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The clean energy transformation: a new paradigm for social progress within planetary boundaries

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The world is on the cusp of the most profound and rapid transformation of the global energy system in history. The demise of the age of fossil fuels is unstoppable, but whether human civilisation will survive dangerous climate change is still an open question – and depends on the societal choices we make today. The right choices could open an unprecedented possibility space enabling a new era of clean energy abundance. Those new possibilities could empower humanity to solve some of its most intractable problems: energy scarcity and volatility, the persistence of food insecurity and malnutrition, global poverty and widening inequalities.

However, recognising and creating this new possibility space requires a whole systems analysis that acknowledges how the energy system is interconnected with other key sectors of the economy. A holistic systems approach allows us to see not only the tremendous opportunities of these disruptions, but also to better understand the risks involved in delaying them by protecting the most problematic incumbent industries.

The disruptive transformation of civilisation

Conventional methodologies approach technologies and sectors in isolation, rather than recognising how they work as interconnected systems. But the energy disruption is not happening in isolation. It is intimately connected to disruptions in the information, transport, materials and food sectors, and understanding the dynamics of each of these disruptions requires recognising their connections. Most mainstream institutions fail to understand the crucial nexus between disruption, societal change and system transformation.

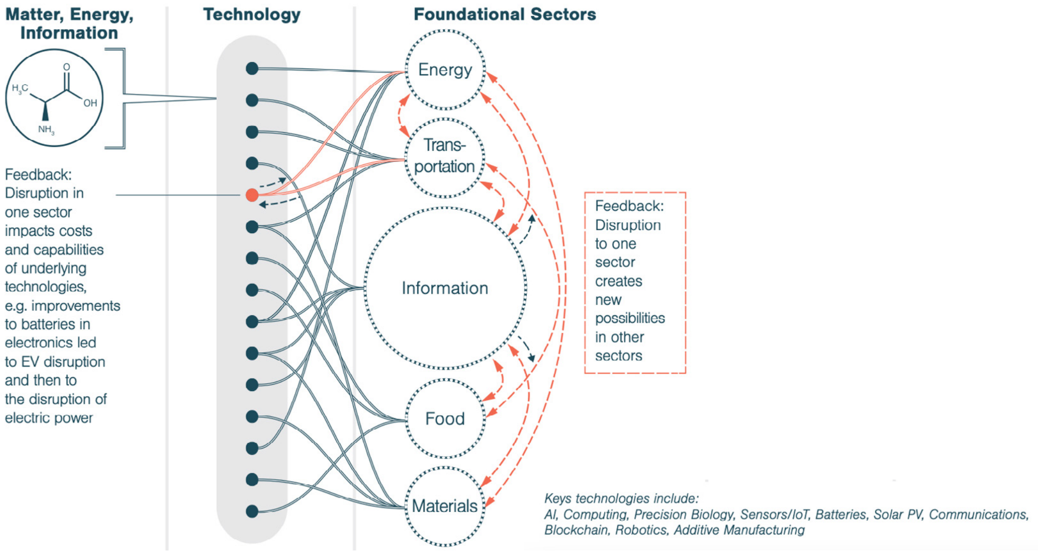

Figure 1. Key Technologies, Convergence and Interaction Between Sectors.
Source: Rethinking Climate Change (2021)

Today, a series of overlapping and interconnected technology disruptions in every one of the five foundational sectors that define civilisation is upending incumbent industries.

Mainstream governance institutions' siloed way of seeing the world prevents them from anticipating how disruptions in each sector represent phase changes with cascading effects across all sectors. These will not only accelerate one another, but transform the disruptions themselves. One of the biggest obstacles to understanding the opportunities of today's disruptions in the energy, transport and food sectors is a failure to see how they will bring in entirely new system dynamics that will render obsolete the rules of the old, incumbent system.

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When we examine the role of technology disruptions in the growth spurts of civilisations (both past and present), what we see is that disruptions are not one-for-one substitutions where one technology merely displaces another.

Instead, they entail complete phase changes in how that part of the production system operates. Sometimes they cascade across other sectors. In fact, some production-sector technology disruptions are so pivotal that they entail total transformations of the structure of economic activity.

For instance, as Arbib and Seba show in *Rethinking Humanity: Five Foundational Sector Disruptions, the Lifecycle of Civilizations, and the Coming Age of Freedom*, the 15th-century invention of the printing press – an information disruption – was not an incrementally better way of manually writing on manuscripts made from animal skins. The ability to rapidly print large volumes of text on paper at costs 10 times cheaper not only led manuscript industries to collapse but opened the way for a fundamental transformation in the ownership, production and distribution of information. The disruption broke the Church's cultural dominance in Europe and, combined with other social and political transformations, paved the way for the Enlightenment and Scientific Revolution. This disruption in the information sector had transformative implications for wider economic structures. It overturned the Church's medieval monopoly on information, and distributed the production and distribution of information across an emerging merchant class, undermining feudal property ownership.

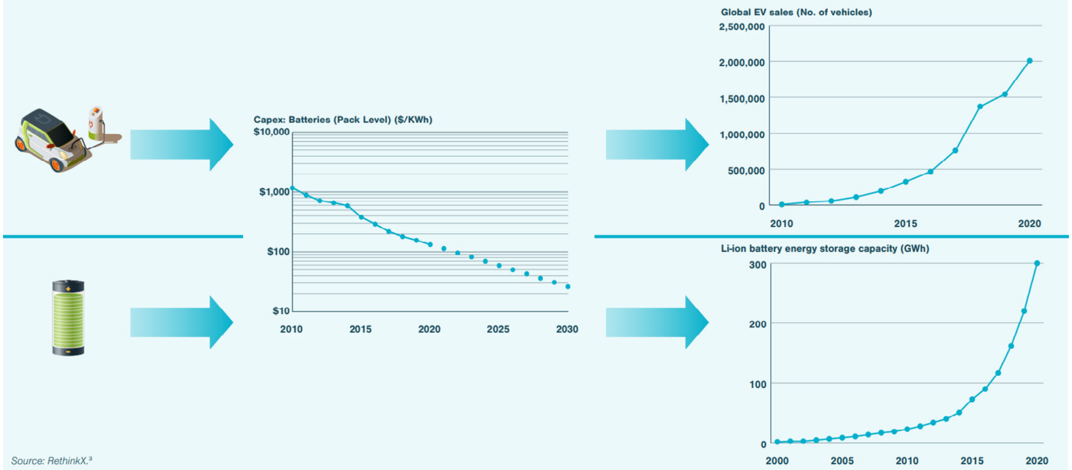
Similarly, the car was not just a faster horse, it was a phase change in the transport system that led to fundamental transformations in everything: the design of cities, how we produced and distributed food and clothes, and how we fought wars. It also created negative consequences in the form of carbon pollution.

In other words, technology disruptions at the production sector level change the rules that define an entire system of production at the sector level. Depending on how they play out, they can lead to and drive changes across other sectors and whole societies.

Most importantly, these are not slow, incremental changes. Disruptions happen rapidly, driven by exponential performance improvements and cost reductions that enable the new technologies to out-compete incumbents.

