THE SUPPLY-SIDE RENEWABLE ENERGY REVOLUTION

Why Clean Energy Is Now the Cheapest Baseload Power

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Summary

- Climate policy has long been predicated on the idea that fossil fuels will always be cheaper than non-carbon-emitting energy and a permanent carbon price was needed to bring emissions down to a safe level.

- However, rapid technological advances in renewable energy generation and battery storage have reduced the price of clean energy to the same range as fossil-fuel-generated power. Further progress in the coming years will make renewables unambiguously cheaper.

- This revolution in electricity generation will enable renewables integrated with battery storage systems to supply baseload power to European grids.

- Future climate policy should focus less on managing demand and more on creating market incentives for technology on the supply side. This is because of the compounding effect of technological improvements. Previous waves of clean energy technological development have significantly reduced the overall cost of mitigating emissions relative to expectations of what measures designed to operate on the demand side were expected to achieve.

Considering the importance of minimising opportunities for rent-seeking and cronyism, this paper provides recommendations in the following areas including:

Grids: As renewables' share grows, the grid's character will change, particularly the extent of its centralisation. The paper provides a scorecard against which the EU's Grids Package can be assessed.

Heat: Lack of access to financing is one of the main impediments to adopting non-carbon-emitting heating technologies; Significant further research work is needed to simplify the operation of the EU's Emissions Trading System 2 (ETS2).

Innovation: Finally, notwithstanding the need to improve Europe's overall innovation ecosystem in general in order to speed up the development of privately financed clean technology a parallel effort should apply the insights gained from supply-side technological innovation to other areas of climate technology policy, specifically that the benefits of technological improvement compounds and the market-like instruments can more quickly adapt to this fast changing field than regulatory policy instruments.

About the author

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Conflict of interest declaration: Dr Walshe is leading an initiative, funded by the European Climate Foundation, to promote electric aviation in Europe.

Introduction

In March 2026, the Trump administration decided to pay $1 billion to cancel two wind power projects in the US.[1] The company compensated was Total, a French energy giant that produces both fossil and renewable energy. Why was such a large intervention needed to second-guess the market's view of what constituted profitable energy investments?

Part of the reason is that it is not possible to speak of 'the market's' view of energy investment without recognising the long history of state intervention in the energy sector. On the one hand, political lobbying influences the regulation of electricity supply markets in the US and other regions. On the other hand, the Biden administration instituted huge subsidies for renewable energy.[2] There were also continuous and frequent smaller-scale occasions for intervention: the granting of permission for drilling

1 'The Trump admin paid a French company $1 billion to not build offshore wind farms. Blue states are suing', CNN, 3 June 2026 (https://edition.cnn.com/2026/06/02/climate/trump-totalenergies-lawsuit-offshore-wind).

2 Precise figures for the size of these subsidies are difficult to obtain, because the original Inflation Reduction Act documentation has been deleted by the Trump administration, and the Act contained numerous other non-climate-related measures. The Climate Policy Database estimates it at $361 billion (€311 billion). Not all these subsidies were disbursed as the Trump administration restricted their operation. 'Inflation Reduction Act United States of America (2022)', Climate Policy Database, 2022 (https://www.climatepolicydatabase.org/policies/inflation-reduction-act).

or constructing turbines, guaranteed pricing mechanisms for renewable energy, emission standards that affect downstream demand, efforts to change those standards, and the establishment of emission trading systems. Two aspects of this interference will be addressed: (1) the opportunity for rent-seeking and the risk of regulatory capture involving specific instruments for adjusting prices; and (2) the question of how to set the baseline for non-interference. A carbon pricing mechanism or tax can mitigate the former but setting the baseline against which interference is judged presents a greater, perhaps insoluble, challenge.

Nevertheless, it is striking that such direct intervention now appears necessary to deter the construction of renewable energy.

During the past five years, energy technology has approached a tipping point. Technological advances in renewable energy generation and battery storage are upending the economics of electricity production while making the energy conversion of larger portions of the world economy to electric power feasible. Because energy accounts for the lion's share of greenhouse gas emissions, this is producing a paradigm shift in our understanding of climate policy and economics.

Conventional wisdom about climate change mitigation holds that the huge net costs are justified because the price of inaction is greater still. This view has been endorsed by both advocates and critics of decarbonisation for decades. The UK's climate economist Nicholas Stern, whose work would shape the UN Framework Convention on Climate Change, estimated the cost of mitigation in current currency at $1 trillion per year (see 'Why the Supply Side Matters'). Former EU Climate commissioner Frans Timmermans sold the EU's Green Deal to the European

Parliament by stating, 'This is costly, yes, but don't forget what the cost is of not acting'.[3]

The comparative cost argument has begun to show strain. At the Petersberg Climate Dialogue in Spain, 2026, Friedrich Merz, Chancellor of Germany, coupled his defence of the EU's emissions trading scheme system as 'a market mechanism', with a warning that 'climate protection must not endanger the industrial base in Germany and in other countries. A transformation that leads to deindustrialisation will not find acceptance among the public.'[4] His government has proposed easing requirements that new heating systems be powered by renewable energy and has made attempts to procure new gas power plants.[5] Merz's government is one of many facing pressure to abandon climate policies completely. Polish President Karol Nawrocki has twice proposed a referendum on whether decarbonisation is too expensive.[6]

Nevertheless, there was consensus across the political spectrum – from Timmermans, who led the GroenLinks–PvdA social democratic green alliance at the 2025 Dutch parliamentary elections, to Germany's far-right AfD – that the cost of addressing

3 'Closing statement by Frans Timmermans, Executive Vice President of the European Commission', European Parliament, 11 December 2019 (https://ec.europa.eu/commission/presscorner/detail/en/speech_19_6753).

4 'Speech by Federal Chancellor Friedrich Merz at the high-level segment of the Petersberg Climate Dialogue in Berlin, 22 April 2026', Press and Information Office of the Federal Government, 2026 (https://www.bundesregierung.de/breg-en/news/speech-merz-2423054).

5 'Merz: Climate protection must not hold economy back', *Deutsche Welle*, 23 April 2026 (https://www.dw.com/en/germanys-merz-climate-protection-must-not-hold-economy-back/a-76903241).

6 'Polish president renews bid for referendum on climate policy', *Notes from Poland*, 24 July 2026 (https://notesfrompoland.com/2026/07/24/polish-president-renews-bid-for-referendum-on-eu-climate-policy/).

climate change would be high: the disagreement was over whether it was worth paying it.

This consensus relies on two assumptions. First, that a fossil fuel-based energy system is the most economically efficient means of creating useful energy and, second, that as both carbon-emitting and clean energy technology advanced, this would remain the case. That is, both technologies would be expected to advance at the same pace, allowing fossil fuels to maintain their advantage. Therefore, if we were to avoid the costs of failing to prevent or adapt to climate change, we would need to artificially make fossil fuels less attractive. The means chosen would depend on one's political stance. A social democrat might prefer direct economic regulation – stipulating emission standards for certain activities or even banning technologies, such as the internal combustion engine, while others, from the economic centre to the classical liberal end of the spectrum might prefer imposing a carbon tax or a cap on emissions, auctioning permits to set an efficient carbon price. But, in all cases, the policy would have to continue indefinitely, making energy more expensive than it otherwise would be to avoid the still more costly effects of inaction: heatwaves, rising sea levels, disruptions of the monsoon or gulf stream, and the rendering of significant parts of the planet uninhabitable by human beings.

