# TRANSITION TO REALITY

## The prospects for rapid global decarbonization

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The Global Warming Policy Foundation

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## About the author

Robert Lyman is an economist with 35 years' experience as an analyst, policy advisor and manager in the Canadian federal government, primarily in the areas of energy, transportation and environmental policy. He also has eleven years' experience as a private consultant, conducting policy research and analysis on energy and transportation issues as a principal for ENTRANS Policy Research Group. For the last five years, he has been a frequent contributor to the publications of the Friends of Science, a Calgary-based independent organization concerned about climate change-related issues. He resides in Ottawa, Canada.

## Executive summary

Those who consider that human actions are causing catastrophic global warming have argued that the world must soon transition to a low-carbon, or 'decarbonised', economy; they embrace scenarios in which a 'zero-emissions' future is achieved well before 2100, perhaps as early as 2030. This paper comments on the conceptual and practical challenges governments would face in promoting such a transition.

Historically, the availability and use of energy sources was determined largely by geography and technology. The changes over time followed a pattern in which less-dense energy sources (e.g. wood) that required large areas of land to produce were replaced by denser and denser ones (e.g. oil, natural gas) that required less space. The choices as to which new energy technology to adopt were made in energy markets; generally, the technologies that offered significant advantages in terms of cost, performance and reliability won out. Past energy transitions have been slow, painstaking and hard to predict.

According to the *British Petroleum Statistical Review of World Energy 2018*, today, 85% of world primary energy consumption is provided by fossil fuels (oil, natural gas and coal), while hydro (6.8%), nuclear (4.4%) and renewables (3.6%) make up the rest. This pattern of energy consumption is embedded in global energy systems and infrastructure.

Proponents of the so-called 'wind, water and sunlight' (WWS) vision claim that we already have the technology for a 100% renewables world energy economy, and that this can be achieved in the period from 2030 to 2050. Others, including even those who agree with the decarbonisation objective, have found such analysis to be deeply flawed. To quote one critic,

> A study must, at a minimum, show through transparent inputs, outputs, analysis, and validated modelling that the required technologies have been commercially proven at scale at a cost comparable with alternatives; that the technologies can, at scale, provide adequate and reliable energy; that the deployment rate required of such technologies and their related infrastructure is plausible and commensurate with other historical examples in the energy sector; and that the deployment and operation of the technologies do not violate environmental regulations.

The WWS vision does not meet these criteria.

Recent academic research on the timescales required from invention (i.e. discovery) to widespread commercialisation of energy technologies included empirical reviews of the timescales required by 13 products and technologies. The average of these was between two and four decades, with a median time of 32 years, or 43 years in the case of electricity generation technologies. This does not factor in the time required to achieve a turnover of the capital stock in which society may have invested hundreds of billions, or trillions, of dollars. Typically, for example, the life expectancy of rail tracks is 50 years, bridges 50 years, electricity generating plants 35– 80 years, and apartment buildings 60– 80 years. Similarly, new technologies cannot achieve widespread dissemination in the face of consumer resistance. Government policies and regulation may eliminate certain choices, but they cannot force people to buy.

The most prominent authorities that now publish forecasts of future global energy supply, demand and emissions are the International Energy Agency, the United States Energy Information Administration, EXXON, and British Petroleum. None of them foresees renewable energy rising above 10% of global energy consumption by 2035.

One must acknowledge a number of very significant barriers to rapid global decarbonisation. Professor Vaclav Smil, in his book *Energy Transitions: History, Requirements, Prospects*, provides a number of examples. He concludes that decarbonisation is extremely challenging and describes the idea that it can be achieved in a few decades as a 'grand delusion'.

Professor Smil did not address another major barrier, which is the effect of decarbonisation policies on the distribution of economic benefits and burdens in society. Promoting wind and solar energy, for example, may increase incomes for the companies that produce these technologies (mostly in China), but policies that undercut the viability of oil, natural gas and coal production and fossil-fuel-based power generation impose large losses on the regions and communities where that production occurs. It would be unwise to ignore the political resistance that will result. In addition, an important premise of decarbonisation advocates is that the entire economy can be electrified soon. In many sectors, including notably transportation, the necessary technologies are still in the research and development stage.

An argument can be made that, in the face of high market costs and barriers, governments can use policy instruments to force the pace of change. This is true, especially if one assumes that they will retain the support of the electorate in doing so. Outside of the centrally planned economies, however, no government has attempted to prescribe the timelines for commercialisation of new technologies or the dates by which a large share of society's needs must be met by a new technology. Governments that try to do so will face difficult choices as to the policy instruments that they will use. 'Picking winners' may be an increasingly popular aspect of national industrial policy (despite its history of failures), but a prudent government should be hesitant about committing billions of taxpayers' dollars to technologies that are not ready and cannot compete without permanent subsidies.

Much of the current public discussion concerning future energy transitions is based on speculation about the timing, cost, and pace of commercialisation of new technologies. It would seem more prudent to base one's judgments on what has actually happened in past energy transitions. The period from scientific discovery to widespread commercialisation has been much longer than is currently estimated by advocates of rapid decarbonisation. None of the steps in the innovation pathway – research, discovery, testing, demonstration, initial market development or widespread commercialisation – operates according to a fixed or predictable schedule. Governments that seek to impose their policy preferences will face perhaps insurmountable obstacles.

