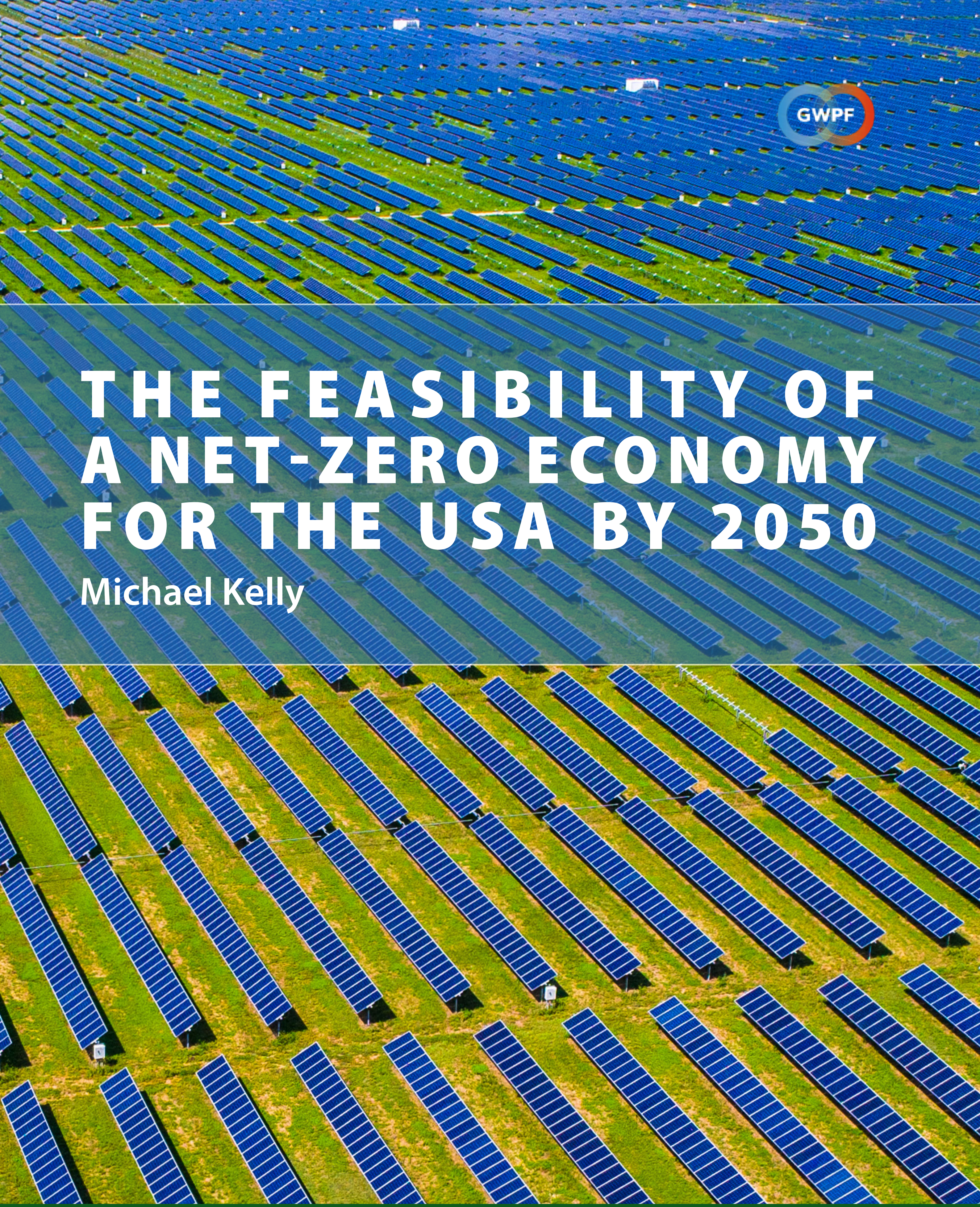

THE FEASIBILITY OF A NET-ZERO ECONOMY FOR THE USA BY 2050

Michael Kelly

The Global Warming Policy Foundation
Note 39

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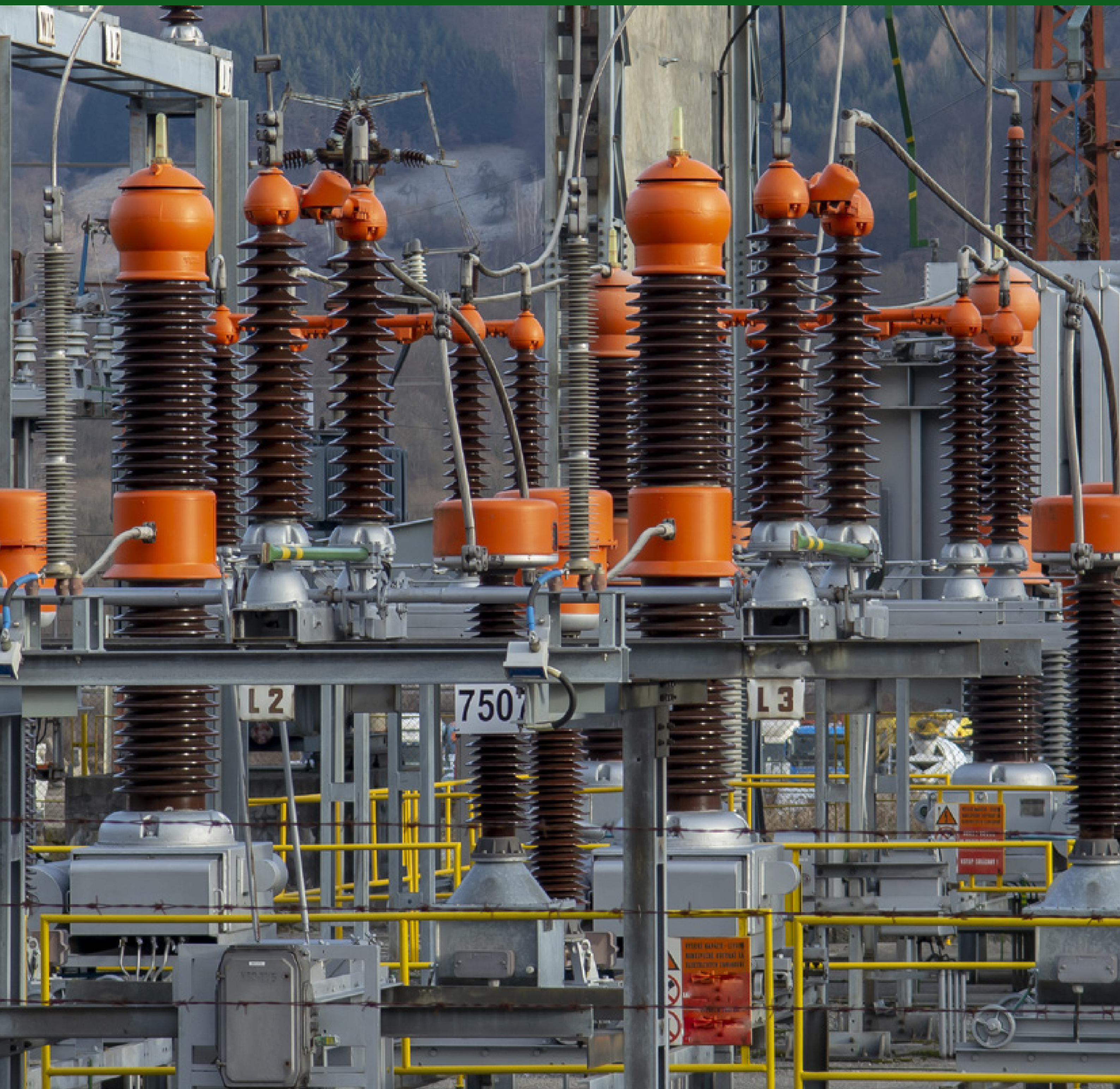

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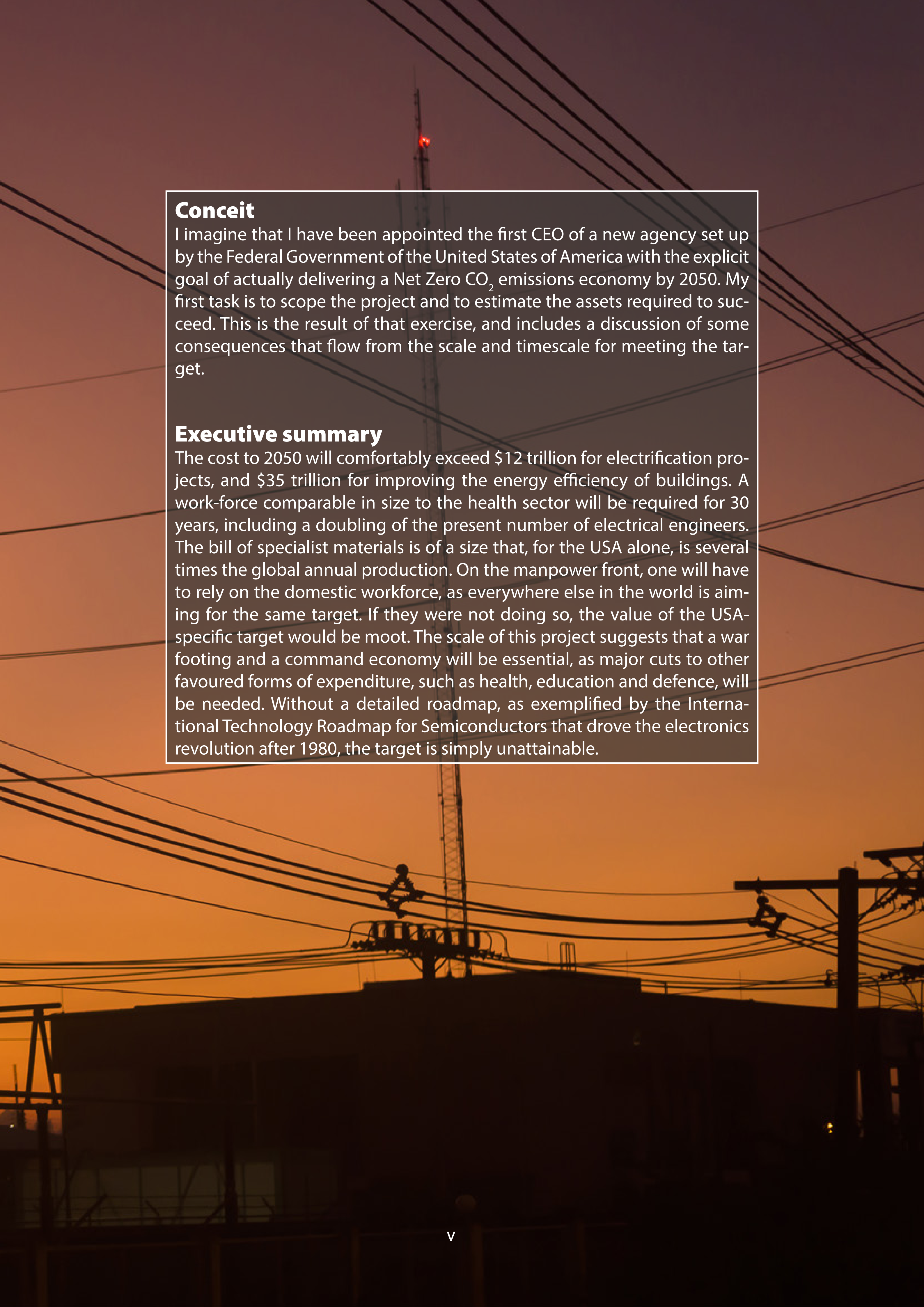
About the author

Michael Kelly is the Emeritus Prince Philip Professor of Technology at the University of Cambridge. He was a Chief Scientific Advisor to the UK Department for Communities and Local Government. He is a Fellow of the Royal Society and the Royal Academy of Engineering and is a trustee of the Global Warming Policy Foundation (GWPF).