Such policies were rational but costly: to avoid a great cost, it is not irrational to adopt a measure that costs less.[7] They however came with drawbacks not obvious from a calculation of rational self interest. The politics of all such arrangements are extremely difficult, because they are not even zero-sum, but negative sum. They require distributing the losses rather than continuing ‘business as usual’ with a fossil-fuel economy. Worse, this must be done at a global level, where countries or blocs such as the EU do not trust each other and possess only weak mechanisms to enforce climate commitments against free-riders.[8] This combination of effects has led to significant pessimism about addressing climate change (e.g., the European Union Institute for Security Studies (Stang and Ujvari, 2015) labelled it a ‘wicked problem’). The concerns about free riding impinge particularly strongly on regions, such as Europe, that have strong climate policies, but are responsible for relatively small proportion of total global emissions. However, if climate policies result in a cheaper energy system that also avoids carbon emissions, this argument becomes less convincing. We are not in fact loading long-lasting costs on ourselves but incurring some temporary expense to save money in the near future. It has therefore become important

7 This raises philosophical issues related to time and the non-identity problem. The time question is that in standard economic and utilitarian philosophical reasoning, costs and benefits that occur in the future are less valuable (or painful) than those that are incurred immediately. They are – in a manner similar to financial quantities – ‘discounted’. In Nicholas Stern’s report, the rationality, or not, of pursuing a climate policy based on imposing a permanent carbon price depends on the discount rate chosen. If future harms of climate change were discounted more, the rational self-preserving individuals that Stern sought to make the subjects of his analysis might not necessarily see climate action as rational. In the utilitarian ethical tradition, it is difficult to project future harms and benefits onto future generations. See Parfit (1984) for a discussion of the non-identity problem.

8 Some mechanisms do exist. Carbon border-adjustment mechanisms limit the attractiveness of free riding by economies that don’t impose a carbon price. Trade instruments and other international diplomatic measures can also be conceived. It is however unlikely that a state would impose economic sanctions, let alone resort to military force, to enforce climate commitments.

to remove all obstacles to the shift to the newer less expensive clean energy.

These new technologies have radically transformed the economics of energy production, storage, and transmission. In many parts of the world, fossil fuels are no longer the most efficient source to base an energy system on. Moreover, the rate of technological improvement in non-emitting technologies has come to outstrip that of fossil fuels. Though certain areas of energy remain hard to decarbonise, and some greenhouse gas emissions, mainly to do with agriculture, land-use change, and forestry, are largely independent of the type of energy used in that sector, for the first time in two hundred and fifty years, the most efficient way to produce usable energy is not by burning fossil fuels but capturing the energy in wind and sunshine and converting it into electromagnetic fields without intermediate combustion. Instead of stockpiling lumps of coal or liquid petrol, energy storage and transport will shift to preserving an electric charge in increasingly cheap batteries.

This combination of mechanisms, generate and transmit power without combustion, can be termed ‘electrotech’. It is clean energy because it avoids greenhouse gasses and air pollution. It is more efficient because it avoids the waste inherent in combustion and in mining or drilling for fuel. But most importantly, it is cheaper. In most of the world, solar power backed by batteries outperforms other technology. Even in the darker, wetter parts of northern Europe, it is becoming competitive with fossil fuels, because falling battery costs will make solar and wind power competitive by the time needed to bring new power capacity online: cheap baseload is clean baseload. In road transport, electric cars and trucks are replacing petrol and diesel engines. Electricity generated by the new baseload is also beginning to make progress in the heating sector. Aviation, long thought difficult to decarbonise – will soon be able to take advantage of new batteries to begin to electrify short-haul routes. We thus may be said to be in the middle of the electrotech revolution.

The revolution has caught policymakers by surprise. The technologies they had thought to be necessary, such as carbon capture and storage (CCS), as well as, in many cases, hydrogen combustion for many applications, have been left by the wayside. These, which would have required the least change to our established industrial systems because they would have made most use of existing infrastructure for transporting fuel, have been outmatched by the direct generation of electricity.

We are faced with a paradox: climate policies themselves do not appear to have achieved the change they were supposed to, yet they have through *unplanned* consequences of those policies achieved results stronger than their proponents could have hoped for. This raises some important questions for the future of climate policy in Europe and across the world. Most fundamentally, why has this happened? Why have relatively weak policies (Stanchev 2024) led to such profound change? This paper argues that it is because attention has focused on the demand side, while action has taken place on the supply side. Secondly, does this provide lessons for the decarbonising of difficult sectors, such as high-temperature heating, aviation and shipping, and (though outside the scope of this research) agriculture and forestry? Third, a situation in which the most efficient energy technology is cheapest but has damaging side effects, and one where the most efficient energy is the cleanest, calls for different types of action. The first requires the efficient attribution of externalities to their producers in order to disincentivise their future production; the second to allow market forces to outcompete older, dirtier technology. Legacy electricity and transport technologies have accumulated decades of political influence and support. They can be expected to use this influence to try and prolong their life. Such lobbying will not only lead to less effective climate change mitigation; it will also leave Europeans with higher energy prices. How, then, should this legacy be dismantled?

We are in the middle of disruptive, rather than incremental, innovation; for decades, climate policy was built on the basis that fossil fuels were environmentally dangerous but more economical, and that their replacement would therefore come at a net cost. Now they are being replaced by alternatives that are not only cleaner but also more efficient. To encapsulate the comprehensiveness of this transition, we might say that oil and gas are the Blackberry of energy production; Renewables and batteries are the iPhone.

Why we needed a revolution

Since 1989, when British Prime Minister Margaret Thatcher warned the UN General Assembly of ‘the prospect of irretrievable damage to the atmosphere, to the oceans, to earth itself’, the world has instituted various measures to combat climate change. Thatcher’s, an industrial and business-led supply-side programme of technological development, was not the only one tried. It operated alongside regulatory and what might be called demand destruction tracks, wherein the government would organise the economy for an energy transition away from fossil fuels, individuals would be persuaded to change their ungreen behaviour and organisations would develop policies to attempt to make contributions to greater environmental sustainability.[9]

Her supply side ideas coincided with a further economic change in the developed world, stimulated by her government’s reforms and copied elsewhere in the West, the move from a

9 In paragraph 2 of Annex VII to the EU Staff Regulations, the mission staff are encouraged to use rail travel for distances up to 550 km per travel segment as well as for distances above 550 km where it is an efficient alternative to air travel, for example, in the case of high-speed and/or night trains. When assessing the financial cost, the greener alternative should be favoured where the price of rail travel is not more than 40% above the price of an economy class plane ticket for the journey or segment, if it remains within the budgetary constraints of the DG. EU Staff regulations are available at https://eur-lex.europa.eu/eli/reg/1962/31(1)/2026-01-01/eng

manufacturing-led to a services-led economy. This shift has occurred in all advanced economies (Posen, 2021) since services generate greater economic value than manufacturing. Manufacturing has become just part of a chain of activity in which the lion's share of value comes from services such as design and marketing while the production of physical goods yields low profit margins (Baldwin 2019). This transformation has reduced the resource intensity of the economy. By severing the link between resource use and output, it has increased developed countries' environmental productivity.[10]

At the same time public demand for increased output has not abated. Measured at purchasing power parity, about 1 billion people are estimated to be earning what is considered a good income in a developed western economy of around €56,000 ($65,000) per year. The remainder would need to increase their output more than three-fold to achieve this standard of living. Even if this growth could be made twice as environmentally productive, doing so by burning hydrocarbons would require greenhouse gas emissions that greatly exceed the atmosphere's capacity to absorb them.

As part of the natural carbon cycle, the earth can process the equivalent of around 20 billion tonnes of carbon dioxide (a unit known as $GtCO_2e$, or gigatonnes of carbon dioxide equivalent). The 2022 Intergovernmental Panel on Climate Change (IPCC) assessment report, based on 2019 data, estimated total annual human-generated emissions at 59 $GtCO_2e$. This is three times

10 It could be argued that the AI boom has changed this. AI, as currently conceived, is very energy hungry and capital-intensive. The economics of major AI firms resembles that of old steel mills: Expend large amounts of money training an AI model, and then provide its output to large numbers of customers. This economics is more challenging than that of the software boom that preceded it, in which small expenditures produced software that was then sold to large numbers of customers. A discussion of the fate of the AI industry, and whether it constitutes a bubble, is outside the scope of this work.

as much as can be processed every year without leading to the accumulation of greenhouse gases in the atmosphere (IPCC, 2022). Though the IPCC's figures are now seven years old, they still provide a robust baseline for comparisons and a clear sectoral breakdown that allows us to compare what we had expected to happen before the electrotech revolution began to transform the situation.

