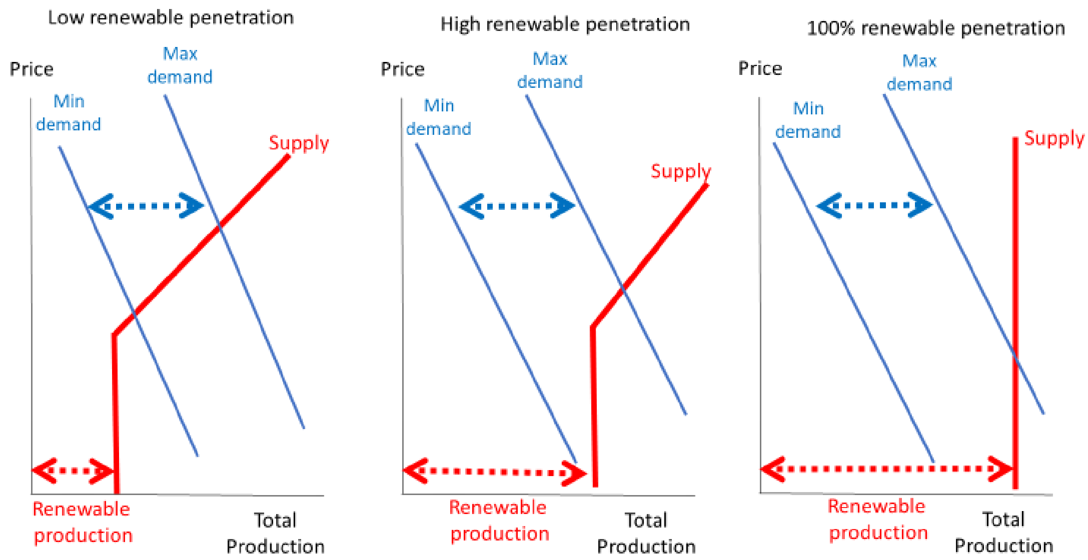
a) Stage 1: Low renewable penetration. The fossil fuel technology is always the price maker technology. The average power price is lower and more volatile than a market with a 100 per cent fossil fuel generation fleet. Still, the liberalized market works without problems.

b) Stage 2: High penetration of renewables. There is a sort of dual system of prices depending on the technology that is supplying the market at any moment. When the production from renewables is very high compared with demand, renewables supply the whole market and the price is zero[16]. When renewable production is lower than the demand, fossil fuel generators supply the market and they set the price of power. Price volatility is high.

c) Stage 3: One hundred per cent penetration of renewables. The supply is totally rigid and determined by renewables' production regardless of the price. Prices are highly volatile, since supply does not react to changes in demand. We argue that this scenario is highly unlikely.

[16] In some instances, the prices are even negative. For illustration purposes, see for example, Pilita Clark in the *Financial Times* (2016) or Jesper Starn in the *Independent* (2017).

Figure 5: Stages in the energy transition



Source: authors

The lower and more volatile prices generate problems for long-term investments during Stage 2. New investments in fossil fuel power generation are not profitable enough. However, new capacity is needed to supply power to the market when demand peaks or when solar or wind conditions are unfavourable. In this context, capacity payments for fossil fuel generators emerge as a system to guarantee the security of supply and avoid future shortages[17]. However, it is paradoxical that because of the transition towards a decarbonized energy mix, policymakers are subsidizing fossil fuel generators.[18] In addition to this political reason, in the case of renewable generators, the lower market power price discourages new investments and reinforces the need for subsidies. This consequence is known as the cannibalization effect[19]. The cannibalization effect takes place when there is a depressive impact on wholesale electricity prices due to high output from intermittent renewables, such as solar or wind farms. Recent data suggest that renewable energy can compete against fossil fuel power generators in terms of LCOE, but renewable investments are not profitable if the price-maker is not a fossil fuel technology. It is paradoxical that renewable energy needs fossil fuel energy to profit from higher price levels.

In addition, there is also a debate on how the cost of intermittency of renewables is borne by the system. It is similar to a negative externality in the power system. Some experts argue that renewable energy providers need to bear this cost and simultaneously provide a form of firm energy, such as natural gas with CCS, batteries, interconnections with other power systems, and so on. In this case, the marginal cost of power services is likely to increase, as penetration of renewables increases cost of intermittency and, hence, the issue associated with natural monopolies minimizes.