Conceit

I imagine that I have been appointed the first CEO of a new agency set up by the Federal Government of the United States of America with the explicit goal of actually delivering a Net Zero CO_2 emissions economy by 2050. My first task is to scope the project and to estimate the assets required to succeed. This is the result of that exercise, and includes a discussion of some consequences that flow from the scale and timescale for meeting the target.

Executive summary

The cost to 2050 will comfortably exceed $12 trillion for electrification projects, and $35 trillion for improving the energy efficiency of buildings. A work-force comparable in size to the health sector will be required for 30 years, including a doubling of the present number of electrical engineers. The bill of specialist materials is of a size that, for the USA alone, is several times the global annual production. On the manpower front, one will have to rely on the domestic workforce, as everywhere else in the world is aiming for the same target. If they were not doing so, the value of the USA-specific target would be moot. The scale of this project suggests that a war footing and a command economy will be essential, as major cuts to other favoured forms of expenditure, such as health, education and defence, will be needed. Without a detailed roadmap, as exemplified by the International Technology Roadmap for Semiconductors that drove the electronics revolution after 1980, the target is simply unattainable.

Introduction

Imagine the USA in 2050 has a net-zero emissions economy. Three very large, interrelated, and multidisciplinary engineering projects will have been completed:

- Transport will have been electrified.
- Industrial and domestic heat will have been electrified.
- The electricity sector – generation, transmission and distribution – will have been greatly expanded in order to cope with the first two projects.

A fourth project is to secure the buy-in of the public for what will be 30 years of social disruption, diminished living standards, and living under a command economy. The successful completion of these projects is necessary to meet the high-level target, but they are not sufficient, as I have not dealt explicitly with agriculture and other matters, as described below.

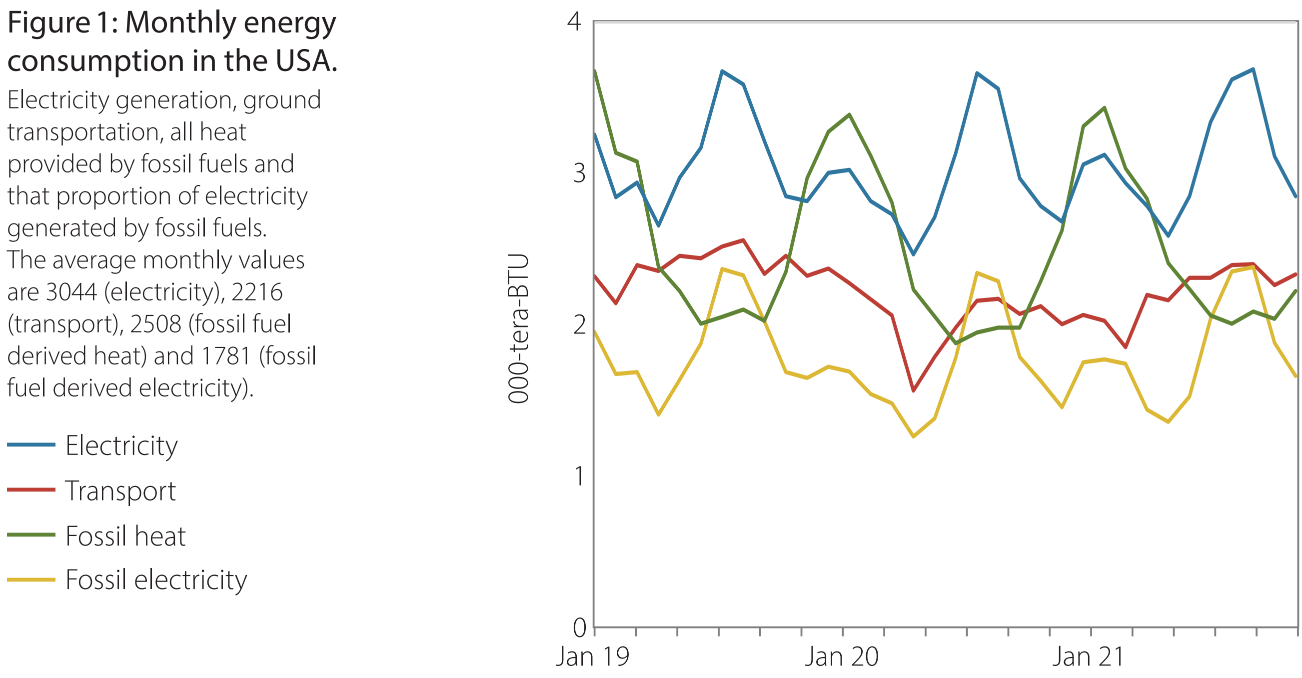
Current USA energy consumption

The data in Figure 1 give an indication of the energy used over the months from January 2019 to October 2021 for transport, heat and electricity (in total, and the fossil fuel contribution) in the USA. I have derived this diagram from the US Energy Information Agency data.[1]

Throughout the year, the use of transport fuel is approximately constant, whereas heating energy is 75% higher in winter than summer, and much of the baseload heat is of industrial origin. Electricity use peaks in summer, as a result of the use of air-conditioners for cooling, and has a subsidiary peak in winter from heating.

Figure 1: Monthly energy consumption in the USA.

Electricity generation, ground transportation, all heat provided by fossil fuels and that proportion of electricity generated by fossil fuels. The average monthly values are 3044 (electricity), 2216 (transport), 2508 (fossil fuel derived heat) and 1781 (fossil fuel derived electricity).