Table 1. Final emissions by sector (% of total) in the ancien régime and electrotech revolution scenarios

Sector	Ancien régime		Post-electrotech revolution	
	Feasible	Difficult	Feasible	Difficult
Buildings	3	13	10	6
Transport	2	12	10	5
Industry	3	30	10	34
Energy production	2	10	12	0
Total (%)	10	65	42	35
Total (GtCO2e)	6	39	25	20
Agriculture, forestry, and land use (beyond the scope of this paper)	0	22	0	22

Note: Because the entries in each column have been rounded to the nearest percentage point, the 'ancien régime' and 'electrotechnical revolution' figures for transport and industry do not match exactly if added up.

Source: Calculations derived from the IPCC´s Sixth Assessment Report.

The IPCC report calculates both direct emissions (emitted by each sector, but excluding electricity and heating) and indirect, or final, emissions, where the emissions from heat and electricity supply to a sector are attributed to that sector. Agriculture, forestry, and land-use change are outside the scope of this paper and hence excluded from the analysis. This study details the change between scenarios in Table 1 as follows:

Buildings: 10% of the total emissions are attributed to heating and electricity. In the pre-revolution context, what we might call the ‘ancien régime’ scenario, a third of these contexts are considered feasible for decarbonisation. Following the renewable energy revolution, all building-related electricity and heating are treated as feasible. In both scenarios, emissions related to construction, maintenance, and renovation are considered difficult.

Transport: The main difference between the two scenarios is in how land transport is treated. In the ancien régime scenario, trains and certain electric vehicles can be decarbonised. In the post-revolution scenario, the decarbonisation of all land transport is treated as feasible (through electrifying trucks and cars). Decarbonisation in aviation – despite recent advances suggesting short-haul electric flights may become feasible in the next decade or two – is classified as difficult but constitutes only 1.9% of total emissions.

Industry: Electricity and heat supplied to industry are considered feasible for decarbonisation in the post-revolution scenario. Industrial processes are treated as difficult. This is only an approximation because certain industrial processes require high temperatures (>1,000°C) and so are currently hard to decarbonise.

Energy production: Extracting and refining fossil fuels generate a significant amount of emissions. In the post-revolution scenario, this energy use would be superfluous and therefore not take place. In the ancien régime scenario, demand is reduced slightly, leading to a 2% decrease in total emissions.

This high-level exercise helps identify where further effort is needed to develop technologies able to meet our needs in an economically efficient manner, and where market forces can be left to do their work. It indicates that industrial processes remain a key area of difficulty, where carbon pricing is still needed to stimulate the invention and deployment of alternative energy; the construction and maintenance of buildings is also difficult and significant as, though it is out of scope of this paper, is agriculture, forests and land use change.

The difficulty lies in avoiding the well-known problems associated with politically directed allocation of resources. At best, governments will tend to reward politically favoured rather than economically efficient because they respond to political incentives rather than economic ones this in turn provides an incentive for economic actors to engage in rent seeking rather than productive activity (Stigler, 1971); at worst allocation is distorted by cronyism and corruption. Opposing these distortions and limiting the emergence of new ones are essential for developing an efficient climate policy.

A second question is the baseline against which intervention is defined. Even in areas such as consumer goods modern markets are not entirely unstructured. They exist against a background of legislation covering consumer protection, competition and other economic regulation determined by a political process. The traditional energy sector is heavily regulated and, indeed, has had long periods of state ownership even in countries with market economies. Climate interventions are not being conducted into a free market, but must engage with a sector already beset by complex and not infrequently self-serving regulation. Policies should be designed to reduce opportunities for rent seeking, rather than merely transferring rents from emitting to clean industries.

A key advantage of market-based mechanisms such as emissions trading or simple carbon taxes over direct regulation is that they reduce the opportunity for politically motivated manipulation, even if they do not eliminate it entirely, as matters such as the scope of output the scheme or tax covers, extent of free allocation of permits or tax exemptions can still be subject to political influence.

Recommendation: At a time when the cost of living has become a significant political concern, the ETS has come under considerable political pressure. The European Commission's ETS review has proposed giving industry more free emission permits to reduce the financial pressure it faces, while retaining the overall ETS mechanism.[11] This is the wrong approach, as new power generation technologies are now competitive without a carbon price. Instead, effort should be focused on industrial sectors that are hard to decarbonise. The ETS should be applied to those sectors fully, in order to provide the incentives for them to adopt new technology, instead of continuing to subsidise pre-decarbonisation industrial processes.

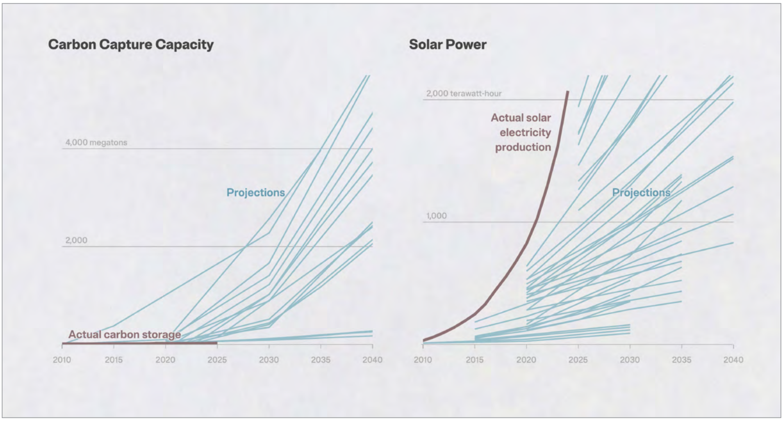
This is consistent with understanding the fossil fuel–driven economy – even without considering its environmental costs – as being stuck in a local optimum, an inability to escape inefficiency because the cost of reaching a new optimum is too high given the risks involved in new technological development.

11 European Commission, ETS, ETS Reviews Section: https://commission.europa.eu/topics/climate-action/eu-emissions-trading-system-eu-ets_en

The effect of environmental policies was not limited to eliminating fossil fuels' economic advantage. Rather, as will be demonstrated later, in the process of doing so, it changed the economics of energy investment, enabling certain, though not all, technologies to take advantage of scientific breakthroughs and economies of scale. Such policies began with early instruments such as California's Low Emissions Vehicle Standards or the UK's Non-Fossil Fuel Obligation of 1989. The EU's solar feed-in tariff, which provided guaranteed prices for solar power supplied to the grid, is often attested as triggering the boom in Chinese solar production, although domestic Chinese deployments and policy direction have also been important (Grau, Huo, and Neuhoff 2011). Policies aimed at changing demand-side behaviour changed supply-side behaviour too, increasing the rate at which relative prices changed. This second-order change is the driving force behind the renewables boom.

These changes are happening at unexpected speed, using technologies that were not predicted to do well. As Figure 1 shows, large investments in CCS and hydrogen technology have failed to reduce emissions but repeated iterative improvement in smaller-scale technologies like solar has.

Figure 1. Carbon capture versus solar power, predicted and actual capacity



Source: 'Why carbon capture can't solve climate change', ProPublica, 25 June 2026 (https://projects.propublica.org/why-carbon-capture-cant-solve-climate-change/).

One response to this might be to ask why certain technologies succeed and others fail, in an attempt to identify rules and implement policy that abides by them. The classical liberal tradition draws a different lesson from this experience. The superiority of solar power over CCS could not have been known in advance. The grey lines in Figure 1 show the market adjusting to information about the relative costs of achieving clean energy production using CCS or solar power, as market participants react to events. The objective should not be to pick winners but to establish a flexible system in which winners can emerge.

Due to the very rapid development of solar and wind power, and now battery storage, within a flexible market-based system, the economics of energy production has been upended completely. The cheapest source of energy, for almost all purposes and in almost all parts of the world, is now a renewable one.

Batteries are now cheap enough to compensate for daily fluctuations, and wind energy and solar power are inversely correlated across the seasons. In Spain, according to figures from the International Renewable Energy Agency (IRENA 2026), the ‘firm levelised cost of energy’ (FLCOE) – a measure that takes into account capital costs, fuel costs, and, in the case of renewables, the installation of batteries to cover most bad weather or nighttime use – was $91/MWh (€79/MWh) in 2025 and expected to fall to $61/MWh (€53/MWh) by 2030. New gas plants in the US, where fuel prices are lower than in Europe, have an equivalent FLCOE of over $100/MWh (€86/MWh).[12] Earlier data from the International Energy Agency (IEA) estimated the levelised cost of solar energy with storage in the US at $45/MWh ($51 in 2026 dollars), equivalent to €44/MWh at current 2026 exchange rates.[13] Though the two measures are not precisely compatible, and LCOE calculations are also sensitive to the cost of capital, fuel prices, and policy effects, both estimates are broadly comparable and reflect major reductions in the cost of solar power and batteries.