The difficulties in accommodating zero-marginal-cost technologies and liberalized markets is well known. This problem resembles natural monopolies. The key characteristic of a natural monopoly is

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[17] For example, this is the justification for capacity payments in the UK (Department for Business, Energy and Industrial Strategy, 2019): 'Part of the government's Electricity Market Reform package, the Capacity Market will ensure security of electricity supply by providing a payment for reliable sources of capacity, alongside their electricity revenues, to ensure they deliver energy when needed. This will encourage the investment we need to replace older power stations and provide backup for more intermittent and inflexible low carbon generation sources.' https://www.gov.uk/government/collections/electricity-market-reform-capacity-market.

[18] From a technical perspective, there are concerns about this regulatory tool. Keay (2016) explains that 'there is good reason to believe that such markets are not the best way forward in the longer term (though they may be necessary to ensure security in the shorter term)'.

[19] See for example, Kraan et al. (2019).

declining average costs, as is the case for renewable production. Marginal costs are lower than average costs throughout the relevant segment of production, which means that the standard marginal cost pricing (price = marginal cost) does not lead to cost recovery (average costs > price). This is the reason why natural monopolies are heavily regulated markets. Therefore, there are reasonable doubts as to whether liberalized markets in their current form are going to survive to the energy transition, since the market price is no longer a signal to allocate new investments[20]. From a political point of view, it is difficult to justify the need for subsidies simultaneously to fossil fuel technologies and to renewable technologies in liberalized markets. In relation to this, Frischmann and Hogerndorn (2015) state that: 'In practice, the answer to the controversy[21] seems to be a theoretical admission that marginal cost pricing would be socially efficient in certain industries with declining average costs and low marginal costs, coupled with a pragmatic argument that subsidizing fixed costs in these industries is politically difficult and so regulatory policy for declining-cost public utilities will often need to set prices above marginal cost.'

All these points raise the question of to what extent renewable energy, current liberalized electricity markets, and renewable policy support are compatible, as pointed out by Blazquez et al. (2018). In fact, there is an increasing debate on the need to reform liberalized markets to favour the integration of renewable technology. Keay (2016) highlights that European electricity markets are already *broken* and discusses some innovative solutions to *fix* them. The analysis of these potential reforms is out of the scope of this road map, but is going to be critical to achieve a cost-efficient decarbonization.

Once the energy transition to renewables is complete (Stage 3), supply is totally inelastic, and demand will set the price. Supply does not respond to prices in the short term. Production is not manageable, and is given by climate conditions. Because of zero-marginal-cost technologies, power plants instantaneously put their production into the market. In this new world, the technical concept of reserve margin makes no sense, since price spikes are needed to keep supply and demand balanced. In other words, price spikes offset peak demands. It is true that, for example, modern biomass and biogas are renewable energies that have a high marginal cost and can mitigate this problem. However, some prospective studies[22] suggest that their role in the energy transition is minor.

This poses the question of the political sustainability of this type of market. Since production is intermittent and unpredictable, and demand varies substantially and is price-inelastic in the short run, prices will be extremely volatile in order to clear the market. However, high price volatility is perceived as an economic and social problem, to the extent that this is an obstacle to smooth consumption over time. For example, in 2016, eleven EU countries implemented some type of interventions in retail the market to control prices. In Bulgaria, Hungary, Romania, Cyprus, Lithuania and Malta almost 100 per cent of the households are supplied under regulated prices. This figure is lower but still very high in France (86 per cent) and Spain (43 per cent), according to CEER (2017).

Given the current technology, batteries and other storage technologies[23] can mitigate price volatility, since they can accommodate short-term variations of supply and demand. Batteries allow producers to sell electricity to final consumers at the most convenient moment, but the problem of price-inelastic supply does not disappear. Given the current technology development, seasonal changes in demand and supply cannot be eliminated using batteries. In this field, hydrogen could be a disruptive technology. Jones et al. (2018)[24] argue that hydrogen can be moved and traded easily, and this could help to

[20] For example, Newbery (2016) explains that zero-subsidy low-carbon generation requires a different auction design. Moreno et al. (2012) explain that, in the case of the European Union, renewable energy reduces wholesale electricity prices, but increases household electricity prices.

[21] The controversy refers to the paper 'The marginal cost controversy' by Coase (1946) that confronted the framework proposed by Hotelling (1938).

[22] Scenarios for IEA, *World Energy Outlook 2018*; BP, *Energy Outlook 2019 edition*; ExxonMobil, , and Organization of the Petroleum Exporting Countries World Oil Outlook 2040.

[23] There different technologies to storage energy like flywheels, flow batteries, liquid-air storage, compressed-air storage and pumped hydro.

[24] This study states that for the UK, 'modern domestic natural gas appliances were found to be compatible with hydrogen-enriched natural gas containing up to 20 mol% hydrogen'.