In converting transport energy and heat – currently mostly derived from fossil fuels – to electricity, we will use today's data, assuming that the increase in demand from population growth will be offset by energy efficiency savings, both at about 10% over the next 30 years. This approximation would have to be revisited in a more detailed analysis than is given here. Note that about 60% of electricity is currently provided by fossil fuels. For Net Zero, this would have to be sourced from renewables and nuclear energy.

Decarbonising the economy

Transport

Transport energy is 75% of average electricity use, and peaks in summer. It is nearly all provided by fossil fuels at this time. Because an internal combustion engine converts the energy stored in its fuel into transport motion with an efficiency of about 30%, while electric motors are more than 90% efficient at using energy stored in a battery, we will need to increase the electricity supply by about 25% to maintain transport in the USA at today's level in 2050.

A small part of this transport energy is used for aviation and shipping, the electrification of which is much less advanced than is ground transport, and will, in the end, be more expensive per journey than using aviation fuel and bunker oil today. The extra cost of alternatives to these fuels is not examined here in detail, and this omission allows us to insist that the estimates below are a lower bound on the total cost of delivering Net Zero. The additional electricity infrastructure required is considered in the third engineering project.

Heat

From Figure 1, we can see that in summer, the USA uses 75% more energy in the form of heat than it does as electricity. If this heat was provided by radiant heaters, we would need an extra grid equal to the size of today's just to keep homes and businesses warm. If we use air-source and ground-source heat pumps, with a coefficient of performance of 3:1 – reasonable given the average quality of the thermal envelope of most buildings is high (because of the need to keep heat out in summer and/or heat in in winter) – then the extra grid would need only to be 35% the size of the present one, for the heat element alone. Combining this result with the figures for transport in the last section, the grid in 2050 will, *prima facie,* need to be more than 60% larger than its present size. We return to this issue later. However, it may be possible to reduce the amount of electricity required by further insulating buildings.

The US building stock is made up of nearly 150 million housing units, commercial and industrial buildings, with an estimated floor space of 367 billion sqft (Table 1). The current thermal envelope varies strongly by geographic region, and a national retrofit exercise would have to be delegated to states to cope with this variation. Such a programme could reduce the amount of green electricity needed but, for this exercise, only a gross approximation of the project to raise all buildings to the optimum thermal envelope is possible. For ex-

Table 1: Buildings in the USA.

Building type	Number (million)	Area (million sqft)
Houses	140.0[10]	246,000[11]
Commercial	5.9[12]	97,000[12]
Industrial	1.3[13]	10,267[13]

ample, the cost in the UK can be estimated with reasonable accuracy as there has been a pilot retrofit programme from which the national scale cost is $1 trillion per 15 million population.[2] The figure in the USA would therefore be about $22 trillion. Using independent but equivalent US data on deep retrofitting, scaled up to 100% emissions reductions, gives a remarkably consistent figure of $20 trillion.[3] Given the extent to which buildings in cold climates are already well insulated, this cost may well halve, but we will need to add the improvement of insulation in hotter regions to reduce the use of air-conditioning, and this will take the cost back up again. In addition, US houses are twice the size of those in the UK on average, which will take the costs higher, to something of the order of $35 trillion. It is a matter of urgency that this estimate be refined based on actual US data on retrofitting a representative sample of US houses and other buildings.

Industrial heat for the manufacture of steel, cement and other materials has been included above. Electric arc furnaces will accomplish some of the job of decarbonisation, but the highest temperatures still require fossil fuels. This latter implies extra costs for reaching net zero, which will need further consideration later.

Electricity infrastructure

The grid needs to be 60% bigger in 2050 than currently if the US economy as we know it now is to continue to function. Clearly, 30 years is also enough time to drive other changes in the economy that may reduce, or, indeed, add to this 1.6 factor.

Taken together, the US grid has been called the largest machine in the world: 200,000 miles of high-voltage transmission lines and 5.5 million miles of local distribution ones. Assuming a scaled-up grid is 1.6 times its present size, we will need to add a further 120,000 miles of transmission line. This last will cost of the order of $0.6 trillion, based on US cost data.[4]

The 5.5 million miles of local distribution lines will have to be upgraded to carry much higher currents. Most houses in the USA have a main circuit-breaker panel that allows between 100 and 200 amps (A) current into the house, although some new ones are rated at 300 A. The 100-A standard was set nearly a century ago, when the electric kettle was the largest single appliance, drawing 13 A. In a modern all-electric home, some of the new appliances typically draw rather higher currents: ground-source heat pumps may draw 85 A on start-up, radiant hobs when starting up draw 37 A, fast chargers for electric vehicles draw 46 A, and even slow ones may draw 17 A, while electric showers draw

46 A. The local wiring in streets and local transformers were all sized to the 100-A limit. Most homes will need an upgraded circuit breaker panel, and much local wiring and many local substations will need upsizing. The UK costs have been estimated in detail at £1 trillion,[5] which would scale to of order $6 trillion on a per-capita basis.

Decarbonising the 60% of the current grid that is fossil fuelled as of now means that we will need four times the current non-fossil-fuel grid capacity. There is limited capacity for new hydroelectricity, and the economics of carbon capture and sequestration is unproven. From Figure 1, we can see that we will have to be able to deliver the peak electricity requirement even at times – in winter – when production in the north of both wind and solar electricity is low. Using a mixture of wind (onshore $1600/kW, offshore $6500/kW), solar ($1000/kW at the utility level) and nuclear ($6000/kW), the capital cost alone is of the order of $5 trillion.[6] Note: there is no provision here for storage of electricity at the state level for 3–6 months, which would be required. Storage will be discussed further below.

We have identified $12 trillion as the cost of providing the generation, transmission and distribution of electricity in a net-zero world. Although not all borne by households, this figure is of the order of $100,000 per household. The cost of battery storage is extra, and would dwarf this sum. Current hydropower storage would run a net-zero grid in the USA for a few hours; current battery capacity could do so for a few minutes.