This technological development has three major consequences. First, in almost all of Europe, the most affordable form of baseload electricity will be renewable, backed by batteries operating on a more decentralised grid. This is a major change from a system based on thermal plants (e.g., nuclear or fossil fuel), with renewables adding supply on top. Thermal systems, the mainstay of twentieth-century electricity supply, will evolve into

12 The figures in this report are for 95% battery coverage. Above that level, it is still often more economical to cover the remaining variability with other power sources. See the discussion on capacity markets (‘Understanding Electricity Markets’) for how that could be achieved.

13 The IEA also calculates a measure called value-adjusted LCOE, which includes the technology’s contribution to grid capacity and other system-level properties. ‘LCOE and value-adjusted LCOE for solar PV plus battery storage, coal and natural gas in selected regions in the States Policies Scenario, 2022–2030’, IEA, updated 19 April 2024 (https://www.iea.org/data-and-statistics/charts/lcoe-and-value-adjusted-lcoe-for-solar-pv-plus-battery-storage-coal-and-natural-gas-in-selected-regions-in-the-stated-policies-scenario-2022-2030). Inflation calculations are from the Minneapolis Federal Reserve Inflation Calculator (https://www.minneapolisfed.org/about-us/monetary-policy/inflation-calculator).

niche providers of backup electricity, where their advantage of not being weather-dependent will allow them to remain competitive when supplying to peak capacity. The development of efficient ‘capacity markets’ that can ensure supply during periods of peak demand or low-wind, low-sunlight weather will pose a significant policy challenge.

Second, across the world, the cheapest energy will be generated in sunny places with stable climates, giving them a comparative advantage for energy-intensive production. All else being equal, heavy industry will move there. Within Europe, this will make Spain, Greece, and the rest of the Balkans potentially competitive. Italy could also benefit, though it currently has high electricity prices due to gas dependency. Beyond, this bodes well for economic development in North Africa, Latin America, and Southeast Asia. Currently, poorer countries stand to benefit the most from clean energy.

Third, just as those countries leapfrogged western technology by declining to build extensive landline networks, they are now increasingly generating power without resorting to centralised grids. In Pakistan, for example, off-grid distributed solar power now accounts for 28% of the energy mix[14] and has contributed to important growth in Pakistan’s air-conditioning market. This happened without any policy intervention whatsoever. Indeed, the widespread adoption of decentralised solar power, backed by privately owned batteries, across emerging and developing nations has been significantly underestimated by data that rely on reported grid connections.[15]

14 ‘The solarisation of Pakistan’s energy system’, EMBER, 25 June 2026 (https://ember-energy.org/latest-insights/the-solarisation-of-pakistans-energy-economy/).

15 ‘Renewables first, “Customer Owned Renewable Electrification (CORE) Finance Mapping”’, 2026 (https://uploads.renewablesfirst.org/Customer Owned Renewable Electrification (CORE) Finance Mappings.pdf).

A similar, though less advanced, transition is happening in the transport and heating sectors. Road transport and heating are being electrified. Here, the requirement is a little different because it is often households, rather than investors in electrical utilities, who need to decide what equipment to buy. Even when the total cost of ownership of a clean energy system is lower than a traditional alternative, higher upfront costs can discourage adoption. There is still considerable work to be done in removing obstacles to the use of technology to efficiently reduce overall energy costs by switching to up-to-date clean heating and transport.

Why the supply side matters

The speed with which this new technology is developing calls into question a number of assumptions in climate policy that have been held since the 1990s, specifically that a world in which we have a stable climate will be one with higher energy costs than one in which climate change is allowed to continue unabated,[16] and that permanent demand-side measures are needed for a successful transition to a clean energy system. By what mechanism has climate policy been far more effective than it was thought to be? It is first necessary to distinguish between the families of policies to influence carbon emissions, and, second the theories of the economic causes of climate change. The policy families may be categorised as direct intervention (or central planning), regulation, and market price mechanisms.

Under direct intervention, the use of carbon emitting technologies is simply banned or the installation of renewable energy, for example, required. Thus the EU had planned to ban the sale of new internal combustion-engine based cars, and France, bans domestic flights where a high speed train journey of less than 2.5

16 This is separate from an argument about higher overall costs. In any plausible scenario of uncontrolled emissions, the costs of dealing with climate change will exceed the energy costs saved.

hours can be taken instead,[17] and requires car parks with roofs over a certain size to install solar panels.[18] The problems with this kind of policy are familiar from a free market perspective. The flight ban imposes costs on passengers, who will face lower competition on specific routes. Airlines will have to make money in other ways, perhaps by raising fares on other routes or diverting traffic to cars, thereby increasing congestion and undermining the desired decarbonisation effect if the cars are not electric. Conversely, mandating the installation of solar panels on car park roofs is largely superfluous, since if increased solar production is desired, car park owners would make money by installing solar panels, selling the electricity back to the grid, or using it to power charging stations for their customers.

The second, regulatory, mechanism creates incentives, other than direct price signals, for economic actors to change their behaviour. These can take the form of taxes, rules governing spending decisions, or subsidies for clean alternatives. They can range from regulations limiting particular types of emissions to efficiency standards for equipment, feed-in tariffs to guarantee prices for renewables connecting to grids. Though these policies seek to shape behaviour rather than directly intervene in the economy, they still require state interventions to set the permitted emissions, the tariff rate, and so on.

Market-price mechanisms of which cap-and-trade systems, such as the EU's ETS, are the canonical example, are far better. In the purest form of such a system, a cap on permissible emissions is set, and emitters are required to buy permits to emit, which are auctioned and preferably traceable, allowing for the tracking of emission rights relative to demand. Auctions for grid connection contracts (where a power provider agrees to supply power at

17 Loi climat et résilience, Article 145.

18 Loi relative à l'accélération de la production d'énergies renouvelables, Article 40.1.

a specified price) have a similar structure, although one could argue that those are simply markets.

Recommendation: In the seminars that informed this research, both suppliers and purchasers of energy told us they faced the problem of grid connection hoarding. A developer would obtain a grid connection and hold it without supplying power to it; or, conversely, a power user would hoard a grid connection despite not using the power supplied. Grid connections should therefore require maintenance payments to keep them available when not in use. Failure to make those maintenance payments should result in the connections being put up for auction again.

Orthogonal to the mechanisms for reducing emissions are the theories that claim to identify the economic cause of climate change. The direct physical cause is, of course, greenhouse gas emissions; the theories seek to explain why we emit them.

The first, which might be called neo-malthusian,[19] attributes the problem to too much resource use caused by excess economic growth. It adapts a theme from late twentieth-century environmentalism that we are running out of resources,[20] which has seen a revival in the more recent ‘degrowth’ movement.[21] Its advocates are concerned that our economic system has outrun the planet’s ability to provide for it and that climate change – which can be considered a resource exhaustion problem if the ‘resource’ in question is the planet’s ability to process greenhouse gases – is one of several instances of this phenomenon. To

19 After the eighteenth-century English economist Thomas Malthus, who believed that population growth would always exceed our ability to feed people.

20 *The Limits to Growth* by the Club of Rome was a prominent and influential example of this genre (Meadows et al. 1972).

21 This approach gained considerable credibility in the 2020s, leading, for instance, to the Beyond Growth Summit, held at the European Parliament in 2023 (https://www.beyond-growth-2023.eu/).

this concern about resource exhaustion is added worry about climate tipping points: If temperatures rise beyond a certain level of carbon emissions, they could cause other phenomena, such as the melting of the permafrost that could further accelerate the greenhouse effect, possibly making it impossible to control.