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increase clean supply in areas with insufficient generation from renewable technology, playing a similar role to natural gas. In the same way, the IEA (2019) argues that this energy can help to achieve a clean and affordable energy future. The marginal price of hydrogen would be different from zero, creating a supply curve with a kink. Nevertheless, current hydrogen technology is far from being able to replace natural gas[25].

Liberalized markets of developed countries are the result of a deregulation and privatization process of vertically integrated monopolies that were either state owned or privately owned and subject to price and entry regulation as natural monopolies (Joskow, 2008). Public monopolies have a different approach to electricity markets. From a purely economic approach, a public utility would generate electricity minimizing the cost while meeting the required standards of security of supply and reliability. In principle, this approach makes the integration of renewable technologies easier. The public utility can simply compensate power plants individually according to their total cost of generation. Given the structure of many liberalized power markets, it seems easier for a public monopoly to transition to a decarbonized power system. Going back to public monopolies in developed economies is not in the political or academic debate. It is clear that the way electricity is traded in liberalized markets must change to accommodate renewables. If the existing market design is not substantially changed, it is likely that renewable energy will be traded in long-term fixed-prices schemes, probably with some type of government intervention, with a stronger focus on compensation of costs than on efficient pricing.

Proposition 3: The energy transition to renewable technology is going to be incomplete

Sometimes there is confusion between the decarbonization of the energy system and an energy system with 100 per cent renewable energy. It is possible to decarbonize the energy system through other technologies. We argue that the energy transition to renewable sources, given the current technologies, is going to be incomplete. In other words, renewable sources will represent a very large share of the energy mix, but fossil fuels are not going to disappear. There are two reasons for this.

First, the full decarbonization of the power system could generate a political problem, at least in current liberalized markets. As discussed, price spikes are perceived as an economic and social problem. However, if the electricity supply is rigid and constrained by weather conditions, any increase in the demand must be offset by an increase in prices. Spikes would be more frequent and severe. With the existing technologies, the easiest solution to the price spikes is to have fossil fuel generators as the reserve margin to supply the system with cheap energy when demand increases. In practice, it is a hybrid system with a high penetration of renewables and fossil fuel generators as backup. In this power system, the marginal cost of the fossil fuel generator determines the maximum price of electricity.

One might think that a potential solution is to overinvest in renewables. If the production of renewable energy is sufficiently high under all types of climatic conditions, the probability of price spikes decreases. However, this solution could be time inconsistent and obviously not cost-efficient. If the generation of electricity is always very high compared with the demand, the price will be zero in most instances, and this would stimulate additional electricity demand in the future, creating the need for additional investments. It is possible to curb the supply artificially by disconnecting renewable facilities from the grid in most instances, creating a permanent economic inefficiency: output is produced but not consumed. Another technical solution is to reduce demand when it is high by disconnecting consumers from the grid. But this alternative is not easy to implement since the operator of the grid has to rank and prioritize consumers.

Second, there are sectors that are intrinsically difficult to decarbonize. The Energy Transitions Commission (2019) identifies heavy-duty transport (trucking, shipping and aviation) and industry (steel,

[25] Hydrogen is a promising technology for transportation and to facilitate the integration of renewable energy, but its current role in the energy transition is still marginal (Hydrogen Council, 2017).

cement and plastics)[26] as hard-to-abate sectors. These represent 40 per cent of carbon emissions of the current energy system. As we mention in the introduction, it is relatively easy to decarbonize electricity and, for this reason, the current energy transition is also a transition to electricity from direct fossil fuel consumption. However, there are some sectors where shifting to electricity is not technically possible. According to the IEA (2018), '65 % of the final energy use could be technically be met by electrification', which also means that there is a limit to the penetration of electricity.

It should be highlighted that an incomplete energy transition does not imply that carbon emissions cannot be very low or even net-zero. Emissions from the power sector or the industry can be captured, used, stored and removed from the air (CCUS[27], direct air capture, ocean fertilization, and so on). Most of the carbon emission scenarios consistent with the Paris Agreement include CCS to differing extents. For example, the IPCC (2018) in its *Special report. Global Warming 1.5^{O}C* describes four main pathway scenarios, three of which include CCS as well as bioenergy with CCS (BECCS). These technologies complement the energy transition and mitigate the negative externality from fossil fuels. The Global CCS Institute (2017) says that to reach the Paris Agreement target the world would need around 2,500 CCUS facilities by 2040 (around 4 $GtCO_2$ captured per annum). Interestingly, they are a potential brake to the deployment of renewable technologies. If carbon emissions can be captured at a competitive cost, the need for decarbonized sources of energy decreases.