Human resources

We now consider the human resource requirements to deliver the target economy. Atkins (a UK engineering firm; private communication) estimate that a $1-billion project in the electrical sector implies about 800 years of professional engineering time, and somewhere between 2000 and 3000 years of the time of skilled tradespeople. This amounts to 24 or more engineers and 100 or more skilled tradespeople, employed fulltime for 30 years. Scaling up these figures for the $12 trillion electricity sector projects just described, we will need 500,000 professional electrical engineers and of order 0.8 million skilled people employed fulltime for the 30 years to 2050 on just this aspect of the net-zero project. There are approximately 400,000 licenced engineers at present, so we will need to more than double that number to accommodate these projects. Training this many people will take time and resources, and will therefore hamper progress in the coming decade, during the initial build-up phase, meaning even more will be needed later on.

In the building retrofit sector, a range of skills – from semi-skilled to highly skilled – is required. Based on the budget, we might expect the retrofit sector to need a similar workforce, of roughly three million people, to deliver everything from the design of individual projects, through the materials supply chain, to the actual retrofitting work. Clearly these are both major perturbations to the national workforce. There are no prior examples of skilled workers being generated and maintained on such a scale over 30 years.

Bill of materials

The actual costs of the materials required are covered above. Here we consider the quantities required. The transition from fossil fuels to renewables is a move from a fuel-intensive energy sector to a materials-intensive energy sector. There is already considerable popular concern about the role of mining in reducing biodiversity; this problem is about to get much worse.

For example, a 600-MW combined-cycle gas turbine (CCGT) comprises 300 tonnes of high-performance steels. We would need 360 5-MW wind turbines, each running at an average 33% efficiency, and a major energy storage facility alongside, to achieve the same continuous 600-MW supply. In fact, since the life of wind turbines at 25 years is less than half that of CCGT turbines with a single life-extension refit, we would actually need more than 720 of them.

The mass of the nacelle (the turbine at the top of the tower) for a 5-MW wind turbine is comparable to that of a CCGT.[7] Furthermore, the mass of concrete in the plinth of a single CCGT is comparable to the mass of concrete for the foundations of each onshore wind turbine, and much smaller than the concrete and ballast for each offshore one. A corollary of the multiplicity of turbines or solar panels is that connecting them to the grid is more materials intensive.

A 1.8-GW nuclear power plant and turbine produce about 1000 W/kg of steel in the combined unit, compared with around 2000 W/kg for a CCGT and 2–3 W/kg from solar panels or wind turbines. These factors, of order 1000, show that the use of high-value materials (steels, silicon and long-life polymers for wind turbine blades) is much more intensive in renewables. This effect is offset somewhat by their fuel-free operation. However, the extraction of oil and gas only has a small impact on the earth's surface compared with the opencast mining of the minerals used by wind turbines and solar farms.

If the US were to convert overnight to an electric vehicle fleet, the materials requirements for the batteries alone, compared with annual production today, are estimated, by scaling UK estimate by the population ratio, as:[8]

- 1 million tonnes of cobalt – almost 20 times the annual global production;
- 1.3 million tonnes of lithium carbonate – over 7 times the annual global production;
- at least 36,000 tonnes of neodymium and dysprosium – nearly 5 times the annual global production of neodymium;
- 10 million tonnes of copper – nearly the global production in 2018.

If the world is to go all-electric in 30 years, we need to convert the USA in 1.7 years.* As a result, there is a need for a very steep rise in the mining of these materials. Unregulated and child labour is implicated in much mining of cobalt, so there are intense research efforts to replace it without losing too much battery efficiency. Biodiversity will be under even great threat from increased mining.

Energy storage

Fossil fuels are much more effective at storing energy than any known non-nuclear alternatives (Table 2).[9]

One illustration of this issue was prompted by a member of Extinction Rebellion, who assured me that the back-up electricity supply for emergency wards in hospitals would be provided

Table 2: Energy density of different fuels

Technology	Energy density (MJ/kg)
Wind turbine	0.00006
Lead-acid battery	0.15
Hydro	0.72
Wood	5.0
Petrol	50
Hydrogen	143
Nuclear fission	88,250,000
Nuclear fusion	645,000,000

Source: MJ Kelly, 'Lessons from technology development for energy and sustainability' *MRS Energy and Sustainability* 2016; 3: 2–13.

by batteries by 2025. The 100-MW, 128-MWh battery installed by Elon Musk near Adelaide in 2018, at a cost of $100 million, would power the emergency wards – 30% of the total – of Mt Sinai Hospital in the New York area for 24 hours on a single 80–20% discharge. If a storm took out the transmission lines in the New York for a week, seven such batteries would be required. The back-up today is typically provided by diesel generators, costing about $0.5M, which run for as long as there is fuel. This means there is a capital:cost ratio of 200:1 per day or 1400:1 per week for battery versus diesel. This economic mismatch applies to all other suggested applications of batteries, for example protecting Wall Street against blackouts.

There is no short-term likelihood of low-cost large-scale electricity storage. Even hydrogen is very expensive, and the fuel needed to make it would be much more effectively used to perform directly the functions that the hydrogen would be scheduled to deliver.

* Based on US population as a proportion of global total.