More recently, for instance, the impact of the dawn of the internet and the smartphone in the information sector has cascaded into other sectors as well as disrupting traditional centralised models of the mass media. In *Rethinking Humanity*, Arbib and Seba explain how the arrival of the smartphone not only disrupted the telecoms market, but also disrupted retail, food and transport. New information business models have enabled the introduction of ride-hailing and food delivery services, disrupting taxi and restaurant businesses. There have been rapid improvements in lithium-ion batteries which, in turn, have made electric vehicles (EVs) far more affordable and competitive. Therefore, the disruption in the information sector has played a crucial role in the disruption of the global oil industry and a reduction in demand for conventional energy.

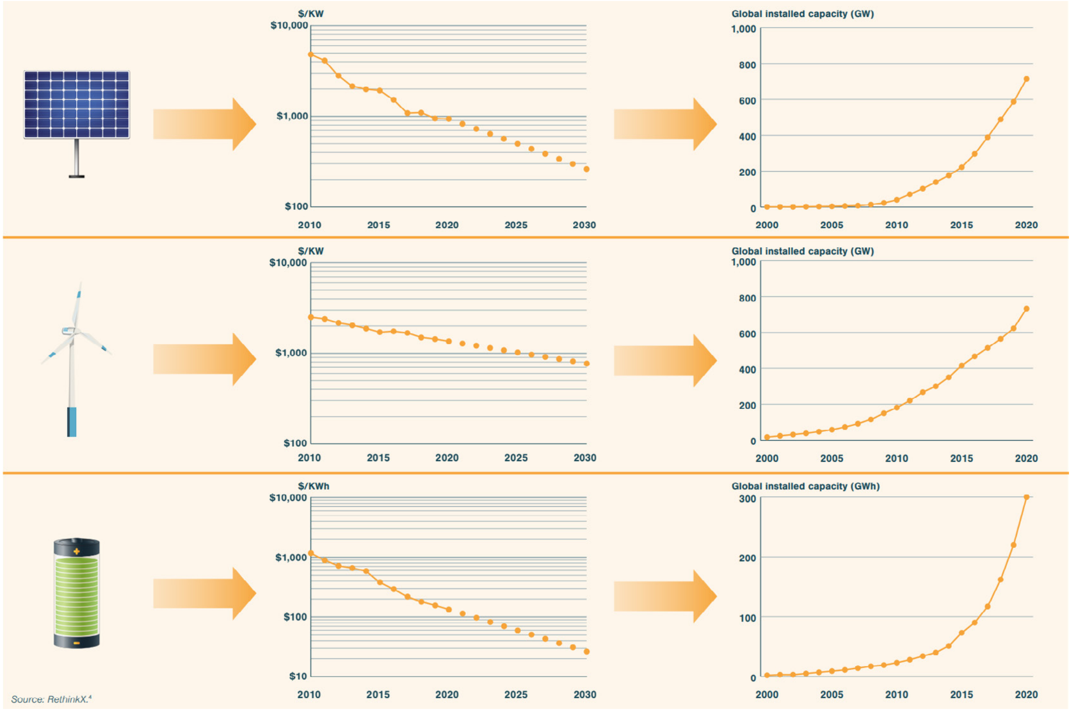
Further, as costs of EVs plummet, they are on track to make ride-hailing even cheaper than private ownership of internal combustion engine (ICE) vehicles. Autonomous driving technology is improving so much thanks to information technology that it will soon make self-driving cars a reality. The combination will disrupt private ownership of ICE cars, as transport-as-a-service (TaaS) becomes 10 times cheaper.



Source: RethinkX.[3]

Figure 2. The disruption of the transport sector, as exemplified via exponential cost decline and exponential adoption rates.

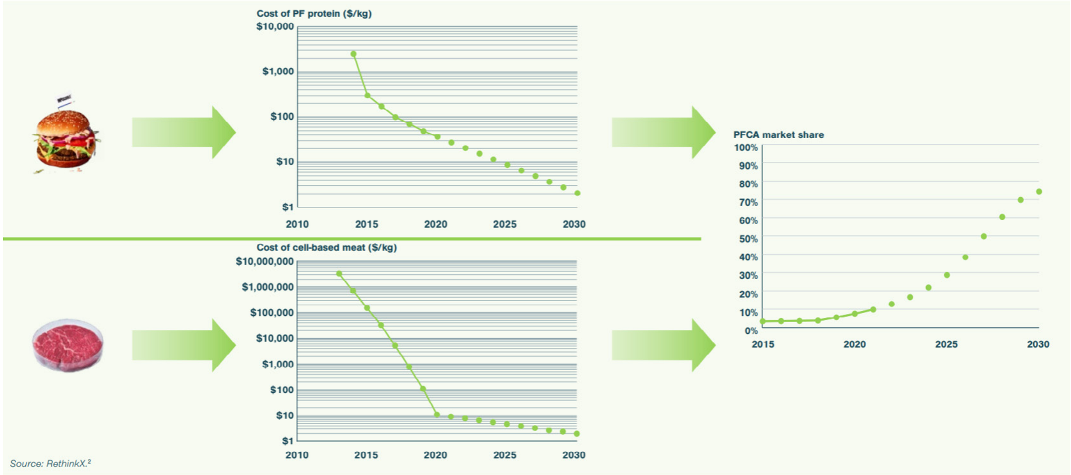
Battery costs are dropping, with a huge impact on the energy sector, which is experiencing broader disruption from the combination of solar, wind and batteries. These technologies are getting better at converting sunlight and wind into electricity and storing it. Their declining costs are making them the cheapest forms of electricity in most regions of the world: they are also on track to become up to 10 times cheaper over the next two decades.



Source: RethinkX.[4]

Figure 3. The disruption of the energy sector as exemplified via exponential cost declines, and exponential adoption rates.

The impact of the information disruption on materials has driven the rise in 3D printing, nanotechnology and precision biology. That is now impacting the food sector, where information advancements are now enabling us to manipulate matter at ever-smaller scales, and to brew and program proteins any way we want. The costs of precision fermentation (PF) and cellular agriculture (CA), which will allow us to create real animal meat products without killing animals, are dropping so fast that PF is on track to become 10 times cheaper than the livestock industry within about 10–15 years. The technology will next begin disrupting industrial agriculture for products such as soya beans and palm oil.



Source: RethinkX.[2]

Figure 4. The disruption of the food sector, as exemplified via exponential cost declines and the beginning of an exponential adoption rate.

The history of technology disruptions reveals that when emerging technologies become 10 times cheaper than incumbents, they wipe out the incumbents, which can no longer compete. Adoption of the new technologies, which at first starts slowly, accelerates exponentially along an S-curve, slowing down as it reaches mass adoption. This doesn't happen in a prolonged, linear, incremental fashion. It happens rapidly, often in as little as 10–15 years.

> Disruptions prevent a continuation of business-as-usual within the current industrial paradigm.

Disruptions prevent a continuation of business-as-usual within the current industrial paradigm. They entail the opposite: they are *replacing* that paradigm and affecting every defining foundational sector of industrial civilisation. New technologies will outcompete conventional industrial carbon-intensive energy, food and transport technologies – which happen to be responsible for 90% of carbon emissions – within the next two decades.

As these disruptions encompass every foundational production sector of civilisation, the entire production system of civilisation is on the cusp of transformation.

Interconnection of disruptions and the coming material contraction

We cannot hope to understand the energy transition in a silo, but only as an integral part of a wider process of disruptive transformation across the five foundational sectors that define civilisation.