This argument has initial plausibility. As discussed earlier, measured by purchasing power parity, perhaps 1 billion people have what is considered a decent income by western levels – about $65,000 annually.[22] The remainder need to increase their output more than three-fold to achieve this standard of living. Neo-Malthusians are concerned that reducing emissions to required levels cannot be done without radically reducing output. They are mistaken, however, about the link between output and carbon use. In fact, output can keep increasing, provided its carbon intensity (emissions per unit of output) decreases sufficiently. This occurs through two main mechanisms: the increasing environmental productivity (output per unit of emissions) of industrial production and, as economies develop, the tendency for value to be concentrated in service industries that emit less carbon or are, in general, easier to decarbonise.[23] The growth of solar power in developing and emerging countries will contribute strongly to this. Historically, these countries have had little access to cheap energy, but this is now changing. The growth in clean electricity is now also happening where it is needed to support lower- and middle-income countries: India, for example, added 53 TWh of solar energy (compared with 85 TWh in the US) in 2025.[24] Although neo-malthusianism with respect to climate might have been true in the past, in the same way as the original

22 'GDP per capita, PPP (current international $)', World Bank Open Data, accessed April 2026 (https://data.worldbank.org/indicator/NY.GDP.PCAP.PP.CD).

23 Posen, A. 'The price of nostalgia: America's self-defeating economic retreat', *Foreign Affairs*, 20 April 2021 (https://www.foreignaffairs.com/articles/united-states/2021-04-20/america-price-nostalgia).

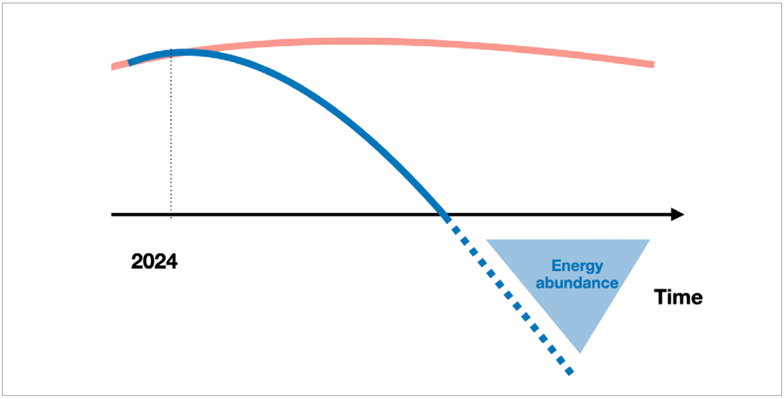
24 'Solar, biggest changes in 2025' (Table), 2025 *Electricity Review*, EMBER, 2026.

malthusianism was true before the eighteenth-century agricultural revolution, in both cases, scientific advances helped us get out of the trap that static technology would have imposed.

The second set of theories that explain why emissions are increasing despite their contribution to climate change focuses on the relative prices of emitting and non-emitting energy. It has two aspects, which are related though not strictly the same. The first considers carbon emissions as an example of a pollution externality – that is, costs imposed on people not responsible for the emissions. Were these costs imposed correctly, the price of emitting-energy production would increase, making it less attractive. The second aspect focuses on the price difference. As long as the emitting energy is cheaper, all other things being equal, it will be preferred by rational actors in a market system. Policy, using any of the families of mechanisms discussed above, is therefore needed to remove fossil fuels' advantage. Though both addressing externalities and the price gap have the same effect, there might still be additional justification for requiring fossil fuel emitters to pay for the externalities caused by their pollution, even if there were no price gap. This question is not within the scope of this paper, however.

All the same, it matters whether the gap is permanent or temporary. In his report, *The Economics of Climate Change*, a study conducted for the British government that heavily influenced the United Nations Framework Convention on Climate Change (Paris Agreement), Stern considered it probably would be permanent (Stern 2006). The technology available to be deployed at the time (nuclear power) or expected to be deployable at scale in the future (CCS) was believed to advance at roughly the same pace as fossil fuel energy generation. Stern (2006) estimated the costs of either replacing emitting with clean technology or adding systems, such as CCS, to emitting technology to turn it into clean technology to amount to 1% of the world's gross domestic product (GDP).

Figure 2. Illustrative Demand-side (red curve) versus supply-side (blue curve) carbon pricing policies



Source: Author's analysis

The third mechanism is technological change. This has always been held in suspicion by part of the environmental movement; for whom environmentalism is a normative commitment against human interference with nature, and which not inaccurately sees technology as part of that interference. The technological view is that if clean technology advances sufficiently more quickly than emitting technology, it will become cheaper to power our societies without emissions than with them. The supply-side electrotech revolution is dramatically speeding up the electrification of much of the economy while enabling the rapid decarbonisation of electricity generation itself. This is now on the cusp of happening in many sectors. As far back as 2023, one economic forecasting model concluded that 'a globally irreversible tipping point may have passed where solar energy gradually comes to dominate global electricity markets, without any further climate policies' (Nijsse et al. 2023). Even if this model is on the optimistic end of predictions, the speed of development of solar and wind power and battery storage indicates that, in many cases, the cheapest baseload power for the world's energy systems will now be renewable.

The electrotech paradox

The paradox is that these changes are happening despite climate policies being considerably weaker than was previously thought necessary. How did this happen? We shall first consider the magnitude of policy effects and then attempt to explain why the change has significantly exceeded, quite frankly, our wildest hopes.

If the task had been the reduction (or perhaps elimination) of the price differential between emitting and clean technology so that carbon emissions were brought down, and if Stern's estimate of 1% of GDP is accurate, the EU should have spent around €180 billion per year at current prices as part of this effort. How much has actually been spent? The EU provides data on energy subsidies for both clean and emitting energy provided by it and its member states and on revenues raised through the ETS, which act as a negative subsidy for emitting generation (Table 2). The data need to be assessed in two periods because following Russia's full-scale invasion of Ukraine, the subsidies increased and changed composition, excluding assessment of subsidies for electricity and energy in general, which are not broken down in the EU data and which will vary depending on the energy mix of each member state in each year.

Table 2. EU subsidies for fossil fuel and clean energy

	2015–2021	2022–2023	Total	Annual average (billion €)
Renewable energy subsidies	577	129	706	78
Fossil fuel subsidies	412	247	659	73
Cost of ETS permits[a]	−79	−57	−136	−15
Net fossil fuel subsidies	333	190	523	58
Renewable subsidies are less than net fossil fuel subsidies	244	−61	183	20
Gross green effort (renewable subsidies + emission permit fees[b])	498	72	570	63

a These costs are negative because they are a cost to emitters, whereas subsidies are a receipt; this calculation is from the perspective of the emitter or generator.

b In this case, the fees are added because, though they are a cost to emitters, they are – for the purposes of the calculation in this row – operating to the same effect as renewable subsidies.

Source: European Commission (2022, 2025) (The data were separated into two sections to account for changes in policy following Russia's full-scale invasion of Ukraine, which led to the EU adopting emergency energy subsidy policies.)

A change in price levels compared to the underlying market fundamentals of €20 billion per year (or about €45 per year per European) is simply not enough to equalise energy prices at the demand side between clean and emitting energies. Even if subsidised fossil fuels are treated as a baseline and ETS permit fees are considered part of what might be termed 'gross green effort', averaging at €63 billion per year (€140 per European per year), the amounts are far from sufficient.

In fact, considering the price differential at the point of purchase is the wrong intuition for energy markets. Although energy is purchased just like any other good, it predominantly serves as an intermediate input. A business does not typically buy energy for itself; it uses it to make products or provide services; similarly, drivers do not buy petrol as an end in itself either but to enable their vehicle to reach a destination. The decision on which energy source to use is made at the supply side: by the infrastructure fund financing a power station, the car manufacturer choosing between a combustion and an electric production line, and the householder installing specific heating equipment or preferring an electric car to a petrol-powered one. The point at which the economic decision relevant to decarbonisation is made is upstream from the consumption of energy.