The global context of USA actions

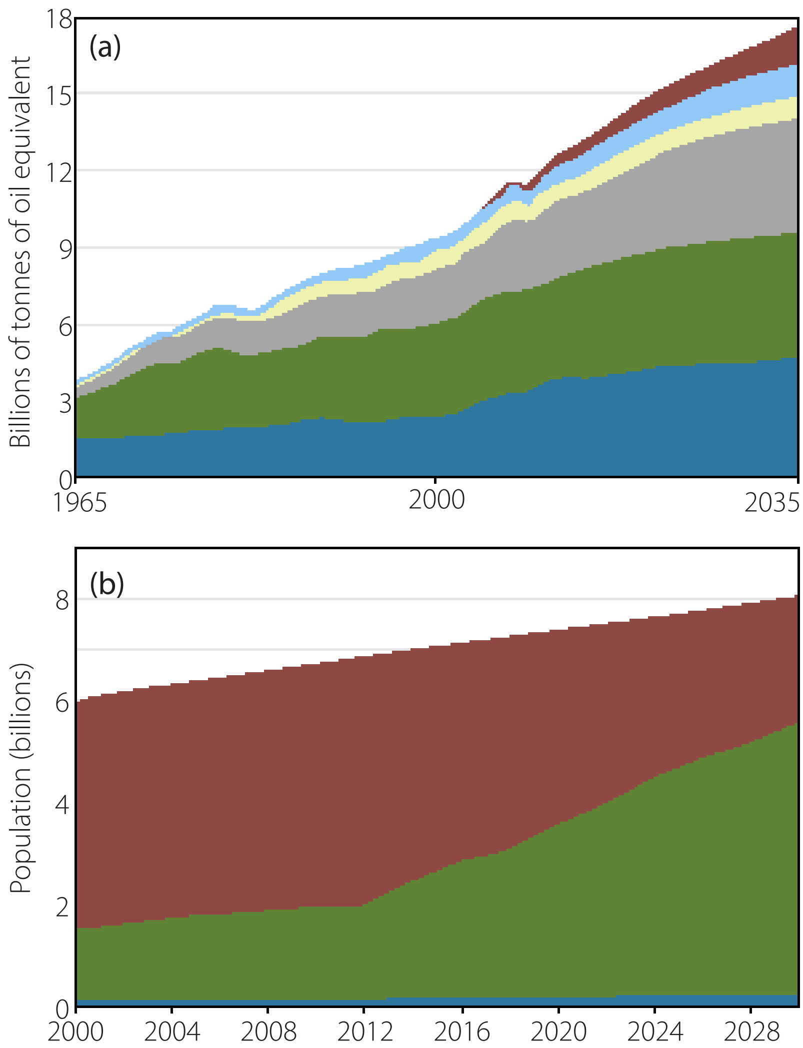
If the target of a net-zero economy in 2050 already seems a very unlikely proposition, there are several other pieces of data that reinforce this view. Figure 2 shows the principal driver of the growth in energy use and CO_2 emissions over the last 40 years and the next 30 years, namely the growth of the global middle class. Consider a person who leaves an urban slum or rural hovel moving to a high-rise apartment in a city with electricity for heating, lighting and communication: if they use between three and four times the amount of energy per day once they have joined the middle classes, the data on energy consumption between 1980 and 2035 (even extrapolated to 2050) can be explained *quantitatively*. Energy consumption per person in the middle class has been approximately steady (on a slightly downward slope) over recent decades, as energy efficiency gains are greater than increased usage. All the increases in CO_2 emissions will come from India, Asia and Africa in coming decades.

Figure 2: Energy and wealth

(a) Global energy consumption by fuels 1965–2035 (BP data) and (b) global population by wealth 2000–2030 (World Bank data). Actuals to 2020, and estimates beyond.

- Coal
- Oil
- Gas
- Nuclear
- Hydro
- Renewables

- Poor
- Middle classes
- Rich



Note, furthermore, that the first and second UN Sustainable Development Goals are the elimination of world hunger and poverty, while action on the climate is the 13th. There can be no question of moving the climate action to first place, on basic humanitarian grounds.

One can see from Figure 3 the dominant role that fossil fuels have had in energising the world economy since the 19th century. All the efforts on renewables have so far contributed only a slight divergence and fall in the fossil fuel fraction since 1980 – this has been of order 85% for a century, but has fallen to nearer 82% now. An extrapolation out to 2050 (Figure 3) indicates a 79% contribution in 2050: there is no sign of a rapid divergence and a zeroing of the fossil-fuel fraction in the next 30 years. These and many other developments, such as the quadrupling of the SUV global market in the last decade, all show the world moving away from the net-zero target.

I have made no allowances for radical technological breakthroughs in the energy sector, which might relieve the situation on the timescale of decades. Equally, however, incremental developments, such as those seen in battery technology, might be slower than anticipated, as the intrinsic limits of materials properties are approached. Any such delays would worsen the situation.

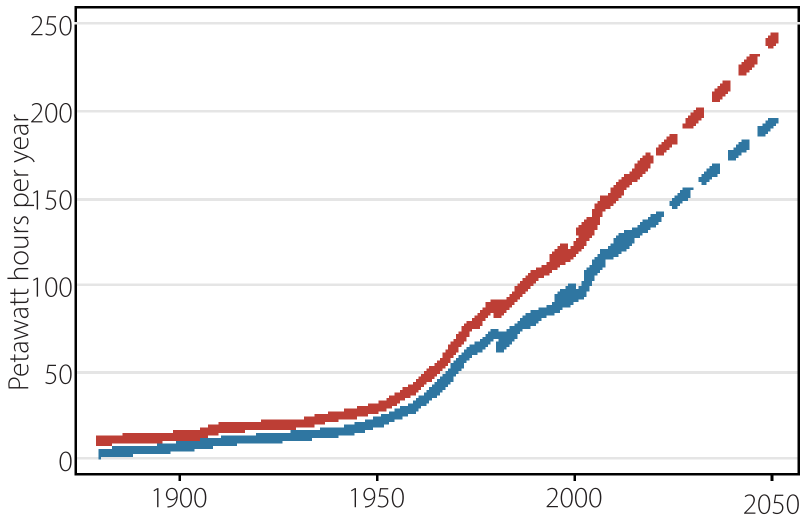


Figure 3: Energy and fossil fuels

World consumption of energy (in red) and the fossil fuel contribution (in blue) from 1880 to the present date and extrapolated to 2050.