# 1 Introduction

The core of the public debate about climate change policy is the difference of views concerning two central theses. The first is that human actions, and especially the combustion of fossil fuels, are causing catastrophic global warming. The second is that drastic, urgent action must be taken to avoid that warming. The debate over the second thesis, in turn, often concerns the costs and benefits of a global 'transition' to a low-carbon or 'decarbonised' world. The supporters of this thesis argue that such a transition must be accomplished as soon as possible, and embrace scenarios in which a 'zero-emissions' future is achieved well before 2100, perhaps as early as 2030.[1]

The recent report of the Intergovernmental Panel on Climate Change (IPCC),[2] known as SR15, postulated that global warming is likely to reach 1.5°C above preindustrial levels between 2032 and 2050, and will probably bring species extinction, weather extremes and risks to food supply, health and economic growth. Accordingly, it recommended that net carbon dioxide emissions (i.e. the difference between the emissions, largely caused by human fossil fuel consumption and other activities, and the sequestration of carbon in various 'sinks' like forests and savannahs) decline by 45% from 2010 levels by 2030 and reach zero by 2050.

Such claims represent only an acceleration of previously stated goals that entail extraordinarily large and fast transitions in the world's energy supply and demand systems. Since at least 2008, the IPCC and several environmental organisations have been calling for the wealthier countries of the world to reduce greenhouse gas emissions by 50–80% below 2005 levels by 2050 and for all countries to eliminate emissions entirely by 2100.

I will not attempt to engage here on the question of whether the benefits of such transitions would exceed the costs. That ground has been covered eloquently by others, and especially in the recent writing of Bjørn Lomborg, President of the Copenhagen Consensus Center.[3] Instead, I would like to explore some of the conceptual and practical problems that governments would have to address if they were seriously to attempt to manage a transition of their countries' energy systems in the periods to 2030, 2050 and beyond.

# 2 The nature of past transitions

History offers us some insight into how energy transitions occur. For many centuries, the availability and use of energy sources was determined largely by technology and geography – in ancient times, people relied on the combustion of wood for heating and cooking, and upon human and animal power for transportation. As civilisation progressed, other ways of generating energy became available and were applied – wind, peat, coal, whale oil, liquid petroleum, natural gas and uranium succeeded one another, generally following a pattern in which more diffuse energy sources that occupied large areas were replaced with denser ones that required less space.

The shape of human settlements in any one place are often determined by the availability and cost of the energy sources available. Thus, in the countries of Europe, where energy was scarce and population density high, cities and infrastructure were built in confined spaces, whereas in countries with better resource endowments, with large areas and low population densities (e.g. the United States, Canada, Australia), patterns of settlement and building sizes were a function of the availability of generally plentiful, inexpensive and secure energy supplies.

Many scholars have studied the transitions from one energy source to another that have occurred historically. Figure 1 shows the trends in the consumption of different energy sources in the United States since 1776, a good illustration of what has happened.

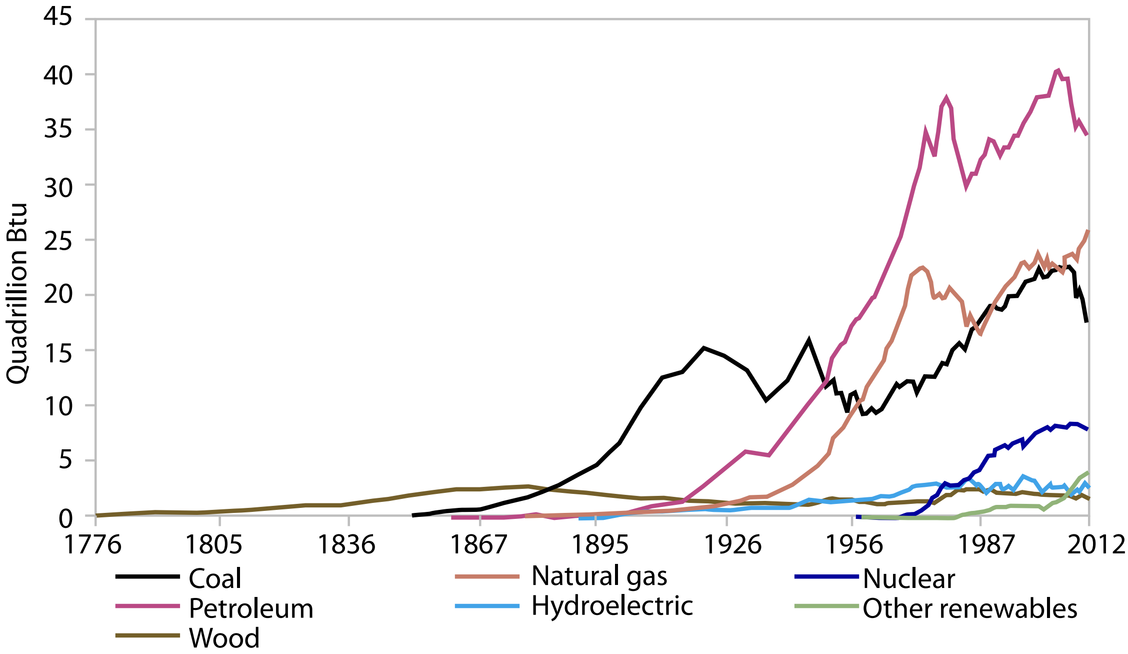


Figure 1: US energy consumption, 1776–2012

Source: EIA.[4]