This allows us to model the economic features of energy-related expenditure. Acquiring any energy equipment, whether a power station or an electric motorcycle, involves certain financial elements: an initial fixed capital outlay, together with recurring payments for fuel and maintenance. Generally, fossil fuel systems incur lower initial capital but higher and more unpredictable operating costs, whereas solar and nuclear energy, for example, entail substantial initial investment but negligible recurring expenditure. To address these differences, the 'Levelised Cost of Energy' (LCOE) metric was introduced to compare power generation projects by taking into account capital and ongoing fuel and maintenance costs. The LCOE is a measure applied to individual projects,[25] but a similar, albeit more complex,

25 See this report by the Fraunhofer institute for a detailed LCOE model. Fraunhofer Institute, *Study: Levelised Cost of Electricity - Renewable Energy Technologies,* 2024. (https://www.ise.fraunhofer.de/en/publications/studies/cost-of-electricity.html)

analysis can yield estimates of the overall cost of different energy systems (Lund et al. 2026). FLCOE, a modified form of LCOE, can be used to estimate the cost of combining renewables with storage to generate power that can be used to provide baseload electricity. Household energy equipment purchases have similar expenses: one installs a boiler and then pays electricity or gas bills to use it. A major difference is lack of personal access to finance, particularly for middle- to lower-income households, which can slow down the adoption of new technology despite the total cost of operation (TCO) being reduced when financing expenses are considered over the equipment's operational lifespan. Nevertheless, at this overarching analytical level, the TCO, which parallels the LCOE, serves as the relevant economic variable: The economically rational decision, assuming all factors are constant, is to select the lowest cost, and from the demand-side perspective, the role of a carbon price is to ensure that the most economical choice is a clean energy system.

However, things are different when considered from the supply side. The energy supplier has to choose among options whose lifetimes often exceed the time needed to develop new technologies: For example, nuclear power stations introduced in the 1970s are still in service. Technological changes affect decisions; but disruptive technological changes, such as the large-scale introduction of new energy technology, are risky and associated with high capital costs. Moreover, incumbent firms tend to avoid new technology, as it cannibalises their existing production and they have developed expertise in the older technology (Aghion, Antonin, and Bunel 2021; Schumpeter 1942). In general, new entrants will focus on and thus engage in innovation; however their capital costs are higher, reflecting their greater risk. If this cost of capital is too high, rational investors will not back the projects, and only incremental innovation using the old technology will be financed. Thus, we find ourselves at a local optimum where a technology superior, even in conventional non-carbon terms, is not developed because the transition costs are too high to finance.

The possibility of inferior technologies being locked-in in conditions of increasing returns is by now well-established (Arthur, 1987). In this case, we encounter two types of technology, one exhibiting returns *to time* (or to R&D investment, rather than to scale) that are increasing faster than the other; the lock-in mechanism does not occur through scale effects (as discussed in Brian, 1989) but because investors expected non-emitting technology to advance no more quickly than emitting technology, therefore were unwilling to fund its development until given a shove in the form of instruments such as feed in tariffs. This complements the conclusion in Arrow (1962) that investment in learning will always be less than optimal because future investors will not benefit from it. Indeed, it follows from Arrow's argument that the faster the learning, the greater the under-investment. Thus, Arrow explains why investors continually underestimated the amount of solar capacity that would be produced (as shown in Figure 1).

There is further a mechanism for path dependency (David 2007) favouring the older fossil fuel technology when the scale of the incumbent emitting industry is so large that it begins with a considerably lower cost of capital than its emerging rival. The conventional climate economics discussed above ('Why the Supply Side Matters') theorised that removing this path dependency required the indefinite equalisation of the price of emitting and non-emitting technology to send the market the correct signals about which energy generation technology to use. In contrast, this paper argues that this path dependency can be overcome less expensively provided the pace of clean technology improvement exceeds that of emitting technologies.

To understand why, let us define the unit TCO of clean energy as c_c and emitting energy as c_e. Let p be the unit carbon price such that both technologies cost the same:

$$c_c = c_d + p.$$

Now we introduce the idea of learning, defined as the amount the cost of a technology reduces over time. Let us define $l = l_c - l_e$ as the difference between the learning rates of the two technologies. A positive l means that the clean technology improves faster than the dirty technology for a given amount of input into the research process.[26] Over time, it follows that

$$c_c - lt = c_d + p_t$$

where p_t is the carbon price in the year t. If learning continues, we reach a point where $p_t = 0$:

$$c_c - lt = c_d.$$

It also follows that the carbon price at t is

$$p = (c_c - c_d) - lt.$$

Therefore, over time, the total unit carbon expenditure required for the transition is represented as $\Sigma^t p = P$, where

$$P = t(c_c - c_d) - \Sigma^t tl.$$

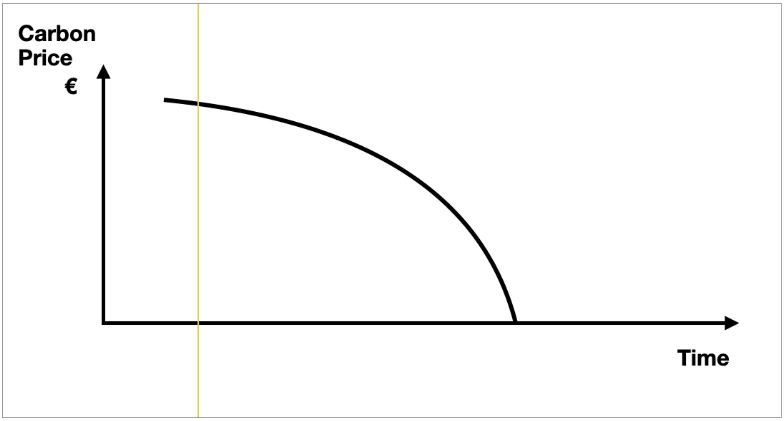
Since the sum term is an arithmetic series, the equation becomes

$$t(c_c - c_d) - \frac{t(l + tl)}{2} \text{ and } t(c_c - c_d) - \frac{tl + t^2 l}{2}$$

26 We could approximate this by money or develop a more complex multi-factor model. It suffices for our model here that the input units are the same for both technologies.

Recall that the difference in the learning rates in these equations is expressed in money per unit energy. From this, it follows that as time increases, the linear terms in the equation will become smaller compared with the quadratic one. Therefore, as time goes on, and as long as the difference in the learning rates between clean and dirty technologies remains constant or increases, the cumulative expenditure needed to balance the cost of clean and emitting technologies will fall quadratically in line with the efficiency of the clean technology (as illustrated by Figure 3). Learning is cumulative, and small differences in learning compound over time. The expenditures needed to stimulate this learning will be less than those required to continuously close the price gap between clean and emitting technologies.

Figure 3. The carbon price required to equalise the costs of emitting and non-emitting technologies, with a constant difference in the learning rates of these technologies



Source: Author's analysis

Understanding electricity markets

This transition runs through European electricity markets: it requires removing obstacles to the adoption of new technology in electricity generation while the amount of energy generation that is electrified grows. Though in many ways liberal in design, European electricity markets are highly regulated, and it is necessary to understand how they work in order to formulate policy recommendations.

In Europe in the second half of the twentieth century, electricity production and distribution tended to be nationalised. The state power company maintained a relatively small number of large power stations, running on coal, oil, gas, and, since the 1970s, nuclear power and distributed it to end industry, offices and households. In the 1980s and 1990s, parts of the system began to be privatised in both western and former communist countries. Because electricity, once generated, has to be used at once and power is transmitted at the speed of light to its destination, supply and demand need to be matched, but demand is variable and outside the control of the grid management authorities (known as transmission system operators [TSOs] in the EU electricity system). Traditional electric grids managed this by adjusting supply, by changing the frequency at which alternating current is supplied by turbines responsible for the ‘baseload’, calling on (dispatching) other sources of power that can quickly be turned on in times of peak demand (often gas turbines or hydropower),[27] and using variable tariffs to deter some demand in order to avoid peaks. Renewables have introduced three other factors that power grids must manage. Firstly, the amount of power they produce can vary with the weather and the time of day. Secondly, they cannot be called upon to provide extra power in all circumstances. Instead, quantities of renewables are built that will in favourable weather conditions produce excess power, and these are 'curtailed' (disconnected) when not needed. More recently, it has become economical to use batteries to smooth out variations in renewable generation, particularly day/night solar supply. Solar panels do not generate power at night, obviously; but a solar array equipped with batteries can be configured to supply a determinate amount of power over 24 hours in constant weather conditions: This is known as 'firm solar' (or 'firm wind'). Finally, renewables are often, though not always, produced at a smaller scale. A grid that had previously connected a small number of power stations must now cope with supply from hundreds, if not thousands, of medium-sized suppliers and potentially even more small-scale 'prosumers' (the word is a portmanteau of *producer* and *consumer*), connecting items as small as roof solar panels to the grid. More recently, off-grid solar and battery systems have been introduced, allowing people to power their own appliances without introducing additional power to the grid. These 'behind the meter systems' can sometimes be quite large (e.g., those on the roofs of warehouses), and grid operators receive no information about the supply they generate.