Public acceptance

The fourth project listed at the outset may be the hardest. It is clear from the public debate that the citizenry has no idea of the scale of the task of a transition to a net-zero emissions economy in 30 years. This is not only a matter of the costs, human resources and materials, but also the disturbance to everyday lifestyles as the target is approached. Opinion polls indicate that few are willing, let alone able, to pay more than very modest sums, and certainly nothing like that implied by the figure of well over $300,000 per household set out above (for electrical and retrofit actions). Worse, there will be no measurable difference in the future climate as a result of all the spending and hardship. To make a difference, we would need the rest of the world, and in particular the developing world, to come on board. Poorer nations, such as India and the countries of South Asia, the Middle East and Africa, would need financial help to do so. If we assume that Europe and North America are to underwrite the rest of the world's net-zero activities, then the costs to the US could rise by a factor of 4.5, assuming the same per-capita spend globally. The resulting cost of getting to the global target then rises to nearly $1.5 million per household, and $200 trillion for the whole of the USA, which is a fantasy in practical terms.

By all commonly understood value-for-money measures, climate mitigation exercises simply do not add up. For homes, the $300,000 per household would be recouped over almost 100 years (at today's cost of energy), far longer than any rational investor would tolerate. Indeed, we would require a command economy during the period to 2050 to secure the finance, skilled workforce, and the materials needed to reach the target. Further, from where we are today, it is not clear how public acceptance can be achieved on the timescale required.

Funding for adaptation to an actual changing climate is an easier ask. Using the Thames Barrier in London as an example, extensive flooding in the 1953 storms in the East of England triggered the commissioning of various actuarial calculations. When should a Thames Barrier be constructed such that over its lifetime the value of flood insurance claims avoided was equal to the cost of the barrier itself? The answer was 'in the 1980s'. In developed countries with seismic activity, it is easy to set aside and invest multiple billions of dollars to cover future earthquakes, but that is because most people know they could be claimants during their lifetimes. For the slow-burning issue of climate change, however, this is not possible. Instead, the use of appropriate actuarial calculations could allow investment in adaptation to be attracted as and when necessary.

Spend profile and secured finance

Most of the preceding analysis assumes a constant 30-year project. In practice, however, the spend will start from near zero and ramp up. If a 40-year retrofit rollout had started in 2010, one would by now have spent of order 15–20% of the total improving housing and other buildings. In practice, the spend has been of order 1%. Each year of delay adds more to what must be achieved in the coming decades, requiring even greater flows of finance, human resources and materials. The training of a skilled workforce and building up the supply chain must precede mass rollout in all sectors. The expansion of the grid must precede the mass uptake of electric heating and transport: having the cars and heat-pumps without the green electricity to power them is the height of folly.

A project on this scale will need bespoke financing at the national level, as it is beyond the scope even of the richest companies in the world today. Even international money markets would struggle if all the world pursued Net Zero. Completely new economic thinking would be needed; the Stern Report of 2006 is way out of its depth on this practical point.

A partial list of factors not yet considered

I have given no attention to agriculture, and especially methane emissions, nor forestry, which permits negative emissions while trees are growing. I have not considered aviation or shipping and the specific costs in those sectors. Aviation fuel will be with us through and beyond 2050, and evolution of electric shipping is very slow beyond commuter ferries in large-city harbours. The global economy depends very much on both these forms of transport, and any severe curtailment will be accompanied by falling standards of living of the middle class. I have also not considered industrial heat currently provided by fossil fuels, for which electrical heating does not achieve sufficiently high temperatures in some refining processes.

I have not included the extra costs of simultaneously running the two new infrastructure systems required to support fuelling internal combustion engines and recharging electric motor batteries. I have not considered the practical choices associated with where and how the extra electricity generation should occur, nor have I factored in the costs of any forms of electricity storage (which are very high, as seen earlier). These issues will need an early resolution, because many of the desired outcomes depend on the new infrastructure being in place. I have not examined the ever-growing costs of balancing the grid, costs which grow dramatically as more intermittent sources of electricity are used.

A major change in peoples' lifestyles, with reductions in travel, consumption, and food variety could make a dent in the numbers above, but will not reduce by much the scale of the engineering projects.

A roadmap for Net Zero

The success of the IT revolution over the last 40 years is in no small part due to the existence of the International Technology Road Map for Semiconductors (ITRS). Representative engineers from every part of the sector, and all parts of the world, have gathered every two years to thrash out in great detail what needs to come out of the laboratory into development, and out of development into production, to keep Moore's Law of transistor miniaturisation on track, and with it the increase in computing power. Every player in the field knows that the other players are investing and working day-by-day to the same agreed objective.

Note the contrast between ITRS and international climate meetings. Meeting the 2050 net-zero emissions target is much more complex than semiconductor development, and can therefore go wrong in many more ways. Despite this, it is being attempted without any kind of roadmap. The project is therefore more likely than not to veer in the direction of the historical Tower of Babel. No engineer would invest time or money in such a project. Investors should expect better given the scale of the enterprise.

Summary

With extra costs comfortably in excess of $35 trillion, a dedicated and skilled workforce comparable to that of the education sector, and key strategic materials demanded at many times the supply rates that prevail today, and all for no measurable attributable change in the global climate, the mitigation of climate change via a net-zero emissions USA economy in 2050 is an extremely difficult ask. Without a command economy, the target will certainly not be met.

The practical alternative

Many in the world are convinced that we face a climate catastrophe in the coming decades if this target economy is not delivered. I suggest we are certain to have an economic and societal catastrophe if we persist on the projects to deliver the net-zero economy by 2050. There is a get-out-of-gaol card, and that is the demographic transition, which started 70 years ago. The number of children per couple has halved, from 5 in 1960 to 2.5 now, and is continuing to fall. In developed countries, with universal primary education and more people living in cities than the countryside, the figure is below 2, and indigenous populations are in absolute decline, as it takes 2.1 children per family to maintain a population. Stable developing countries, such as Bangladesh and Lesotho, are already down to 2.5. The Chinese population will soon peak and the world population in the 2060s. A century from now, when we need copper, we will not mine it, but strip it from abandoned cities.