As the graph shows, until about 1850 the overall level of energy consumption was low and it was supplied by wood. Starting in 1850, coal began to play a larger role, rising quickly to an early peak around 1920. Oil and natural gas began to be produced commercially around 1860, but did not grow significantly in use until the widespread purchase of automobiles and the building of continental pipelines to move oil and gas to places where they could be used for industrial, commercial and residential purposes. Hydroelectric generation began in the late 19th century. With the growth in electricity consumption from the early part of the 20th century, other sources of generation were added, including nuclear reactors and, most recently, renewable sources like wind and solar energy.

The pace of the evolution of the energy markets has generally been guided by the extent to which new technologies offered significant benefits in terms of cost, performance and reliability over the other alternatives. In other words, the transition from one energy source to another was driven by people's free choices in a competitive marketplace. This was less so in the case of electricity, for which other energy sources are not usually a direct substitute. In many places, governments owned and operated the generation facilities and regulated the distribution and sale of electricity, so that the choices of what to produce and sell were not made by private suppliers and willing consumers but rather by politicians and officials.

## 3 The magnitude of the challenge today

At the global level today, fossil fuels dominate energy use. According to the 2018 *British Petroleum Statistical Review of World Energy*,[5] the shares of energy use held by different energy sources in 2017 were as indicated in Table 1.

Table 1: World energy consumption in 2017 by source

| Source | Share (%) |
|---|---|
| Oil | 34.2 |
| Natural gas | 23.4 |
| Coal | 27.6 |
| Nuclear | 4.4 |
| Hydro | 6.8 |
| Renewables | 3.6 |
| Total | 100.0 |

Many governments, concerned that the use of fossil fuels presents a potential risk in terms of global warming, seem persuaded that the uses of energy sources in future should no longer be guided mainly by their underlying characteristics, benefits and costs, but rather should be controlled through public policy. This control could be exercised directly by government fiat, as happens in centrally planned economies. Alternatively, governments could seek to influence market-based choices through the implementation of various 'policy frameworks'. These frameworks today include measures such as subsidies, regulation or taxation, or all three. In addition, many environmentalists argue that governments should intervene in the research and development process so as to favour certain technologies and to discourage (and ultimately, ban) the use of coal, oil and natural gas. The same groups that support government intervention to promote decarbonisation technologies also oppose on principle the expanded use of nuclear reactors.

Added to the difficulty of using government action to accelerate decarbonisation is the increasing demand by its adherents that the 'transition' from fossil fuels to renewables must occur according to a pre-determined target date or deadline.

# 4 The inertia of energy systems

Professor Vaclac Smil of the University of Manitoba has written several books on energy, and in particular on the time required to achieve transitions from one set of energy sources to another.[6] Using empirical data to illustrate his case, he has argued that past transitions have been slow, painstaking and hard to predict. Existing technologies, both for generation and consumption of electricity, have a lot of inertia. For example, the first tractor appeared in the late 1880s, but the use of horses in US farming did not peak until 1915, and continued in other countries, for example in eastern Europe, into the 1980s. The use of horses and oxen to pull ploughs continues in much of the world today.

# 5 Can we deliver a 100% renewables economy?

In 2012, a study by the US National Renewable Energy Laboratory (NREL) concluded that an 80% decarbonisation of the United States electric grid could be achieved at 'reasonable cost' by 2050.[7] It had a major influence on the public debate about the feasibility of decarbonisation, at least in the US electricity system. Only a little cold water was thrown on the idea when, in 2014, the International Energy Agency estimated that the cost to decarbonise the global electricity sector by 2050 would be $44 trillion.

Subsequently, Mark Jacobson and Mark Delucchi published a series of papers advocating for the so-called WWS (wind, water and sunlight) vision, in which the entire energy needs of the United States and other countries, including Canada, would be met by renewable energy sources by 2050.[8] These papers were influential in convincing a number of US states and Canadian provinces to endorse complete decarbonisation as a public policy objective.

I addressed the WWS vision in an article published by the Friends of Science in May, 2018.[9] In that article, I did not attempt to address the question of whether or not it might be *technically* feasible for renewable energy sources of electricity generation to supply rising proportions of the generation capacity in many countries. Rather, I argued that no authoritative source of energy supply and demand projections sees renewable energy rising above 10% of global energy consumption by 2035. In fact, every authority in this area foresees fossil fuels continuing to supply by far the majority of the world's energy needs for decades to come. Countries that have given preferential contracts and system access to wind and solar energy have incurred extremely large costs in the process, and the resulting sharp rises in electricity prices have provoked strong opposition to the continuation of such policies.