As described in our Rethinking Climate Change report, the combined impact of the energy, transport and food disruptions mean that the entire infrastructure of the incumbent fossil fuel–based energy, transport and food paradigms will become obsolete. With demand for oil, gas and coal crashing down, the huge global logistics and shipping infrastructure that operates today to transport vast quantities of oil, gas and coal around the world will no longer be necessary. Neither will the vast infrastructure of oil rigs, coal power plants or pipelines; nor will the complex networks of shipping to transport livestock and livestock products across vast distances, as they will be disrupted by local PF and CA production hubs.

Vast quantities of vehicles dedicated to heavy transport by land, air and sea will therefore become unnecessary. By disrupting private ownership of cars, the EV and autonomous EV transformation and the rise of TaaS will mean that only a fraction of today's number of cars will be on the road. Instead of everybody owning their own car, most miles travelled will be ride-hailing by TaaS, with a much smaller fleet of vehicles in service. Rather than replacing petrol vehicles as a one-for-one substitution, EVs will instead enable us to use a fraction of the number of vehicles we use now. Models that predict raw materials scarcity based on a one-for-one substitution of petrol vehicles with EVs are wrong.

Maintaining the old industrial fossil fuel infrastructure with its huge raw mineral and metal inputs will no longer be necessary. An analysis by Carbon Tracker compared the material inputs for the fossil fuel system and the clean energy system. Coal generation needs 2,000 times more material by weight than does solar electricity. The fossil fuel system requires over 300 times

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more materials by weight than a clean energy system. This means that although clean energy requires an increase in production of specific minerals over the next two decades, it still offers a dramatic reduction in the global energy system's total material footprint. Materials production will taper off dramatically after 2040 because once the clean energy system is built it will have a lifetime of at least 50–80 years, if not longer.

Conversely, the fossil fuel energy system's huge infrastructure, as well as that of the internal combustion engine, will make a vast global repository of metals such as steel, copper, aluminium, nickel and cobalt available for recycling into the clean energy, transport and food industries. Studies that warn of impending raw materials bottlenecks due to the roll-out of clean energy infrastructure completely fail to account for this side-effect of the obsolescence of incumbent industries. We will therefore be able to meet growing demand for many metals and materials from the clean disruptions by a combination of new mining and recycling at a much higher order of magnitude than conventional models recognise.

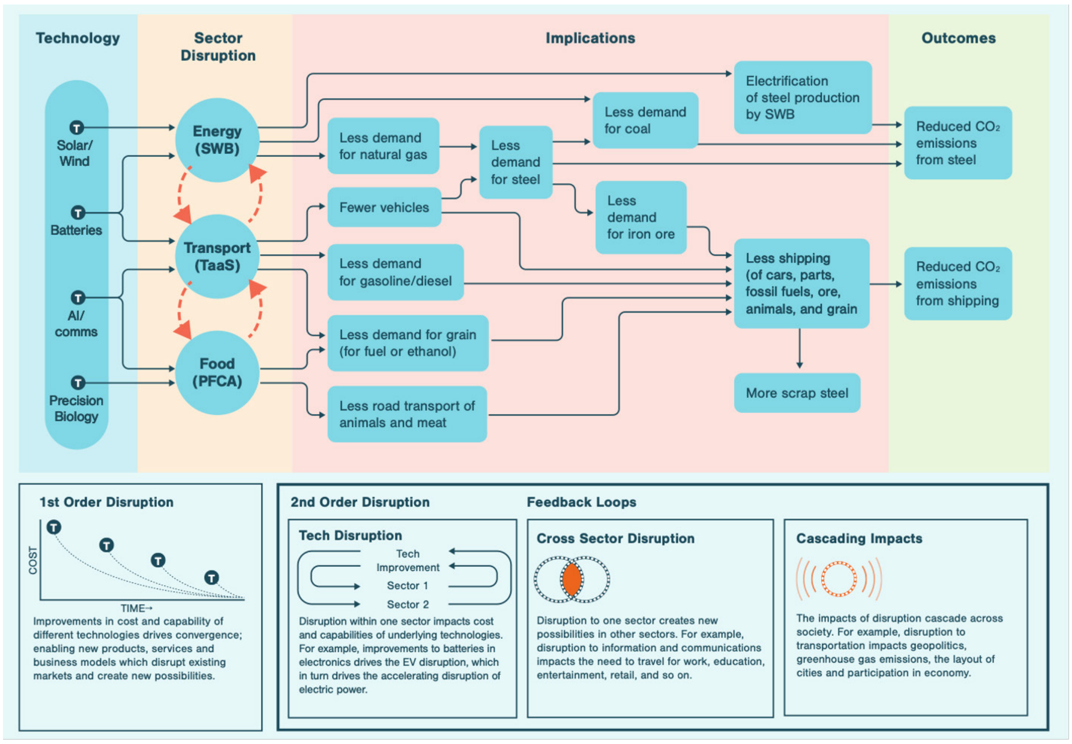
So far, no studies have modelled these cascading effects of the energy, transport and food disruptions in relation to minerals and recycling. However, some research offers more accurate insights.

The first major global life cycle assessment of a potential renewable energy system, published in the *Proceedings of the National Academy of Sciences (PNAS)* in 2015, corroborates the analysis set out here. However, it didn't fully appreciate or account for the novel dynamics of the new clean energy system since it focused on only the energy sector. Nevertheless, the PNAS assessment, led by the Norwegian University of Science and Technology, found that the environmental impact of extracting raw materials for clean energy technologies would decline over time, so the total quantity of those materials would be a fraction of the volume of materials being mined today.

In the *PNAS* scenario, solar, wind and hydropower would make up 39% of total global power production. But because wind and solar power generation require no additional raw material inputs over their lifespan (unlike conventional power plants, which require continued additional mining and refinement of oil, gas and coal), overall renewable power requires far fewer raw materials. Other models have neglected that crucial nuance.

In the *PNAS* scenario, new clean energy installations would increase demand for iron and steel by just 10%, with the copper required for solar panels equivalent to two years of current global copper production. When solar and wind installations need to be replaced, the raw materials to do so would be available from recycling older power generators. Other benefits would be marked: freshwater pollution would reduce by half and air pollution would decline by 40%. The human health benefits alone of a decline in air pollution would be enormous.

There are significant gaps in this model, as it does not incorporate the vast scope for metals recycling from the incumbent fossil fuel infrastructure in a 100% global clean energy scenario. However, if its findings were extrapolated to such a global system, much of the excess iron, aluminium and copper production required could be acquired from the recycling of that obsolete infrastructure.



Improvements in cost and capability of different technologies drives convergence; enabling new products, services and business models which disrupt existing markets and create new possibilities.

Disruption within one sector impacts cost and capabilities of underlying technologies. For example, improvements to batteries in electronics drives the EV disruption, which in turn drives the accelerating disruption of electric power.

Disruption to one sector creates new possibilities in other sectors. For example, disruption to information and communications impacts the need to travel for work, education, entertainment, retail, and so on.

The impacts of disruption cascade across society. For example, disruption to transportation impacts geopolitics, greenhouse gas emissions, the layout of cities and participation in economy.