Proposition 4: The energy transition demands new business models

While the focus of this paper so far has been on generation, nevertheless, decentralized technologies and digitalization are disrupting the power sector at the consumer end. The energy transition is also driven by a change in consumer preferences, not only towards cleaner energy, but also towards locally produced energy. Consumers place a value on being independent from utilities. This would have implications for both the power sector and for transportation, heating and cooling of buildings, and industrial uses.

In this section we therefore argue that energy transition is also driven by a change in consumer preferences towards cleaner energy, which feedbacks from the political processes on climate change. The relevant question to address is whether the market would be able to satisfy these new individual preferences or whether consumer demand for carbon free energy is ultimately constrained by the system. In other words, can consumers just go and get what they want? This new and unsatisfied demand opens up possibilities for new business models and also jeopardizes traditional ones. The new electricity consumer demands information on how electricity is generated, showing a strong preference for renewable power, at least in developed economies.

The electricity system transforms different energy sources into a homogenous type of energy. Switching fuels to produce electricity is invisible to consumers, as long as there are no price changes. These changes do not have a direct impact on their welfare either, if externalities are not accounted for. In other words, electricity from coal or wind generates the same utility and service for the consumer if carbon emissions are ignored. However, currently consumers are specifically demanding electricity produced by renewable sources. A meta-analysis by Sundt and Rehdanz (2015) concludes that, in general, people are willing to pay for green electricity[28]. This willingness to pay more for a specific source of energy is not unusual. For example, the market does not price the same per calorific unit from natural gas or from coal. The main difference is that the consumer of electricity does not have direct access to the renewable energy market, given the current structure of the system. For this reason, the willingness to pay for renewables can be reinterpreted as internalization of the externality.

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[26] These industrial sectors emit carbon during their industrial processes. Van Ruijven et al. (2016) argue that a high price of carbon (100 $/ton of CO^2) and CCS can reduce emissions from these sectors in a significant manner.
[27] Carbon Capture Utilisation and Storage
[28] This meta-analysis is based initially on 149 different primary studies. The authors find that individuals have a preference for solar over generic green and wind. Biomass and farm methane are found to be the least preferred sources.

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From an economic point of view, the preference for 'renewable' electricity does not represent a challenge. It adds complexity to the short-term standard demand curve, which depends on the price of electricity and, in addition, on the level of emissions. In other words, the electricity demand, for a given price, can shift, depending on the level of emissions – which depends on the generation mix at any moment. However, this preference can have an impact on the structure of the market since it provides new information to suppliers that now can discriminate the demand. New business models must recognize sophisticated customer segmentations and tailored offers accordingly.

Traditionally utilities' business model is a relatively straightforward one. Their value proposition is to generate electricity, fed it into the grid, so that customers can consume it and pay for it as a commodity. The industry structure is comprised of a small number of large assets, and the challenge is to minimize its operational costs and take advantage of economies of scale. With the first generation of renewable technologies, like wind, utilities were able to profit from policies and from a more 'eco-friendly' corporate image.

Some utilities are currently offering consumers the possibility to consume renewable energy[29]. Currently this means that the utility will generate, by means of renewable technology, the same amount of electricity as the client consumes. However, there are other possible options, since some consumers might prefer different combinations of renewables and fossil fuels[30]. This willingness to pay for renewables allows utilities to discriminate demand, increasing their revenue. It is important to highlight that this demand discrimination does not represent an automatic reduction in consumers' surplus, since consumers' preferences depend also on the structure of the energy mix and the level of emissions.

New renewable and distributed technologies allow customers to self-generate and trade electricity with other households, or sell it back to the grid, on a small scale. This would enable customers to bypass, to some extent, utilities infrastructure. These new technologies would transform the power system from one with a few very large assets to one that would have a large number of small-scale assets. This could fragment the industry both in its value chain and in the services traded, and would increase the transaction costs (KAPSARC, 2016). In this new market, regulatory intervention and central control will eventually be heavily constrained when there are millions of decision makers. Markets will become increasingly important to provide real-time and long-term efficient price signals.

New business models would focus on how to monetize them. For example, and in addition to the emergence of prosumers[31], storage could become an additional part of the value chain, located in the blurred frontier between distribution–retail–consumption. Storage can offer a stack of services ranging from reliability, frequency and voltage correction, to arbitrage[32]. Overall, these changes would imply a shift from an industry focused on a commodity to business models focused on services[33].

The current energy transition is the result of polices aimed at decarbonizing the energy mix, but also there is a change in consumer preferences. Utilities are developing new business models to exploit a new unsatisfied demand. This preference for clean energy is not restricted to electricity, but it is the sector where new business models are more evident.