The movement away from feed-in tariffs towards procurement by competitive bidding has led to much lower prices, but also flattened the growth in investment. Some European countries are now considering making intermittent energy suppliers bear a larger share of the system costs they bring to the grid; these costs have previously been shared across all generators and have ultimately been borne by electricity consumers. If these plans go ahead, the incentive to invest in wind and solar may decline even more. Moreover, in the countries where renewables have made the largest inroads, such as Germany, further increases in market share are heavily contingent on the development of an economically competitive bulk electricity storage technology. In a recent speech,[10] Professor Fritz Vahrenholt, an expert on German electricity policy, stated that electricity from battery storage currently costs €0.50 per kilowatt hour (kWh), and that, despite years of research, the development of a competitive storage technology at the scale required is 'not foreseeable'.

Many other objections to the Jacobson/Delucchi WWS vision have been made, even by those who share their belief in the need for a rapid energy transition. A critique published by Clack *et al.*[11] in June 2017 included the following points among many others:

> To show that a proposed energy system is technically and economically sound, a study must, at a minimum, show through transparent inputs, outputs, analysis, and validated modelling that the required technologies have been commercially proven at scale at a cost comparable with alternatives; that the technologies can, at scale, provide adequate and reliable energy; that the deployment rate required of such technologies and their related infrastructure is plausible and commensurate with other historical examples in the energy sector; and that the deployment and operation of the technologies do not violate environmental regulations.

The WWS paper does not meet these criteria. In addition, they said, the WWS paper:

> contains modelling errors: incorrect, implausible, and/or inadequately supported assumptions; and the application of methods inadequate to the task…In short, the analysis performed does not support the claim that such a system would perform at reasonable cost and provide reliable power.
>
> The study assumes a total of 2,604 GW of storage charging capacity, more than double the entire current capacity of all power plants in the United States. The energy storage

capacity consists almost entirely of two technologies that remain unproven at any scale: 5146 TWh of UTES (Underground Thermal Energy Storage) (the largest UTES facility today is 0.0041 TWh) and 13.26 TWh of phase change materials (effectively still in research and demonstration phase) coupled to concentrating solar thermal power (CSP). To give an idea of scale, the 100% wind, solar and hydroelectric power system proposed envisions UTES systems deployed in nearly every community for nearly every home, business, office building, hospital, school, and factory in the United States, although only a handful exist today.

This is what the supporters of an eventually all-renewable energy future say. Others are far more critical. In effect, there remains an enormous gap between the aspirations of those who would like to see a rapid, comprehensive transition from current to newer energy technologies and the economic and technological conditions foreseeable by the most prestigious authorities in this field. Much, however, remains unknown about the availability of new technologies in future and about the best public policy for influencing this.

# 6 Results of recent research on innovation timetables

Many other experts have attempted to determine the timescale from invention to widespread commercialisation in energy supply and demand technologies. An excellent recent example is the article published by Professor Robert Gross *et al.*,[12] which describes the ongoing controversy about the time required for innovations:

> It has been suggested that technological innovations typically take between five and seven decades to travel from invention to significant market shares. Perez (2002) considers 'radical' innovations from the 1770s to 2000s, and observes that successive 'technological revolutions' took between 43 and 66 years to reach maturity. These include innovations associated with the industrial revolution, steam railways, steel and electricity and automobiles. Wilson and Grubler (2010) cite a variety of examples and conclude that on a global scale it has taken 80 to 130 years for new energy technology clusters to achieve market dominance, and about twice as long when considering the entire technology life cycle from first introduction to market maturity…
>
> However, there is no consensus definition of technological maturity in the sense of when or at what market share a particular technology can be considered as firmly established, widely available and commercially viable.

Gross *et al.* studied the actual 'innovation timescales' that were required for different technologies. They found that it varied depending on which of three categories the technology fell into:

- novel products for new markets (end use electricity-consuming products)
- replacement products (end use electricity-consuming products)
- electricity generation technologies.

Generally, replacement products may reach widespread commercialisation faster than those that require the creation of new markets, infrastructures, regulatory environment and consumption patterns. The location chosen to assess the timeframe for innovation is also important, as in many cases particular countries or regions (usually those with higher incomes) have provided important early markets for new technologies. It should not be assumed, for example, that a new technology that increases its market share in Europe or North America will do so at the same rate in developing countries like India.

The key findings are based on empirical review of 13 products and technologies: cars, cathode ray tubes, nuclear power, combined cycle gas turbines, solar photovoltaics, video cassette recorders, wind electricity, cash cards and ATMs, mobile phones, compact fluorescent light bulbs, lithium ion rechargeable batteries, thin film transistors, and LED lighting. Many new technologies failed to commercialise, but for those that did, the average time from discovery to widespread commercialisation in advanced economies was between two and four decades. The median time from invention to widespread commercialisation was 32 years. Overall, electricity generation technologies exhibited the longest commercialisation time periods, with median times from invention to widespread commercialisation of 43 years for the four electricity generation technologies included in the study.

As to the policy consequences of these study results, those who see the global warming challenge as urgent and potentially catastrophic will argue that there simply is not enough time to indulge in more research and development. (Indeed, if one accepts the findings of the IPCC SR15 report, there is not even enough time to fully deploy the technologies already in existence!) Those who see only modest or no risks from longer timetables for mitigating the effects of increased carbon dioxide concentrations would prefer to avoid the economic impacts of forced or heavily subsidised deployment of existing technologies. Instead, they would argue for increased spending on research, hoping to discover new, potentially more proficient technologies. This is likely to have a lower cost in the long term.