Figure 5. Cascading effects of disruptions on iron and steel. Source: Rethinking Climate Change (2021)

In 2014, the World Wildlife Fund commissioned Ecofys, the leading Dutch energy consultancy, to explore supply risks for critical materials. Their report, *Critical Materials for the Transition to a 100% Sustainable Energy Future*, found that minerals such as indium, gallium and tellurium used for solar panels would not pose bottlenecks due to easy substitutability with other abundant materials such as silicon. As for the rare earth elements neodymium and yttrium, which are used in wind turbines, their supply is projected to exceed demand. And while the report said supplies of lithium and cobalt could pose challenges, these can be solved through recycling, substituting lithium in other sectors, and substituting for cobalt in cathodes. Nickel and cobalt are not used in lithium-iron-phosphate batteries, for instance.

Current recycling rates for critical metals are below 1%, with some rare earth elements not being recycled at all. This means that the potential for recycling is vast. According to a 2021 study by the Sydney University of Technology's Institute for Sustainable Futures, the assessment of the International Energy Agency (IEA) regarding how critical materials recycling could alleviate demand for new mining is far too conservative. The Sydney study finds that demand for raw nickel, cobalt, lithium and copper for EV batteries could be reduced by as much as 55% through increased recycling. A 2022 study commissioned by Eurometaux, Europe's association of metal producers, finds that by 2050, up to 75% of Europe's clean energy metal needs can be met through local recycling starting from around 2040.

There is therefore no serious evidence that the clean energy disruption will face insurmountable obstacles from minerals or raw materials bottlenecks, if we pursue optimal circular economy practices.

Net energy

The concept of energy return on investment (EROI) is an important metric to understand the efficiency of an energy system. It is a simple ratio of the energy obtained from a given source divided by the energy it takes to extract it. The challenge with producing accurate assessments of the EROI of any resource is in ensuring correct assumptions about that resource, including exactly how and where the energy inputs and outputs are measured to derive the most accurate figures.

EROI is an important measure because it can provide useful insights into the amount of net energy available to society. The higher the ratio, the more surplus net energy available to support other social and economic activities. The lower the ratio, the less energy available. A decline in EROI implies economic decline.

There is now a compelling body of scientific literature showing that the EROI of the global fossil fuel energy system has been in decline for several decades and is experiencing a vicious cycle of diminishing returns from which there is no prospect of recovery.

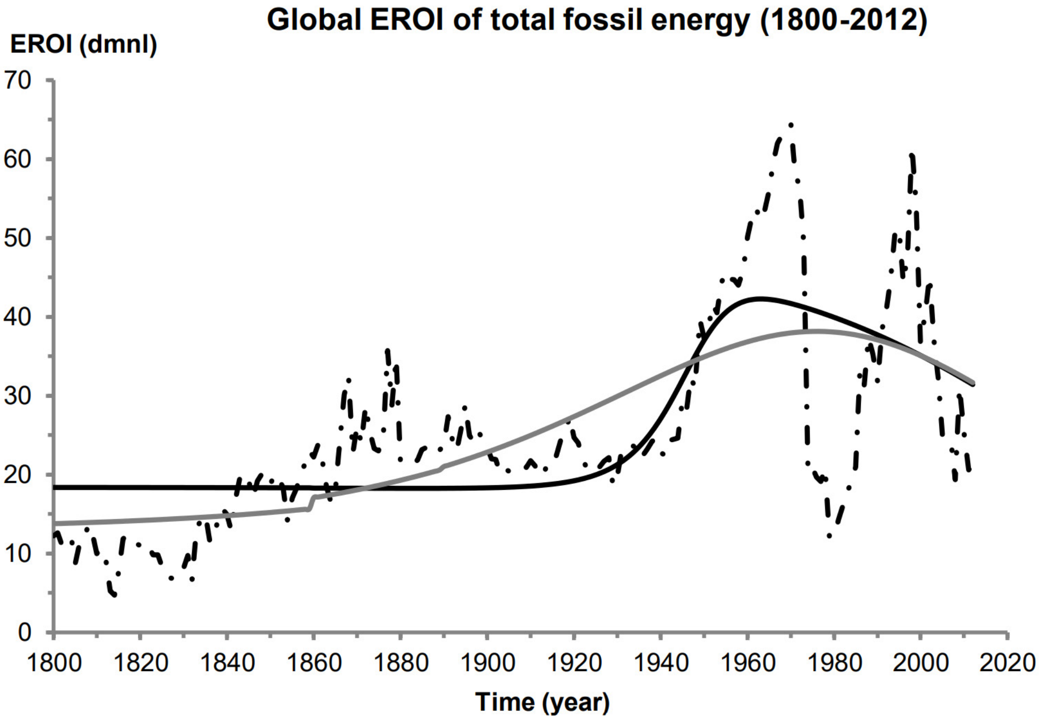


Figure 6. Source: Court and Fizaine, Ecological Economics (2017)

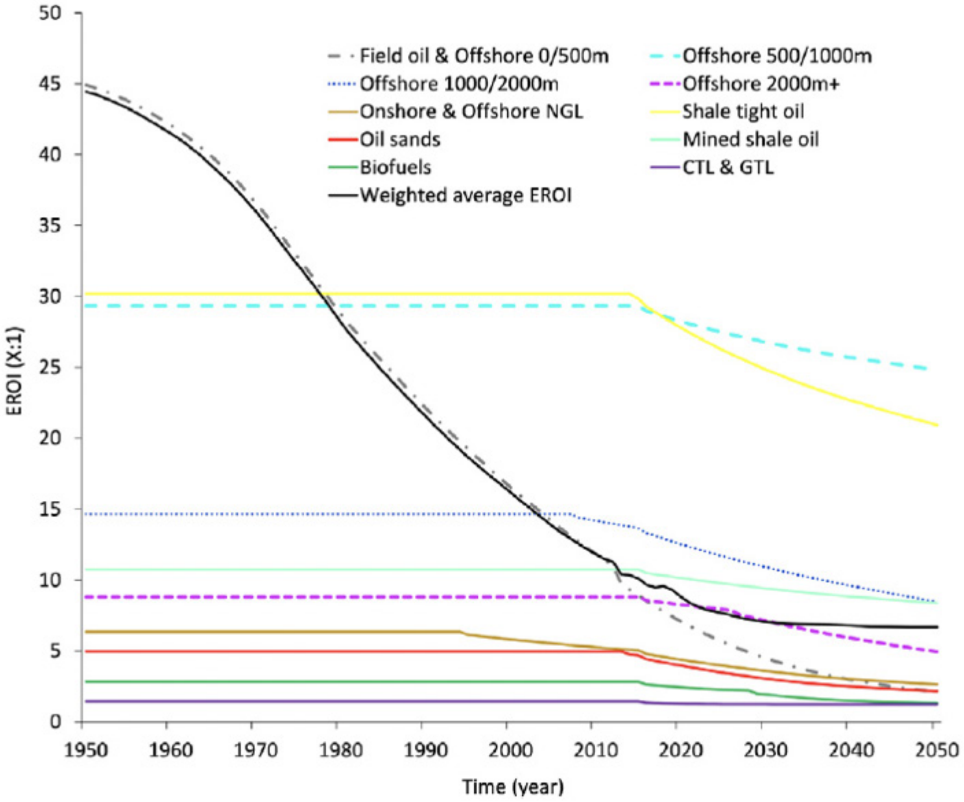


Figure 7. Source: Delannoy, Longaretti, Prados and Murphy, *Applied Energy* (2022)

Yet it is often argued that while EROI decline is inevitable with fossil fuels, renewable energy represents **a further decline in EROI** that means they cannot accomplish the same levels of societal and economic complexity.