My analysis requires the climate-change community to go back, in all humility, and ask themselves really how bad will (as opposed to might) the world's climate become? The proposed solution seems far worse for society than the problem. Half of their analyses of the future climate are based on a CO_2 emissions scenario (RCP8.5) now debunked as excessively high rather than the more likely RCP2.5 scenario. Their candour at this point would assist those making the case for funding climate adaptation, which will only be carried out when it becomes necessary. In the parlance of the Second World War, 'Is this journey really necessary?'

Personal view

I hope this report gives the bare facts about what is implied by committing to a net-zero emissions economy for 2050. Short of a command economy, it is simply an unattainable pipe dream, and we will struggle to get 10–20% of the way to the target, even with a democratic mandate to proceed. I think that the hard facts should put a stop to urgent mitigation and lead to a focus on adaptation. Mankind has adapted to the climate over recent millennia, and is better equipped than ever to do so in the coming decades. With respect to sea-level rise, the Dutch have been showing us the way for centuries. Climate adaptation in the here and now is a much easier sell to the USA citizenry than mitigation. There is a very strong case to repeal the net-zero emissions legislation and replace it with a rather longer time horizon. The continued pressure towards a net-zero economy will become a crime of sedition if the public rise up violently to reject it. The silence of the National Academies and the professional science and engineering bodies about these big picture engineering realities is a matter of complicity.

Afterword

This report can be criticised on three grounds: the assumptions, the facts cited, and the logic. The comments made about this paper on the Tom Nelson, Judith Curry and Anthony Watts blogs are revealing. Most agree with the analysis. One says that even conceding the role of CO_2 in climate is an abdication of the moral high ground, but my response is that no matter how severe or benign the future climate may become, the concept of engineering net zero by 2050 in the simplest way possible, as I describe, has no integrity at all. It is incumbent on those who do not like this analysis to come up with an alternative route to achieve Net Zero that costs no more than 10% – in costs, human resources and materials – of what is proposed here. I am not holding my breath.

Notes

1. Data from the Energy Information Agency of the USA, with thanks to several members who checked my interpretation of their data to derive Figure 1: all the implications therefrom are by me and they bear no responsibility. https://www.eia.gov/totalenergy/data/monthly/.

2. In 2009, as Chief Scientific Advisor to the then Department for Communities and Local Government, I briefed Lord Drayson, the then Science Minister, about the challenge of retrofitting all existing buildings to reduce the energy consumption and hence emissions of carbon dioxide. I suggested a detailed pilot programme be put in train. This became a £17 million expenditure programme called 3 'Retrofit for the Future', a series of projects in which over 100 social houses (i.e. smaller than the average) were subject to various measures. One group of 45 houses received complete makeovers – double and treble glazing, external cladding, extra loft and underfloor insulation, and new energy-efficient appliances. Detailed studies of emissions before and after for this group showed that for an average expenditure of £85,000, the average emissions reduction achieved was 60%, with only three dwellings achieving the 80% emissions reduction target, and another three not even reaching 30%. Linearly scaling the result to the whole housing stock and a 100% emissions reduction, produces a cost estimate of £4 trillion. See the results at: Rajat Gupta, Matt Gregg, Stephen Passmore and Geoffrey Stevens. 'Intent and outcomes from the Retrofit for the Future programme: key lessons', Building Research & Information, 43(4); 435–451, 2015. See https://www.tandfonline.com/doi/pdf/10.1080/09613218.2015.1024042.

3. Report: *Deep Retrofits Can Halve Homes' Energy Use and Emissions*. ACEEE

4. MISO USA: $2.4 million/km for 132kV, $3.0 million/km for 275kV and $4.8 million/km for 400kV line. See https://nocapx2020.info/wp-content/uploads/2019/07/Transmission-Cost-Estimation-Guide-for-MTEP-2019337433.pdf.

5. *The Hidden Cost of Net Zero: Rewiring the UK*. https://www.thegwpf.org/publications/net-zero-every-urban-street-and-front-drive-will-be-dug-up/.

6. Cost of electricity by source (per Wikipedia):

- gas/oil combined cycle power plant: $1000/kW (2019)
- combustion turbine: $710/kW (2020)
- onshore wind: $1600/kW (2019)
- offshore wind: $6500/kW (2019)
- solar PV (fixed): $1060/kW (utility), $1800/kW (2019)
- solar PV (tracking): $1130/kW (utility), $2000/kW (2019)
- battery storage power: $1380/kW (2020)
- conventional hydropower: $2752/kW (2020)
- geothermal: $2800/kW (2019)
- coal (with SO2 and NOx controls): $3500–3800/kW
- advanced nuclear: $6000/kW (2019)
- fuel cells: $7200/kW (2019).

7. Development of 5-MW Offshore Wind Turbine and 2-MW Floating Offshore Wind Turbine Technology (hitachi.com).

8. https://www.nhm.ac.uk/discover/news/2019/june/we-need-more-metals-and-elements-reachuks-greenhouse-goals.html.

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About the Global Warming Policy Foundation

People are naturally concerned about the environment, and want to see policies that protect it, while enhancing human wellbeing; policies that don't hurt, but help.

The Global Warming Policy Foundation (GWPF) is committed to the search for practical policies. Our aim is to raise standards in learning and understanding through rigorous research and analysis, to help inform a balanced debate amongst the interested public and decision-makers. We aim to create an educational platform on which common ground can be established, helping to overcome polarisation and partisanship. We aim to promote a culture of debate, respect, and a hunger for knowledge.

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