## 7 The rate of capital turnover

Regardless of the pace at which new technologies are discovered, commercialised and deployed, there is substantial 'inertia' built into economies because of the long economic lives of important assets. Cars and trucks can easily last ten years or more, and infrastructure assets much longer. Table 2 shows different assets and of their typical design lifetimes.

Table 2: Average life expectancy of selected assets.

| Sector | Example of asset | Design lifetime (years) |
|---|---|---|
| Transportation | Paved roads | 10–20 |
| Transportation | Rail tracks | 50 |
| Transportation | Locomotives | 30 |
| Transportation | Bridges | 50–100 |
| Transportation | Buses | 20–30 |
| Energy | Transmission lines | 50 |
| Energy | High-voltage transformers | 40 |
| Energy | Generating plants | 35–80 |
| Residential | Apartment buildings | 60–80 |
| Water | Reservoirs and dams | 50–80+ |
| Water | Treatment plants | 60–70 |

Typically, there are billions of dollars of society's capital invested in these different assets; replacing them just because a new technology arrives would impose enormous economic costs. In addition, any new technology that enters the market will incur first-of-a-kind costs and will typically be late and over-budget.

Similarly, the availability of new technologies cannot assure widespread dissemination in the face of consumer resistance. Governments may try, for example, to promote by subsidy the sale of electric vehicles, but that may continue to meet strong resistance in the face of consumer concerns about EVs' cost, driving range, reliability in cold weather and the availability of recharging stations. Governments may prefer that people all live in densely-populated urban areas with limited lands available for traditional family homes, but consumers will 'vote with their feet' and choose to live far outside the urban boundaries.

# 8 Barriers to decarbonising the entire global economy

While this essay is primarily about the timetables required to achieve energy transitions, it would be inappropriate to omit some discussion about the feasibility of the transitions proposed. The public may perceive the changes that proponents seek as small and incremental, the equivalent of turning down the thermostat, putting on a sweater in cold weather, or taking the bus rather that driving to work. Casting the transition in terms of a percentage or two of change every year tends to reinforce such perceptions. To add a sense of realism, Annex A gives examples of the major barriers to rapid decarbonisation given by Vaclac Smil in his book, *Energy Transitions: History, Requirements, Prospects.*[13] In essence, he says the changes in technology and infrastructure required to decarbonise the world's economy are extraordinarily challenging and expensive; he describes the idea that this can be done in a few decades as a 'grand delusion'. However, in his book, Smil did not address one major barrier, which is often referred to as the effect of decarbonisation policies on the distribution of economic benefits and burdens within society. Promoting wind and solar energy may increase incomes for the companies that produce these technologies (mostly in China), but policies that undercut the viability of oil, natural gas and coal production and fossil-fuel-based power generation impose large losses on the regions and communities where that production occurs. In a country like Canada, a government that chooses to pursue global environmental benefits (if any) from forcing decarbonisation would have to justify severely harming the resource-based economies of western Canada, Newfoundland and Labrador and the northern territories, as well as energy-intensive industries across the whole country. I have argued elsewhere that such policies may pose a threat to Confederation.

Much discussion of decarbonisation focuses on eliminating fossil-fuel-based electricity generation. Globally, this represents only about 20 % of energy demand, although the share is higher in the wealthier countries. Adair Turner, head of the UK Energy Transitions Commission, recently claimed that a zero-emission global economy in all sectors can be reached by 2060 'at very small economic cost'.[14] All that is required, according to the Commission, is to increase electricity's share of global energy demand from 20% today to more than 60% by 2050. In other words, total generation must grow from 20,000 TWh to up to 100,000 TWh. Further, Turner claimed that it is 'physically possible to run grids that rely on intermittent renewables for 85 to 90 per cent of their power, while still delivering electricity whenever needed.' All that is needed is to quintuple our annual investment in renewables capacity for the next 40 years.

This should be viewed in context. According to Bloomberg Energy Finance,[15] an optimistic source of news about renewable energy, global investment in renewable energy rose from US$181.4 billion in 2008 to US$279.8 billion in 2017. The pattern of investment from year to year has been volatile, rising sharply some years and falling in others, and has averaged US$275 billion per annum for the past eight years. In 2017, China represented 45% of world investment. Europe's share fell to just 15%, the lowest recorded since the data series began in 2004. As recently as 2011, Europe accounted for as much as 45% of the global total. Renewables investment in the UK was down 65% at $7.6 billion, Germany down 35% at $10.4 billion, and Japan down 28% at $13.4 billion. The US slipped 6% to $40.5 billion.

A quintupling of global investment would mean that annual expenditures would rise to about US $1.4 trillion per year, an unprecedented departure from current trends. It is very difficult to foresee in which countries such major increases in investment would come. In June 2018, China, by far the largest subsidiser of solar energy equipment supply and generation, announced the ending of all subsidies for utility-scale solar projects in favour of competitive bidding and greatly reduced feed-in tariffs. The decision to sharply reduce subsidies is likely to slash demand there by about 40%, according to *Forbes* magazine.[16] Yet this was inevitable because of mushrooming costs. China's state-run renewable energy fund, financed by a surcharge on users' energy bills, is in deficit by more than 100 billion yuan (US$15.5 billion).