In a **recent *Nature* Energy study** Professor Paul Brockway at the University of Leeds reported that as fossil fuels are becoming "harder to reach" they "require more energy to extract and, hence, are coming at an increasing 'energy cost'". The study noted that fossil fuel EROI is often overestimated because it is measured right at the well-head rather than the most relevant point, which is where the energy enters the economy as electricity or petrol. The study concluded that EROI for fossil fuels is "very low... around 6:1 and declining". It has already declined by at least 10% over the last 25 years.

A second crucial conclusion of the paper is that, taking into account the point of electricity consumption, renewables already have **a higher EROI** than fossil fuels. As most fossil fuel EROI studies are undertaken at the wrong stage, they are not comparable with wind and solar generation, which produce electricity requiring no further stages. While fossil fuel EROI is declining, wind and solar are experiencing the opposite: an increasing EROI trend with increasing returns and declining costs. Therefore, Brockway et. al conclude that "the renewables transition may actually halt – or even reverse – the decline in global EROI at the final energy stage".

The *Nature Energy* findings are corroborated by a **more recent RethinkX study** of the levelised cost of electricity (LCOE), which measures the average cost of generating electricity across the entire lifetime of a power plant, including its building and operating costs. That study found that conventional LCOE estimates by the International Energy Agency (IEA) and the Energy Information Administration (EIA) underestimate the per-kilowatt hour cost of coal, gas and large-scale hydropower by up to 400%. This would suggest that their EROI is significantly lower than most published estimates.

Meanwhile, as even conventional LCOE figures show that solar, wind and batteries (SWB) have already reached parity with fossil fuels, these findings indicate that SWB is already much cheaper, consistent with a higher EROI.

Flaws in conventional thinking

Despite the findings of the Brockway paper, the idea that renewables have a lower EROI than fossil fuels is a persistent misconception that has plagued numerous other studies that fail to make a full account of these technologies. These mistakes can be found in many places, not least in the famous feature documentary by Michael Moore, *Planet of the Humans*. More recently, the Geological Survey of Finland published a paper repeating such errors, as did the journal *Energies*.

There are significant problems with these approaches. One of the most egregious is the statement that solar panels have a lifespan of around 20–30 years. Conventional conservative EROI calculations for solar therefore put EROI calculations at somewhere around 10:1 for Switzerland. This is already higher than the 6:1 of fossil fuels demonstrated by Brockway et. al.

However, solar panels do not spontaneously combust after two or three decades. Rather, their efficiency declines over time by a small amount every year. This means that after 20 years, most solar panels will still operate at 90% capacity. This suggests that their lifespan is likely to extend many decades beyond 30 years – as much as 40–50 years if not more – with a gradual decline in efficiency, suggesting that even the 10:1 estimate is far too low, and solar EROI may be closer to 20:1.

Similarly, a 2014 *Renewable Energy* study confirms that the lifespan of wind turbines will extend to at least 25 years, and more recent turbines may last longer. Today, some of the most important components for wind power, such as transformers, copper ground cables and towers, among others, last for 50 years or more. Once again, the trajectory is for a higher EROI value, particularly as these technologies continue to improve in performance.

The energy payback from solar and wind is also phenomenal and comes at a fraction of the carbon footprint of fossil fuels, even if carbon capture and storage worked. A 2017 *Nature Energy* study found that the lifetime carbon footprints of solar and wind are about one twentieth of coal and gas, including manufacturing and construction. Solar and wind installations also produce 26 and 44 times more energy than the energy used to build them, respectively.

The battery equation: the Clean Energy U-Curve

So far, we have compared solar and wind with fossil fuels as if they will substitute for them in a one-for-one fashion. Instead the clean energy disruption will transform the entire energy system architecture.

As one example of this, many influential models reduce the EROI of solar and wind installations when incorporating the role of battery storage. Battery storage is of course necessary to address the intermittency issue: the sun doesn't always shine and the wind doesn't always blow. Battery storage is added to solar and wind generation to capture energy while it's being produced and then dispense it when it's not. It helps reduce the need to "curtail" clean energy, that is, deliberately cutting the energy output due to the inability to transmit it.

A linear analysis accounts for the additional energy inputs needed to manufacture and install battery storage, concluding that this implies more energy going in to produce the same energy output, and a lower EROI overall. However, that conclusion is only one half of the answer, based on a narrow approach to solar, wind and battery (SWB) design. It calculates EROI values for each component and then aggregates without fully recognising the extent to which such a system can produce surplus energy. Indeed, it doesn't reflect how an SWB system works in practice.

When scientists at the University of Waterloo attempted **their own analysis** by examining real data from renewable power installations, they found that far from reducing the EROI of solar and wind farms, the addition of lithium-ion batteries actually increased EROI by making available energy that would otherwise be lost to curtailment: "We find that lithium-ion batteries increase the EROI of both wind and solar farms." Better transmission lines to the grid would enable further improvements.

This study was also too narrow, as it focused on single renewable energy plants, rather than seeing how SWB systems would operate in the context of an entire city, region or nation. As a result, most analysts end up further underestimating the potential EROI of SWB systems because they neglect the net systemic benefits of such systems on wider scales, and overestimate the role of batteries in the system. SWB installations will not simply replace fossil fuel plants: they will create new energy system architectures that require a new understanding. As a result, studies that assume that EROI for a global renewable energy system will shrink compared with that of fossil fuels are comparing apples and oranges.

A 2019 ***One Earth* review** thus concluded that a global shift to SWB would not diminish EROI at all. The study noted that the pessimistic view is based on a linear methodology of extrapolating forward "short-term transitional trends in the energy transition (PV and wind replacing coal, biofuels replacing oil)" in a way that will not reflect the full possibilities of "an energy system based on massive deployment of cheap PV and wind power".

For instance, the paper points to a scenario rarely considered by any model: "The much-touted problem of intermittency requiring fossil backup can be turned around by significantly overbuilding PV and wind and converting the intermittent electric oversupply into fuels."

In this approach, building far more solar and wind than is needed, and then putting in place systems to extract the surplus energy for other uses, reduces the need for battery storage while making more total energy available. In this case, the suggestion is to use the new clean energy system to generate synthetic fuels, but that is only one option. In the One Earth scenario, the EROI of the new clean energy system is around 10:1, which is not that different (and already higher) than the current fossil fuel system. However, this scenario is far too conservative, and underestimates the full transformative system-wide implications of the clean energy disruption due to mass deployment and economies of scale that do not emerge when looking at single power plants in isolation.

RethinkX's report, *Rethinking Energy 2020-2030: 100% Solar, Wind and Batteries is Just the Beginning*, shows that to supply energy through the darkest days of winter, we will need to build significant overcapacity in solar and wind generation. This will produce larger amounts of energy than the incumbent fossil fuel system, with much less need for batteries. A 100% SWB system designed to provide power 24/7 when the sun doesn't shine and wind doesn't blow would be some five times bigger than a one-to-one replacement of the fossil fuel system, but could meet winter demand with 30–40 times less battery storage.