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[29] According to the webpage British Business Energy, there are 12 utilities selling green electricity to home and business consumers https://britishbusinessenergy.co.uk/green/ (accessed on 28 January 2019)

[30] For example, 50% renewables and 50% gas, excluding coal.

[31] Another immediate consequence of the change in preferences is the increase in PV solar at residential scale to have direct access to clean energy. A standard approach to model this new market compares the levelized cost of electricity (LCOE) of PV panels with the cost of electricity from the grid. However, this approach assumes that the consumer is indifferent between a kWh from the grid or a kWh from its own PV solar facility. . Nevertheless, consumers prefer clean kWh and they are willing to make an investment.

[32] Together with prosumers, a niche for smart home management systems would emerge where businesses provide smart meter services – maintenance, and the connection to the grid – but also data storage and data analytics for the prosumer. After the final customer, new business models can offer a gateway to other markets thanks to the data generated in the process.

[33] The value proposition is to offer customized solutions with mechanisms and business ideas that help to keep transaction costs in check, like blockchain 'sharing-economy' platforms, or by bundling services that help them to integrate the new configuration of the industry efficiently.

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Conclusions

The energy transition that is taking place is a shift towards low-carbon energy sources and, given the relative ease with which the power system can be decarbonized, towards electrification. In this context, the paper analyses the main economic characteristics of the current energy transition, describing a road map based on four key proposals to navigate this process.

It is important to highlight that the energy transition is taking place in record time. In general terms, energy transitions are slow processes. However, policies implemented since mid-1990s are favouring an accelerated change of the energy mix. The Paris Agreement might lead to even faster transition in the next three decades.

The first proposal of our road map is that the energy transition is policy driven. This is something new compared with previous energy transitions and has relevant consequences. The policies implemented vary between countries, impacting on energy markets. Two identical countries, in terms of the initial energy mix and cost of generation, can achieve the same level decarbonization with a different energy mix, different level of energy supplied, and different level of prices. The climate change challenge reinforces the need for new policies to decarbonize the economy in the coming years. An implicit conclusion is that, if the current energy transition is policy driven, it can also be derailed by the lack of policy.

The second proposal is that energy markets and, more specifically, liberalized electricity markets are being disrupted by renewable technologies. We define three theoretical stages in the energy transition: a) Stage 1: Low renewable penetration; b) Stage 2: High penetration of renewables; and c) Stage 3: 100 per cent penetration of renewables. The main technical characteristic of renewable technology is an (almost) zero marginal cost, which does not allow for textbook pricing where price equals marginal cost. In addition, the inelastic response of renewable generation to prices could generate price spikes that are difficult to manage from a political perspective. Markets need to be redesigned to efficiently integrate renewable technology which is cheap, but not dispatchable and, to a lesser extent, unpredictable. It is unclear to what extent Stage 3 and fully liberalized markets, at least with the current design, are compatible.

The third proposition is that the transition towards renewable sources is going to be incomplete, given the current renewable technologies, the difficulties of electrifying some activities, and the existence of hard-to-abate sectors. In addition, the political and social preference for stable and predictable energy prices represent a push for fossil fuel technologies. An incomplete transition to renewables does not imply a high level of carbon emissions. Technologies to capture and store carbon emissions can eliminate the negative externality from fossil fuels.

The fourth proposition is that the energy transition needs different business models. There is a change in the preferences of consumers that its mirrored in their willingness to pay for clean energy. This willingness to pay can be reinterpreted as an internalization of the negative externality of consuming fossil fuels. In the same way, the demand for clean energy generation on a residential scale is a signal of an unsatisfied demand. Traditional business models provide energy at the lowest price. However, new business models are moving away from ‘energy only’ towards ‘energy services’.

To sum up, we think that these proposals have relevant consequences: first, each country can have a different energy transition, depending on the policies applied to decarbonize the energy mix. Second, a complete transition towards renewable energy in electricity may be technically possible, but politically difficult to manage in liberalized markets. To avoid extreme price spikes when there is low renewable generation due to weather conditions or unexpected peak in demand, policymakers would prefer a power generation mix based on renewables and fossil fuels with CCS. Third, there is a change in consumer preferences towards decarbonized energy, creating new business opportunities. This change should imply a shift from an industry focused on a commodity to business models focused on services.

Finally, it is important to highlight that technology perspectives are key in this road map. The emergence of a new technology or an unexpected change in the cost of the existing technologies can have an impact on these three propositions. For example, a dispatchable, predictable and abundant renewable source can alter the path of the current energy transition and the validity of this road map.

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