A central premise of the commission, and of others who foresee complete decarbonisation of the global economy, is that all of the economic sectors and services whose energy needs are now met by fossil fuels can be electrified. Yet today the technologies needed to make this feasible do not exist outside the laboratory, if there. That is especially the case in the transportation sector, where the high energy density of oil products makes them the ideal source of motive power. With currently available technology, there is no way to switch to the use of cellulosic ethanol, to commercialise hydrogen vehicles, to electrify commercial aircraft for passenger or freight movement, or to achieve widespread electrification of heavy-duty trucks. While it is technically feasible to electrify passenger-rail and even freight-rail systems, the costs of replacing existing locomotives, cars and infrastructure run into the trillions of dollars, representing a financial risk that no privately-owned and operated rail company would accept. To claim that electricification could be accomplished within a few decades is simply beyond the pale of belief.

The most remarkable claim in the Commission's report, however, may be its view that hydrogen power will play a major role in the future energy economy. Despite the investment of many billions of dollars in hydrogen power research, especially in the USA, the fundamental problems with hydrogen as an energy carrier remain. Consider, for example, the problems of transportation and distribution. Before hydrogen can be transported anywhere, it needs to be either liquified or compressed. To liquify it, it must be cooled to a temperature of −253°C. At this temperature, refrigerators are extremely inefficient; as a result, about 40% of the energy in the hydrogen must be spent to liquify it. In addition, because it is a cryogenic liquid, still more energy would be lost as the hydrogen boils away during transport and storage. As an alternative to liquifying it, one could use high pressure pumps to compress it. This would only waste about 20% of the energy in the hydrogen. However, safety-approved, steel tanks capable of storing hydrogen at 5000 psi weigh approximately 65 times as much as the hydrogen they can contain. Consequently, to transport 200 kilograms of compressed hydrogen, roughly equal in energy content to 200 gallons of gasoline, would require a truck capable of hauling a 13-ton load. In principle, a system of pipelines could, at enormous cost, be built for transporting gaseous hydrogen. But because hydrogen is so diffuse, with less than one third the energy content per unit volume of natural gas, these pipes would have to be very big, and large amounts of energy would be required to move the gas along the line. Another problem is that hydrogen can penetrate readily through the most minutely flawed seal, and can actually diffuse right through solid steel itself. This would create ample opportunities for much of the hydrogen to leak away during transport. As hydrogen diffuses into metals, it also embrittles them, causing deterioration of pipelines, valves, fittings, and storage tanks throughout the entire distribution system. Unless very carefully monitored, the pipeline system could become a continuous source of catastrophes. Given these technical difficulties, the implementation of an economically viable method of hydrogen distribution from large-scale central production factories is essentially impossible.

# 9 A fundamental issue – the role of governments

As noted previously, in most countries the pace of commercialisation of new technologies outside of electricity generation has long depended on their inherent cost–performance characteristics and the free decisions of buyers and sellers. No-one before has attempted to prescribe the dates by which a large share of society's needs must be met by a new technology. Governments that attempt to accelerate the pace of scientific discovery, development, commercialisation and market penetration thus face difficult choices as to the policy instruments they should use.

A key question, of course, is whether governments have the information needed to make choices about which products, services and technologies are the 'right' ones, regardless of whether that choice depends upon their objective appeal in the marketplace or an imposed policy imperative that emissions must be reduced. The history of government economic regulation, of industrial planning, and ultimately central planning of the economy has generally been one of failure, far more often than of success.

Professor Peter Grossman, who has written eloquently about the history of US energy policy, described the repeated attempts by policy makers to promote alternative energy development through initiatives modelled on the Apollo program of the early 1960s.[17] According to Professor Grossman, the Apollo analogy is inapt and unhelpful, because it conflates an engineering problem with a commercial problem, and it deflects efforts away from scientific advance, focusing them instead on grandiose social results.

> The goal of the Apollo program was simply to prove that the United States could accomplish the spectacular achievement of putting people on the moon and bringing them home safely. Cost was not consequential nor was the feat meant to become a regular function of the marketplace…Alternative energy technologies, however, are intended to be more than demonstration projects.

He is especially critical of US government programs that provide financial incentives to consumers to promote technologies like solar heating or electric cars.

> Government forecasts for such programs have been extravagant, unrealistic and seemingly oblivious to the actual processes of industrial adoption. While an argument can be made for the use of tax credits for some types of energy projects (particularly for R&D itself), their successful use in a consumer program is necessarily uncertain because technological adoption rests on the consumer's belief both that the new technology will be cost-effective and that it will perform well over time. Cost effectiveness is not, as the solar program demonstrated, guaranteed by tax preferences; even with tax breaks consumers will be cautious about spending thousands of their own dollars. And operating performance can only be assessed after years, often decades, of experience.

Making successful planning decisions concerning future energy supplies depends in part on governments being able to judge future energy market conditions and prices in a rapidly evolving and highly competitive world. In the past, governments around the world have spent billions of dollars based on the perception that the world was running out of low-cost oil, so that new non-oil alternatives would have a large competitive advantage. In fact, those who forecast the 'end of oil' have been proven wrong again and again, and new exploration and development technologies have increased supply even faster than the rapidly growing global oil demand. Today, in late 2018, the world's oil consumption has surpassed 100 million barrels per day, yet there is so much supply available that prices are falling. In such circumstances, a prudent government should be hesitant about investing billions of taxpayers' dollars in technologies that just are not ready and cannot compete without permanent subsidies.