The report's "Clean Energy U-Curve" maps out the relationship between the costs of battery storage and solar/wind generation, demonstrating that this mix is the most optimal, least expensive, and the fastest and easiest system to deploy.

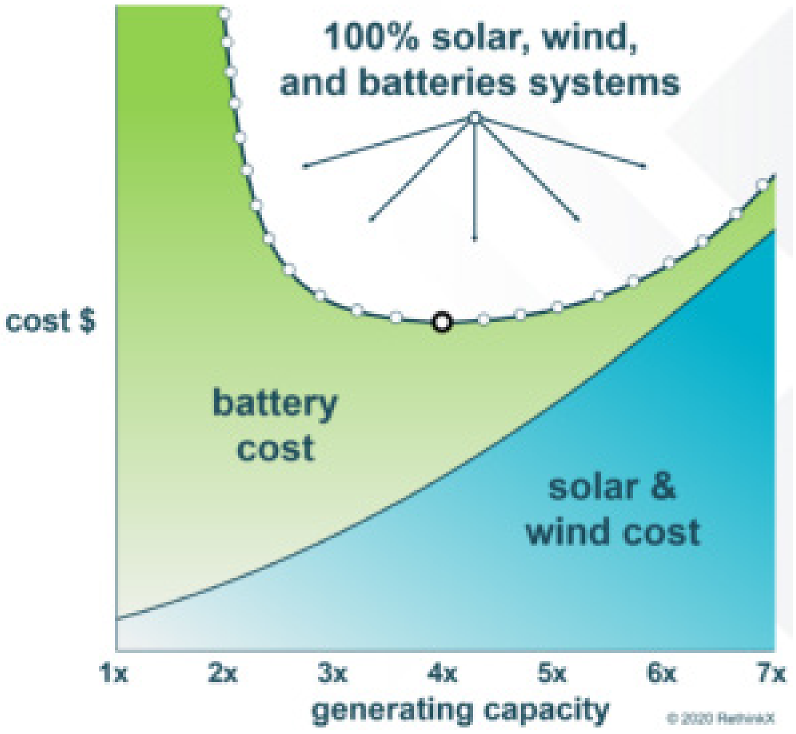


Figure 8. The Clean Energy U-Curve. Source: RethinkX (2020)

The curve can be applied to different regions to determine the specifics of the most optimal roll-out. On most days of the year, this SWB system will generate vast quantities of electricity

The new clean energy system will be able to generate three times as much energy as the incumbent fossil fuel system, much of it almost for free most days of the year.

at near-zero marginal costs. Instead of wasting this energy by curtailing production, the new energy system will create a whole new possibility space for how to use this cheap, surplus energy for endless new applications. Overall, the report estimates that the new clean energy system will be able to generate three times as much energy as the incumbent fossil fuel system, much of it almost for free most days of the year.

The assumption that the incumbent fossil fuel-centric grid will act as a constraint overlooks the reality of how disruptions work. A lack of paved roads did not prevent cars from becoming ubiquitous. Instead cars spurred the emergence of new transport networks. Similarly, computers and smartphones have disrupted landline-era telecommunications firms and spurred them to evolve into the internet. The new possibility space represented by large quantities of near-free electricity for most of the year will incentivise and accelerate the evolution and transformation of the grid into larger, more flexible, diverse and capable systems. RethinkX describes the breakthrough possibility space opened up by the new clean energy system as “Super Power” because while disrupting incumbent fossil fuel-centric business models, it will enable new business models with the potential for tremendous value creation.

Other researchers are now corroborating these findings. For instance, Marc Perez at Columbia University found that **building overcapacity of solar and wind** by a factor of three times peak load not only reduces the need for battery storage, but lowers the cost of electricity by as much as 75%, while eliminating intermittency challenges. Perez’s team also did a case study of Minnesota. They found that overbuilding solar and wind could reduce the battery input for seasonal storage by **as much as 90%**. Global energy firm Wartsila **similarly found** that overbuilding solar and wind by four times peak load requires no seasonal storage, and needs only 4–10 days of multi-day storage capacity, making it the lowest-cost system.

These studies show that conventional assumptions about the role of battery storage in dramatically reducing EROI are based on outdated understandings of an optimal SWB deployment. And further, they did not appreciate the full implications of Super Power, where instead of curtailing this three- or four-times surplus power, the system is designed to make it accessible to the grid.

What, then, would the output of this energy system look like on a global scale? Coming up with a valid figure for this is challenging given that such a system is yet to be built, and given the need to avoid the pitfalls of a siloed, linear approach that neglects the novel properties of the clean energy system.

However, scientists at the Swiss Federal Laboratories for Material Science and Technology made just such an attempt. Their **study in *Energies*** found in its most conservative scenario that overbuilding solar power on the built environment alone would be able to generate 22 terawatts (TW) of electricity, which is more than three times higher than today’s energy consumption levels.

Yet even this figure barely scratches the surface of the possibilities. The scenario didn't incorporate wind power, nor did it factor in the potential of areas of the world receiving the highest solar radiation, such as the world's deserts. Thus, in their most optimistic scenario, a global system that also harnessed and transmitted solar from these areas would be able to generate 71 TW of electricity, around 10 times as much as today's power consumption. This extraordinary conclusion is still conservative as it doesn't factor in wind potential, which would add another order of magnitude to these figures.

The implication is that the most robust data available confirm that a new global clean energy system would be capable of providing a level of energy inconceivable to our societies today. We appear to still be underestimating the potential.

That's because another common mistake is to view SWB systems as static technologies whose performance operates at a fixed level. This is not the case. Fossil fuel extraction industries have entered a death spiral of diminishing returns, declining performance and escalating costs. In contrast, SWB systems are disruptive technologies that would experience increasing returns, exponentially accelerated performance, and exponentially decreasing costs.

In 2017, **Stanford University scientists found** that the EROI of solar was as high as 27 in Arizona and 14 even in a low-sun area such as Alaska. As the addition of batteries for self-consumption only reduced this by 20%, EROI of a solar battery system in Alaska would be around 11, and in Arizona around 22. Adding batteries to avoid curtailment could increase overall EROI by between 12–42%. The study concluded that lowering the contribution of batteries and maximising the capacity to feed excess energy back into the grid would increase EROI.

Indeed, a **meta-analysis** of EROI studies of solar photovoltaics in *Renewable and Sustainable Energy Reviews* found EROIs between 9:1 (already higher than Brockway's 6:1 estimate for fossil fuels today) for older installations and 34:1 for cadmium telluride panels. Given that coal's maximum historical EROI has been estimated at around 80, it's worth noting the conclusions of this study: "Based on the efficiency and embedded energy improvement potentials discussed in this paper, it is likely for PV technology to catch up to the maximum EROI from coal in the future."

Indeed, some studies **already put** solar PV's EROI at over 60:1. As per Wright's Law, which has been **empirically validated** for dozens of technologies, and as per RethinkX's **forecasts** based on the **Seba Technology Disruption Framework**, SWB is heading towards becoming 10 times cheaper within the next two decades, while continuing to improve its performance. A **2021 study** by Oxford University's Institute for New Economic Thinking corroborates RethinkX's findings, seeing cost reductions at the current rate continuing for at least 15 years. This means that assessments based on current technology are likely to be improved by an order of magnitude – tenfold – by 2030.