27 Following the blackout in Iberia in April 2025, there was a lot of talk of 'inertia'. This is because when a turbine is shut down, it continues spinning for a while, so changes related to its powering off affect the grid more gently than when a large solar array or wind farm is disconnected.

In European wholesale electricity markets[28] (the US market works differently), sources are allowed to supply power to the grid in 'merit' order (cheapest first), and the day-ahead spot market price is set at the marginal price needed to make the required amount of demand viable. This is behind headlines such as 'Gas sets the electricity market price'. These headlines are a simplification. What happens is that because gas is more expensive, but also dispatchable, it is often the marginal power supplier. In electricity grids with high renewable energy penetration, such as Spain's, gas rarely sets the spot price. Also, in practice, many industrial customers agree on prices with suppliers and do not depend on the spot price, and household prices are usually heavily regulated.

While excess supply can be dealt with by curtailment, excess demand is more problematic. Batteries, if available, can be used for some time, provided they have been charged. Renewables can be 'uncurtailed' but only under suitable weather conditions. Special 'peaker' gas plants can be turned on, but they must have been built first. Why build a whole gas plant if it will be used only for a few weeks a year? To ensure such generation capacity, capacity markets are created to create incentives to provide capacity during periods of high demand or low supply. However, these were designed for grids with significant dispatchable, as opposed to curtailable, power and may need to be reformed as the power supply mix changes.

Recommendation: To incentivise the changes needed (as well as to ensure grid connections are not hoarded: see recommendation in 'Why the Supply Side Matters'), the forthcoming EU grids package should be assessed against the following criteria,

28 For a full explanation of European energy markets, see Glachant, Joskow, and Pollitt (2021), Schulke (2010), and Meeus (2020).

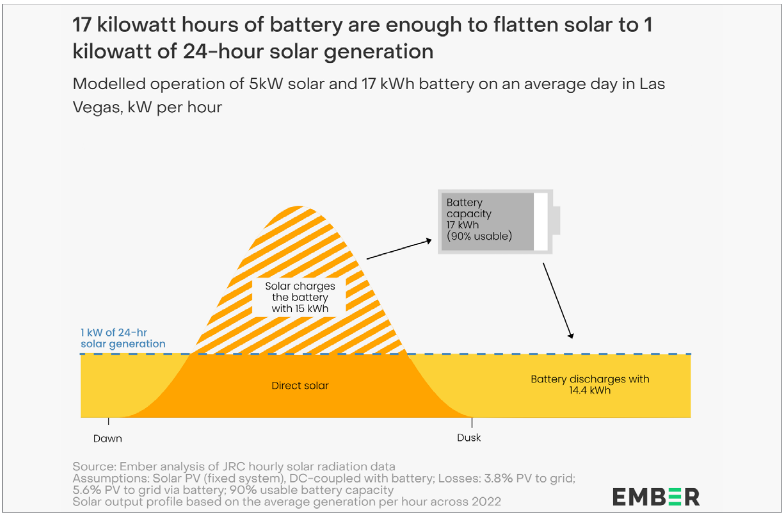
contributing to EPICENTER's EU Regulatory Observatory scorecard. This allows assessment on a scale of 1–10 that:

- Connection and permitting rules give storage and renewables the same queue position, timetable, and cost basis as thermal generation.
- TSO capacity forecasts include an explicit estimate of behind-the-meter generation and publish the method used.
- Network codes and tariffs permit and price decentralised operation, including prosumer export and local balancing, rather than treating it as an exception.
- Member states have a binding smart meter rollout date, with current coverage published as the baseline.

At the same time, dramatic reductions in battery prices have transformed electricity storage. Until two or three years ago, the most feasible technology was pumped hydroelectric, where water is pumped up a hill when there is excess power, and then released to flow down again to turn a turbine to meet peak demand. These systems are expensive and can only run for a short time, but are a useful complement, for instance, to nuclear power stations, whose output is difficult to adjust. Now batteries have become cheap enough to be deployed on both the production and the consumption side. Renewable producers can use such 'grid-scale' batteries – usually supplied in shipping container units – to smooth out short-term fluctuations in supply and solar producers to cover nighttime supply (See Figure 4). Consumers, meanwhile, can use their own batteries – for instance, in electric cars or installed at home as part of their energy system – to store energy across time. This makes flexible electricity pricing much easier to use: Instead of trying to time their appliances to the cheapest time of the day, the battery charges itself when it is cheapest, and people can use their dishwashers when they want. When these storage mechanisms are deployed throughout the network, along with smart meters, it becomes possible for thousands of consumers and producers to match supply and demand in a decentralised electricity grid that operates in effect like a form of Hayekian spontaneous order, mediated through the electricity price. Using storage to smooth supply and demand can have a dramatic effect on the amount of spare capacity a system needs to maintain to handle demand peaks or bad weather (Lund et al. 2026).

Recommendation: As part of the transition to renewables-based grids, adequate technologically neutral capacity market mechanisms are needed to ensure sufficient backup capacity (e.g., in the form of peaker gas plants, interconnection, or storage) to address demand and weather fluctuations. This may be a means of using legacy assets (such as gas plants) that would otherwise be rendered obsolete by technological change.

Figure 4. How storage flattens the midday solar peak



Source: EMBER's analysis of EU Joint Research Centre hourly solar radiation data

Electrification processes

Revolutionising electrification is only half the battle. The second half involves converting parts of the energy sector that often do not use electricity – particularly transport, heating, and certain parts of industry – to electric power. Transport is the easiest; 10% of total emissions originate from road transport,[29] but electric vehicles are now taking over markets for personal cars and trucks. This change is no longer limited to the developed world. Due to the manufacture of affordable electric cars and motorbikes in Asia, electrified ground transport is making inroads in emerging markets and the developing world as well. In Indonesia, by January 2026, about 25% of new vehicles registered were fully battery electric.[30] Aviation is more challenging, but improved batteries are beginning to make a difference for short-haul flights.[31] Long-distance shipping could become a sector where compact, cost-effective small modular nuclear reactors are used.

29 *Sixth Assessment Report,* IPCC, 2022 (https://www.ipcc.ch/assessment-report/ar6/?__cf_chl_jschl_tk__=pmd_e8aedb5999f121c1e35a12141e8ffc7a7ede1b16-1628499618-0-gqNtZGzNAeKjcnBszQo6). (See the discussion in ‘Why we needed a revolution’).

30 See the compilation of data on the BEV Trajectories website (https://leraffl.github.io/LeRaffl-Gallery/#gallery).

31 The author leads a project, funded by the European Climate Foundation, to promote electric aviation. Regional jet equivalents may be in service by the early 2030s.

Heat poses a stiffer challenge because it is the intended product of combustion: what counts as 'waste' heat from a power plant is useful for a heating system; this is the principle behind combined heating and power plants, which are often used for district heating, particularly in northern and eastern Europe.

The most advanced technology for heating at present is a heat pump, which functions as a refrigerator or air conditioner in reverse. These pumps are highly efficient and can generate heat energy several times that of the electricity used to run them by exploiting the temperature difference between two locations.[32] They are expensive to buy but generally cheaper to run than hydrocarbon-based heating systems. The precise pay-off time depends on the ratio of electricity prices to gas prices in the country in question, which varies widely across Europe, often due to national regulatory regimes.[33] In domestic situations, installing a heat pump often requires changing a home's entire heating system, resulting in higher initial costs and disruption; however, newer models can work with an existing heating system and, in places that are not very cold, are literally air conditioners in reverse mode.

Improving a new technology needs a market in which manufacturers can compete by iterating on existing designs to make them better. For heat pumps, such a market involves decisions at two levels. Manufacturers (and their financiers) need to believe that there is likely to be a market for their products. Customers also need to believe that installing a heat pump is worth their while.

32 This does not violate the conservation of energy because the extra energy comes from the temperature differential. It is not created out of nothing.