Most countries already have a raft of programs to directly support research and development and to subsidise early adoption of these technologies. However, some governments, including the Canadian federal government, have added a further layer of public intervention in the form of carbon taxes. These have the merit of avoiding picking technology 'winners and losers', but they are premised on the efficiency of competitive markets in making the choices among new energy technologies how and when the market determines. The economic theory supporting the use of such taxes therefore does not align with the imposition of timelines for market acceptance.

Carbon-tax proponents insist that government intervention is needed because private investors would be extremely unlikely on their own to make the massive investments to hasten the conversion to new sources of energy. Yet most governments in the wealthier countries are struggling to keep up with existing demand for essential infrastructure, mainly because of mounting debts and, in some countries, growing populations. The causes of the debts are unconstrained healthcare costs, significant expansion of social entitlement programs, uncompetitive manufacturing, and tax-revenue shortfalls. In theory, governments could choose to spend trillions of dollars on new energy systems, often at the expense of their existing ones, but where would they obtain the funds? Further, it stretches credulity beyond the limits to believe that the governments of developing countries, struggling to meet the basic needs of their citizens, would instead choose to gamble on emerging, yet unproven, energy technologies.

# 10 Conclusion

Much of the current public discussion concerning future energy transitions is based upon speculation as to the technologies that might be available, their costs, and the rates at which they might be commercialised. Anyone can dream about what the future may hold, but it would seem more prudent to base one's judgments on what has actually happened in the past. Based on the history of energy transitions, the period from scientific discovery to widespread commercialisation is much longer than is currently estimated by the advocates of rapid decarbonisation. Depending on the technology, the process may take between 30 and 50 years, or much longer where widespread commercialisation depends upon the replacement of long-lived infrastructure. None of the steps in the innovation pathway – research, discovery, testing, demonstration, initial market development or widespread commercialisation – operates according to a fixed or predictable schedule. Governments that seek to impose their policy preferences on the outcomes will face perhaps insurmountable obstacles.

# 11 Annex A: Major barriers to rapid decarbonization

(Excerpts from Smil's *Energy Transitions: History, Requirements, Prospects* )

## Biomass

Even if all the world's sugar cane crop were converted to ethanol, the annual ethanol yield would be less than 5% of the global gasoline demand in 2010. Even if the entire US corn harvest was converted to ethanol, it would produce an equivalent of less than 15% of the country's recent annual gasoline consumption.

## Hydropower

Storing too much water for hydropower generation could weaken many environmental services provided by flowing river water (including silt and nutrient transportation, channel cutting, and oxygen supply to aquatic biota).

The total potential energy of the Earth's runoff (nearly 370 exajoules, or roughly 80% of the global commercial energy use in 2010) is just a grand sum of theoretical interest. Most of that power can never be tapped for generating electricity because of the limited number of sites suitable for large dams, seasonal fluctuations of water flows, and the necessity to leave free-flowing sections of streams and to store water for drinking, irrigation, fisheries, flood control, and recreation uses.

## Solar and wind energy

First, direct solar radiation is the only form of renewable energy whose total terrestrial flux far surpasses not only today's demand for fossil fuels but also any level of global energy demand realistically imaginable during the 21st century. Second, only an extraordinarily high rate of wind energy capture (which may be environmentally undesirable and technically problematic) could provide a significant share of overall future energy demand. Third, for all other renewable energies, maxima available for commercial harnessing fall far short of today's fossil fuel flux, one order of magnitude in the case of hydroelectricity, biomass energy, ocean waves, and geothermal energy, two orders of magnitude for tides, and four orders of magnitude for ocean currents and ocean thermal differences.

Average insolation densities of 102 W/m$^2$ mean that with today's relatively low-efficiency PV conversions, we can produce electricity with power densities around 30 W/m$^2$, and if today's best experimental designs become commercial realities, we could see PV generation power densities averaging more than 60 W/m$^2$ and surpassing 400 W/m$^2$ during the peak insolation hours. Fossil fuels are extracted with power densities of 103–104 W/m$^2$, and the rates for thermal electricity generation are similar. Even after including all other transportation, processing, conversion, transmission, and distribution needs, power densities for the typical provision of coals, hydrocarbons, and thermal electricity by their combustion are lowered to no less than 102 W/m$^2$, most commonly to the range of 250–500 W/m$^2$. These typical power densities of fossil-fuel energy systems are two to three orders of magnitude higher than the power densities of wind or water-driven electricity generation and biomass cultivation and conversion, and an order of magnitude higher than today's best photovoltaic conversions.

In order to energize the residential, industrial, and transportation infrastructures inherited from the fossil fuel era, a solar-based society would have to concentrate diffuse flows to bridge power density gaps of two to three orders of magnitude. Mass adoption of renewable energies would thus necessitate a fundamental reshaping of modern energy infrastructure, from a system dominated by global diffusion of concentrated energies from a relatively limited number of nodes (i.e. sites) extracting fuels with very high power densities to a system that would collect fuels of low energy density at low power densities over extensive areas and concentrate them in the increasingly more populous urban centres.