The driving factors of this improvement will come from the EROI inputs and outputs. Technological progress will improve production methods and as production volume increases, producers will enjoy greater economies of scale. The energy inputs to manufacture solar panels will also decrease. Panels are also getting better and better at capturing solar energy, meaning that their output will also increase. As energy inputs decline and energy output increases, the EROI will continue to improve.

Current data indicate how this will unfold. The US Department of Energy's **Solar Futures Study**, in a conservative assessment of the possibilities, predicts continued "improvements in photovoltaic efficiency, lifetime energy yield, and cost" will be able to generate "a 60% reduction in PV energy costs by 2030". Solar PV has already experienced exponential improvements in efficiency resulting in panels generating many times more electricity than several decades ago. Early panels in 1955 started at **2% efficiency**. By 1985 this shot up to 14% efficiency – producing 600% more energy than in 1955. By 2020 it had increased to an average of **around 22%**, producing 57% more energy than in 1985. That improvement **is still continuing**, with new innovations already pointing to coming efficiencies of 27.3%. Wind turbine efficiencies and battery storage are also improving at similar paces. Based on these trends, it is reasonable to expect the EROI of SWB to continue improving.

All this suggests that the EROI of an optimally deployed global clean energy system would be an order of magnitude higher than the incumbent fossil fuel system, especially at sites with optimal deployment and higher solar or wind availability. The conservative One Earth EROI estimate of 10:1 may even underestimate the EROI of a new global clean energy system by 2030. Given the conservative figures cited suggesting a 60% reduction in energy input and another 60% increase in output by 2030, the cumulative energy efficiency increase of 120% would suggest an EROI of 22:1. This is still a low-end scenario. If EROI values today for solar PV are between 30:1 and 60:1 depending on the region, then a 120% increase in performance improvements over a decade could produce EROI values between 66:1 and 132:1. By 2040, that could increase further with more research and development.

The implication is that the clean energy disruption based on SWB heralds the potential to break through to a new energy system the likes of which we have never seen before. It will enable humanity to not only meet our energy needs sustainably, but to electrify a vast array of public services that now generate inordinate energy and environmental costs.

This new possibility space has even been **acknowledged by scientists** in *Energy & Environmental Science*, published by the Royal Society of Chemistry. Asking whether there could be "other uses for electricity generated by wind or solar that would otherwise be stored or curtailed", the paper suggests: "excess electricity could be used in applications where the need for on-demand power is low and are not strongly disadvantaged by intermittency, for example, desalinating or purifying water or driving irrigation pumps. These conditions could result in high EROI_{grid} values with benefits to society that lie beyond the power-grid sector."

The key, then, is to optimise the deployment of SWB using the Clean Energy U-Curve to generate as much surplus electricity as possible, for as cheaply as possible, generating the largest quantity of Super Power in a way that will eliminate intermittency challenges. By then enabling the electrification of a vast array of industries and sectors, from wastewater treatment to recycling, from mining to manufacturing, Super Power will clean their energy footprints.

This means that, for the first time, the vast amount of Super Power generated by the new system will allow us to sustain the extensive new industrial processes required for the circular economy in a way that was previously inconceivable. Super Power in the new system will enable the continued maintenance and replacement of its component technologies sustainably.

Even within the incumbent system, it's possible to see how rising demand for critical minerals will drive up demand for recycling, which will drive increasing economies of scale and cost reductions. In the new clean energy system Super Power will make recycling commercially viable and technologically efficient in a way that was impossible within the old paradigm. All mining and manufacturing of SWB technologies will be sustainable thanks to the vast amounts of cheap electricity generated by the new system.

In the same way, while the clean energy disruption accelerates, it will intertwine with the EV, autonomous EV, transport-as-a-service (TaaS), precision fermentation and cellular agriculture disruptions across the transport and food sectors. The combined and cascading effects of these disruptions will enable us, if we choose, to reduce carbon emissions far faster (90% by 2035) than previously believed possible. They will further enable a wide range of carbon withdrawal mechanisms that are unsustainable under the fossil fuel system and free up of billions of acres of land to allow passive reforestation, active reforestation, rewilding and conservation on massive scales.

The cascading dynamics of these simultaneous disruptions will ultimately culminate in shrinking the material footprint of industrial civilisation. The collapse of carbon-intensive industries in energy, transport and food will end the huge demand for global logistics and transport, free up billions of hectares of land, allow oceans to regenerate, and eliminate air pollution. With the right choices, the new energy, transport and food systems enabled by these technology disruptions will lead to a net reduction in the material intensity of human civilisation.

This is just the beginning.

Next, while the initial roll-out of the new energy, transport and food system will require mobilising the materials and capital resources of the dying industrial economic system, once it's established, the new system will not suffer from the same supply shocks and price dynamics of the old centralised energy system. Instead, compelling data show that with an optimal deployment, the new system will be able to generate at least three times as much energy as the fossil fuel system, but at near-zero marginal costs for most of the year – with the potential to generate 10 times as much.

That will enable the electrification of a vast array of services – such as mining, manufacturing, recycling and wastewater treatment, meaning that we will be able to sustain, maintain and operate the system by harnessing the power of the sun and the wind.

Once the new clean energy system begins supplying the material flows to maintain the global SWB system, an unprecedented possibility space appears. We will be able to maintain and even expand the clean energy system without breaching planetary boundaries. Further increases in material throughput will no longer depend on fossil fuel extraction limits. Instead, the new clean energy system would sustain them without destabilising planetary boundaries. This is not automatic. It requires the right choices to organise those material flows. That means material intensity could increase dramatically, sustained by the clean energy system, if decision makers design the system to avoid damaging ecosystems. This suggests that decoupling will be possible – but only in the new system. This means that the clean energy system will enable the expansion of its energy production power from within the existing system, enabling further potential increases in generating capacity, and therefore further increases in the overall EROI of the system – creating a new foundation for continuously improving global clean prosperity.

With vast areas of land freed up due to the disruptions, and with order of magnitude advancements in clean energy and autonomous machine labour, natural and technological carbon withdrawal methods unfeasible in the fossil fuel system will become cheap and viable – opening up unprecedented opportunities for rewilding and ecological regeneration of our land, air and water. Those technologies are not feasible within the current paradigm but will become so after the transformation of production systems across the current five major technology disruptions, and if society makes certain necessary choices.

This won't happen on its own. We will need to choose this pathway, by adopting a new value-system in which we place real value on protecting our planet. This Earth-centric value-system entails responsibly mining and recycling materials while investing in the restoration of the Earth in a way that will improve conditions for all species. If we choose this path, it could enable a new form of vibrant economic and ecological prosperity. Doing so is a matter of survival. If we refuse to embrace this transformation, if we delay the disruptions by prolonging the life of incumbent industries and systems or decrease our material footprint within these systems, then those industries and systems, and with them our civilisation, could collapse before we break through to the new system.

With the right choices, then, there will be tremendous new ways of creating economic value within a new post-carbon system without hurting the Earth. In fact, leveraging these existing technologies, we can now envisage economic prosperity for all people, providing advanced power, food, mobility, education and infrastructure at a tenth of the costs of the incumbent systems.