33 The European Commission's Electrification Action Plan is expected to include measures to address this, but not all required powers are exercised at the EU level.

If a heating system is due to be replaced, the rational comparison will be between the TCO of the two systems; but the higher capital cost of heat pumps may put people off buying. In such circumstances, financing arrangements can ensure that the lowest total cost of ownership option is available.

The main EU policy for addressing these issues is ETS2, and is named on the principle that it is a continuation of the original emissions trading scheme ETS, but differs greatly in detail. Nevertheless, the differences in access to capital among those interested in installing smaller-scale heating and transportation equipment mean that the policy solutions needed to create incentives to adopt new technologies will also differ.

Recommendation: Further investigation is warranted into the planned operation of ETS2 to focus it on developing market-based instruments to incentivise technological upgrades of equipment.

It may also be beneficial to consider more specific incentives to address the capital structure of modernised heating. This is necessary because non-emitting heating systems have high capital costs relative to running costs, which means that even if the overall TCO of a clean system can deliver sufficient savings, the high capital cost will deter installation. Lack of access to and the cost of financing for individuals and non-profit district heating operators can therefore discourage them from adopting clean technology, even though it would save them money in the long run.

The specific measures outlined here do not address whether policies have been effectively designed to incentivise the kinds of cost reductions, if technically feasible, in heating that we have seen in electricity generation; which would be a topic appropriate for the further investigation into ETS2. Moreover, any measures recommended must consider the risk of rent-seeking and politically directed subsidies associated with such detailed policies and take steps to reduce it.

Recommendation: Other more specific incentives could include changes in financial regulations to enable banks to issue targeted loans, potentially with guarantees to reduce their cost, or discounted electricity tariffs for homeowners, besides the measures set out in the following paragraphs.

If a heating system is not due to be replaced, things become more expensive. If a boiler has not reached the end of its life, the amount of money saved by replacing it with a heat pump would need to be significant to incentivise a new installation. Since the issue is capital cost rather than ongoing cost, simplistically applying a carbon price is likely to create losers, because though it would open up a larger gap between the ongoing costs of gas boilers and systems that use carbon-free electricity, it would not compensate for the capital cost already incurred. Householders would instead have to endure higher energy prices because of decisions they had made in the past before the price rises were imposed.

Decisions to ease financial conditions or provide support through more direct measures, such as scrappage schemes and tax rebates, will necessarily result in redirecting the cost of upgrading heating systems from the buyers, whether householders or district heating operators, to taxpayers – either directly or by increasing the risk attached to bank balance sheets above what has currently been deemed acceptable by financial regulators. This cost transfer may be justified if it contributes to the decarbonisation of heating and thus reduces emissions and their associated costs. If it also stimulates innovation through learning by doing in the heating sector, leading to a reduction in costs, it will help reduce future subsidies for non-emitting heat. In addition, by reducing the financing cost, it will enable greater adoption of heating technology with lower total cost of ownership. The losers in that case would be the suppliers of fuel for emitting heating systems.

It is of course paramount that the incentives outlined in this section are carefully designed to minimise the risk of technological lock-in, capture by lobbying groups through burdensome certification requirements, the gaming of incentives (something to which scrappage schemes are prone). District heating organisations, common in eastern Europe, are often non-profit organisations with limited ability to borrow; while services are sometimes contracted to private companies, these have to comply with stringent regulatory requirements that limit their ability to maximise profits (Komorowska and Surma 2024). Although it is possible to replace a district heating boiler with a large-scale heat pump, heating organisations are not always in a position to finance the upgrades. The rates they charge are usually regulated and cannot easily be increased to cover upgrade costs without significant political blowback.

Recommendation: Cheap financing could also be extended through guarantees to allow building cooperatives and district heating organisations to finance the replacement of emitting heating systems with clean ones. These could also cover the cost of insulation and other building upgrades.

Recommendation: Property owners could be given tax rebates for replacing tenants' emitting heating systems with clean ones.

This leaves high-temperature industrial heat – used, for example, in cement and metal production and chemical-industrial processes; the latter produce emissions for reasons other than energy generation. Numerous promising technologies exist; but, a carbon price is still necessary to incentivise their development in a low-carbon direction.

Conclusion: Creative destruction for the climate

Climate change is a by-product of the fossil fuel economy that powered the industrial revolution and the developed economies it created. These nations achieved their prosperity by harnessing the energy contained in fossil fuels, allowing people to live far better material lives than those living in economies where energy was limited to the muscle power human beings and working animals derive from food. This has come at a cost to the environment, of which climate change is the most serious and potentially the most intractable form of environmental damage.

But excluding food production, outside the scope of this research, we are now at a hopeful turning point. Incredible advances in clean energy production technology are revolutionising energy production and supply, heating and transport.

We are entering a time of radical, discontinuous change in our energy systems. This is the result of a paradigm shift in how energy is produced. In the old paradigm the burning of fossil fuels was the best source of energy. They were plentiful, easy to transport, and their high energy density made them unbeatable as fuel. The problem was the pollution they caused. Expedients, such as scrubbers and catalytic converters, were able to reduce the pollution caused by sulphur and nitrogen oxides, but they struggled to reduce the emission of carbon dioxide, the main greenhouse gas and the principal product of combustion. Climate change is an externality whose costs were not incorporated into the price of the fuel bought. But if the cost of combustion were raised either to a point where the costs of climate change would be fully paid by the users of the energy system or to the point where carbon-emitting technology no longer had an advantage over non-emitting technology,[34] the inherent economic advantages of fossil fuels would no longer cause them to be preferred to cleaner alternatives or the costs associated with them would be internalised in the system. This raised fears of global free-riding by countries, including developing economies, that chose not to increase the price of fossil energy. It also affected the ability of those developing countries that opted for clean energy to remain competitive under a more expensive energy regime. This view rested on the assumption that fossil fuels would always, in the narrowest of economic terms at least, be the best energy source and these advantages had to be permanently compensated for if we were to limit carbon emissions.

But now, the facts have changed. Increasingly, clean energy sources (currently, solar and wind power supported by batteries), along with clean transport (electric vehicles) and clean heating (mainly heat pumps), are becoming cheaper than carbon-emitting sources, and for certain applications, they are able to win out without further policy support. In economic terms, the fossil fuel economy was not the general optimum but only a local one.

What has changed is the 'environmental productivity' of our energy system. The amount of economic output produced per unit of carbon emitted has increased, helped by the shift in value away from manufacturing and towards services, as well as by changes in electricity production technology and the

34 These costs do not actually have to be the same, although they are sometimes conflated.

electrification of previously non-electric activities. This growth in environmental productivity is getting us out of the fossil fuel local optimum. Moreover, because it will lead to cheaper energy, rather than becoming a net cost, the competitive advantage will accrue to countries that have speedily implemented the transition to clean, and cheaper, energy while giving developing countries a chance to leapfrog the fossil fuel economy like they leapfrogged fixed-line telephony.

This has been done by operating at the supply side of the energy market, because, in general, energy is a non-differentiable intermediate good that its users do not consume as an end in itself. They use it to travel, heat or cool buildings, or run their businesses. Though a small minority of environmentally sensitive consumers have sought out green power technology, most energy users make their decisions on price and receive whatever form of energy is most convenient for them. Innovative technology needs adequate financing to support the new ventures that will deliver the technological change required. This leads us to one final, general recommendation.

Recommendation: While a preferred solution would be the development of a true European venture capital sector able to finance riskier startups and scale-ups, this is a significant undertaking beyond the scope of this work and will require major changes to the European financial system, overcoming important vested interests in the process. However, programmes such as ETS, and to a much smaller extent the Carbon Border Adjustment Mechanism, may provide other funding sources that could be used to finance innovation in clean technology. Further research aimed at devising efficient mechanisms to disburse such funds in ways that avoid the bureaucracy and the opportunity cost associated with applications to bureaucratically administered programmes is needed. Guided by principles that preserve market discipline while avoiding the ‘valley of death’ (Frank et al. 1996), the financing gap for new clean technologies caused by the immaturity of the European venture capital ecosystem can be overcome, such principles may stimulate further innovation in clean energy technology and have potential applicability in other areas where financing gaps prevent innovation.

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