In the United States, on average 15 GW of generating capacity were added every 20 years from 1987 to 2007. To make a transition to renewables by 2030, 150 GW would need to be added a year, and the longer the wait to do this the more would need to be added later on, perhaps 200–250 GW or 20 times as much as the record rate of 2008 (8.5 GW added wind capacity). This should suffice to demonstrate the impossibility of doing so. On top of this, the impossible feat would require writing off in a decade the entire fossil-fueled electricity generation industry and the associated production and transportation infrastructure, an enterprise whose replacement value is at least $2 trillion.

The wind would have to come from the Great Plains and the solar from the southwest, yet no major HV transmission lines link to East and West coast load centres. So, before you could build millions of wind turbines and solar PV panels, you would need to rewire the United States first with high-capacity, long-distance transmission links, at least 65,000 km (40,000 miles) in addition to the existing 265,000 km (165,000 miles) of HV lines. These lines cost at least $2 million/km.

Installing in 10 years wind and solar-generating capacity more than twice as large as that of all fossil-fueled stations operating today while concurrently incurring write-off and building costs on the order of $4-5 trillion and reducing regulatory approval of generation and transmission megaprojects from many years to mere months would be neither achievable nor affordable at the best of times. At a time when the nation has been adding to its massive national debt at a rate approaching $2 trillion a year, it is nothing but a grand delusion.

## Notes

1. The United Nations pledged to work towards 'carbon neutrality' in 2007. At the COP21 Conference of the Parties in Paris in 2015, countries agreed to constrain global warming to $1.5\,^{\circ}$C above pre-industrial levels, and called for reducing net anthropogenic greenhouse gas emissions to zero during the second half of the century. Several environmental organisations subsequently have called for zero emissions by much earlier dates.

2. The IPCC SR15 report can be seen here: http://www.ipcc.ch/pdf/special-reports/sr15/sr15_spm_final.pdf

3. https://pubs.aeaweb.org/doi/pdfplus/10.1257/pol.20170046.

4. https://www.eia.gov/todayinenergy/detail.php?id=11951.

5. https://www.bp.com/content/dam/bp/en/corporate/pdf/energy-economics/statistical-review/bp-stats-review-2018-full-report.pdf.

6. Smil's books include *Energy Transitions: History, Requirements, Prospects*, 2010; *Making the Modern World: Materials and Dematerialization*, 2013; *Power Density: A Key to Understanding Power Sources and Uses*, 2015; and *Energy and Civilization: A History*, 2017.

7. The NREL report can be found here: https://www.nrel.gov/docs/fy12osti/52409-1.pdf.

8. Jacobson and Delucchi, *A Plan to Power 100 Percent of the World with Renewables*, Scientific American, November 2009: https://www.scientificamerican.com/article/a-path-to-sustainable-energy-by-2030/.

9. https://blog.friendsofscience.org/2018/03/22/examining-the-claim-that-renewable-energy-will-soon-replace-fossil-fuels/?highlight=Robert%20Lyman.

10. *Germany's Energiewende: The problems are growing*, unpublished presentation to the Portsmouth Conference on Climate Policy Choices, October 19, 2018

11. C.T.M. Clack et. al., *Evaluation of a proposal for reliable low-cost grid power with 100% wind, water and solar*. PNAS, June 27, 2017: http://www.pnas.org/content/114/26/6722.

12. Robert Gross, *Energy Policy*, September, 2018 https://www.researchgate.net/publication/327386750_How_long_does_innovation_and_commercialisation_in_the_energy_sectors_take_Historical_case_studies_of_the_timescale_from_invention_to_widespread_commercialisation_in_energy_supply_and_end_use_technolog.

13. Vaclav Smil (2010) *Energy Transitions: History, Requirements, Prospects*. Praegar.

14. http://www.energy-transitions.org/sites/default/files/Global_PressRelease-MissionPossible.pdf.

15. Bloomberg Energy Finance: Global Trends in Renewable Energy Investment 2018; http://www.iberglobal.com/files/2018/renewable_trends.pdf.

16. https://www.forbes.com/sites/jillbaker/2018/06/18/solar-leader-china-is-slashing-its-subsidies-on-solar-power-what-you-need-to-know/#6e15bccb2f9a.

17. Peter Grossman, *The Apollo fallacy and its effect on U.S. energy policy*, *Energy Policy*, January, 2009. https://digitalcommons.butler.edu/cob_papers/171/.

## About the Global Warming Policy Foundation

The Global Warming Policy Foundation is an all-party and non-party think tank and a registered educational charity which, while openminded on the contested science of global warming, is deeply concerned about the costs and other implications of many of the policies currently being advocated.

Our main focus is to analyse global warming policies and their economic and other implications. Our aim is to provide the most robust and reliable economic analysis and advice. Above all we seek to inform the media, politicians and the public, in a newsworthy way, on the subject in general and on the misinformation to which they are all too frequently being subjected at the present time.

The key to the success of the GWPF is the trust and credibility that we have earned in the eyes of a growing number of policy makers, journalists and the interested public. The GWPF is funded overwhelmingly by voluntary donations from a number of private individuals and charitable trusts. In order to make clear its complete independence, it does not accept gifts from either energy companies or anyone with a significant interest in an energy company.

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