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Enabling and optimising these possibilities will require us to transform the organising system of civilisation. For instance, we will need to break up existing centralised energy utility monopolies and create new individual property rights to own and trade electricity. We will also need to open intellectual property rights to facilitate open-source systems that permit global design and local implementation. These are just a few examples. Such transformations will result in a shift from centralised to decentralised ownership, enabling people to produce their own energy and food. This implies a transformation in the structures of ownership of economic production involving a complete shift in the relationship between labour and capital that does not fit today's economic ideologies.

Existing economic ideologies do not help us understand the next economy. It will involve individual entrepreneurship, collective design processes, shared distribution protocols across participatory interconnected networks rather than top-down hierarchies. It will involve a form of increased economic prosperity, including an expanded capability and efficiency meeting our key material needs, accompanied by a decreased ecological footprint. It will entail the deployment and maintenance of a stock of material inputs and outputs for the system to continue existence, which will then for the first time be able to grow within planetary boundaries thanks to the larger and growing ability to harness clean energy.

We are within sight of a technologically advanced and economically prosperous ecological civilisation. Armed with this understanding of what's possible, we can recognise the need to rethink the conventional industrial economic paradigm in a way that embraces a new possibility space that cannot be defined, constrained or understood using the old tools, ideas, beliefs and values.

But this system won't arrive automatically. Societies and decision makers need to understand the coming possibility space and **make the right choices** to get there. Business-as-usual economics, centralised energy utilities, and the traditional metrics of the old hierarchical energy industries are incompatible with the new system. Its optimal deployment will require rethinking our entire systems of social organisation, beliefs, values and mindsets. If we don't make the right choices now, our **civilisation could collapse** like those before it amid a perfect storm of self-induced crises.

We must first wake up to the possibility that over the next decades we have the opportunity to walk into a new economic paradigm unlike anything we've seen before, one that can enrich all our lives and regenerate the Earth.

The path ahead will not be simple or easy. We must first wake up to the possibility that over the next decades we have the opportunity to walk into a new economic paradigm unlike anything we've seen before, one that can enrich all our lives and regenerate the Earth.

What next?

The main barriers to implementation and acceleration are:

- **The incumbency and its interests and capture of state institutions**
- **Siloed thinking, perpetuated by the incumbents**
- **The lack of foresight among decision makers**

There are some important ways to accelerate the transformation. Not everyone will implement them, but it will be achievable for countries or regions who are able to recognise what's happening and make better decisions. Once some entities pursue these policies, they will have a domino effect.

1. The first step is waking up. Citizens, pressure groups, businesses, industries and of course policymakers need to be fully aware of the tremendous societal and civilisational possibility space that is emerging right now due to the combined potential of technology disruptions in the energy, transport, food, information and materials sectors. Recognising this possibility space does not entail a "technocentric" belief that technology alone can save us. On the contrary, it involves a recognition that while we already have all the tools we need to transform our societies and solve our biggest global challenges (we don't need to wait for breakthroughs), we must adopt new mindsets, governance and organisational systems to manage the production system that is emerging. The more people are able to understand the transformation that is already unfolding and its opportunities for shared prosperity, the greater the scope for conversations and action that can accelerate and harness that transformation.

2. The top policy priority must be to end subsidies and new investments for the incumbent industries (which need not conflict with very specific temporary support to ensure continuity and diversification in the context of fallout from the Russia-Ukraine crisis). Although carbon pricing is an option to make polluters pay, we don't need it. Markets are already distorted by trillion-dollar bailouts to incumbents. The biggest insight here is that these assets are already stranded. Oil, gas, coal, livestock industries and ICE companies are vastly overvalued today, which means investors will not recover or make returns on their investments. Government subsidies to these industries are effectively bailouts to bankrupt industries. Therefore, rather than using carbon pricing, the first step to creating viable energy and electricity markets is ending these subsidies. In doing so, the market will become a level playing field. It will also free up governments to invest those trillions in the innovations that are going to transform societies for the better.

3. The most effective pathway to ending these subsidies is to leverage the governments that are already seeing the writing on the wall and acting on it. The members of the Beyond Oil & Gas Alliance are good candidates. We need to encourage these governments, which are already committed to phasing out fossil fuels, to lead by ending outright their fossil fuel subsidies. The other open door on this is the financial and investment community. Some are too invested in the incumbents, but many financial institutions will begin shifting their portfolios when they recognise that they are investing in effectively bankrupt industries. We need to get this intelligence on the transformation to leaders in the financial sector to spur change. When a significant portion of governments and financial institutions begin pulling money out of fossil fuels, there will be a turning point that will help spur a global shift. We don't need trillions of dollars of state subsidies to fund the transition. Given that the key technologies already exist and are ready to scale (if not already scaling), we can leverage the market to do the bulk of the work. We just need to accelerate them. By levelling the market playing field, we lower the barriers to acceleration.

4. We need to create new rights for individuals to trade in the energy electricity markets. That means breaking up the centralised utility monopolies in energy. This will encourage decentralisation and distribution and will accelerate the transformation. The same applies to the transport and food sectors. Governments must dismantle existing regulatory structures that protect the incumbents. They should create new regulations for the new energy, food and transport systems that, among other things, change intellectual property laws to facilitate global open-source information sharing.

5. There are key areas that the market can't help, such as the electrification of heating and industry. However, governments can accelerate the transformation by redirecting a portion of their vast expenditure on fossil fuels into funding for electrification of heating and industrial infrastructure. This can give rise to important dividends. Instead of spending trillions on things such as carbon capture and hydrogen intended to deal with “hard to abate” industries, we can leverage the scaling potential of solar, wind and batteries to transition industries onto the new clean energy system. The dividend here is the opportunity to bring down costs fast. In a system where clean energy has nearly zero marginal costs for most of the year, we can only imagine what that could do for industries that are currently dependent on expensive fossil fuels.

6. We need to have a plan for protecting people and communities during the transformations. The collapse of incumbent industries does not need to result in the collapse of livelihoods if decision makers plan for this change and invest in transitioning workers into the new systems. This requires winding down the incumbent industries on a science-based timeline and supporting the retraining of workers. This also requires recognising the tremendous opportunities of the new system, which by most estimates will create a larger number of jobs than incumbent industries, involving extensive skills and self-development opportunities. By the same token, oil-producing states should recognise the opportunity before them to become the world’s leading solar super powers. Doing so can allow them to rapidly extract themselves from dependence on oil export revenues, and to lead the way in the evolution of a new economic paradigm premised on clean energy prosperity.

These are some of the most important steps, but at their centre is the need to accelerate awareness of the inevitability of the disruptive change of our production systems, recognising their transformative implications, and understanding the massive opportunities and possibility space of this transformation. That is not properly or widely understood. The prevailing narrative is one of having to make painful sacrifices to save ourselves from almost certain doom, as opposed to accelerating positive transformations that will not only empower us to avoid doom but propel us to new heights of prosperity in a way that benefits all people and all species.

Decarbonisation is not a sacrifice. It will save us trillions and contribute to greater global wealth and greater distribution of that wealth. So, a key step is changing the narrative to help shift mindsets. When key decision makers and influencers wake up to this possibility space, they are more likely to join in moving the needle.

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