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Applying systems thinking to the global transition away from fossil fuel

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Introduction

The global transition away from fossil fuels is often framed as a technical or policy challenge focused on deploying renewable energy technologies or implementing climate policies. Despite scientific warnings for decades and international climate commitments, fossil fuels remain dominant in the global energy system (International Energy Agency, 2023). This continued issue reveals that the dependence on fossil fuels cannot be solely explained based on isolated technological or political failings. Instead, it must be viewed and understood as an outcome within a complex, interacting system, a concept known as systems thinking in political science.

This paper applies systems thinking, drawing on the work of Donella Meadows (2008), to analyse the global energy transition as a dynamic system shaped by reinforcing feedback loops, institutional lock-in and deeply embedded economic and social structures. From this perspective, continued fossil fuel use is sustained by interactions between subsidies, infrastructure investment, political influence and growth-oriented economic models, which together stabilise the existing energy regime (Unruh 2000; International Monetary Fund, 2022).

This research utilises the PESTLE framework to demonstrate how the interactive political, economic, social, technological, legal, and environmental factors drive a reinforcing loop of dependency on fossil fuels, while simultaneously opening possibilities for systemic changes. It therefore focuses keenly on identifying main feedback loops, systemic barriers that are most resistant to change and leverage points where targeted intervention can result in accelerated decarbonization. Another objective is to evaluate the way the systems thinking approach can underpin a just and globally equitable energy transition. There are huge inequities in historical emissions, economic capacity, and vulnerability to impacts of climate decarbonization strategies that ignore equity risk, reinforcing global disparities (IPCC, 2022). This paper applies systems thinking toward an understanding of justice, thus offering what we hope will be both effective and inclusive conceptualisations of the international fossil fuel-based energy transition.

Given the scale and complexity of the global energy system, this paper does not attempt to capture every dimension of the transition away from fossil fuels. Instead, it focuses on the broader systemic patterns that have reinforced fossil fuel dependence over time. Central to this analysis is the argument that reinforcing feedback loops surrounding industrialisation, economic growth and fossil fuel consumption have created deep path dependencies within modern societies. As these systems became increasingly embedded within infrastructure, institutions and patterns of everyday life, substantial barriers to transition emerged. In many ways, the global economy can be understood as being trapped within a deeply entrenched carbon-intensive pathway, where the historical dominance of fossil fuels has created structural conditions that are difficult and costly to escape

Feedback loops in the global fossil fuel system

Systems thinking emphasizes that the behaviour of complex systems is shaped less by individual components than by the feedback loops that connect them over time (Meadows, 2008). Feedback loops occur when an action produces effects that feed back into the system, either amplifying change (reinforcing loops) or stabilizing existing conditions (balancing loops). In this context of the global energy system, reinforcing feedback loops have, however, played a central role in sustaining fossil fuel dependence despite growing awareness of climate risk.

Fossil fuel and subsidies

One of the strongest and most persistent reinforcing loops is that between subsidies and market consumption. Fossil fuel subsidies make energy consumption cheaper for consumers, creating demand while investment flows into extraction and infrastructure development. In this proposed dynamic, production and consumption build the power of fossil fuel interests to lobby for continued subsidies and favourable regulatory conditions both domestically and internationally (IMF, 2022). Consumption increases reinforce because it undermines attempts to increase the competitiveness of alternative renewable energies.

Carbon lock-in

Another reinforcing loop is created by long-lived energy infrastructure. Fossil fuel power plants, pipelines, refineries and transport systems are capital-intensive assets designed to operate over several decades. Once built, there will be strong incentives created by investment recovery efforts to fully maximise their use, whereby adoption of cleaner alternatives can be postponed (Unruh, 2000). This is, however, known as carbon lock-in: present and future choices being constrained by past decisions- energy dependence locking deep inside the system at a much more profound level than just within current consumption patterns.

Political and social loops

Political and social feedback loops further stabilise the existing system. Fossil fuel industry jobs, government revenues emanating from resource extraction, and national energy security interests all translate into public and political support for the continued use of fossil fuels. This support highlights a policy preference for economic stability and short-term growth over long-term environmental sustainability, reinforcing societal norms that associate fossil fuels with development and prosperity (Meadows, 2008). As these norms become culturally embedded, resistance to systemic change increases, even amid escalating climate impacts.

From a systems thinking viewpoint, these reinforcing feedback loops not only sustain our reliance on fossil fuels but are also part of a larger pattern of divergence within the global system (Meadows, 2008). Current forms of energy use do not lead to the development of sustainable ways of living or equitable access to finite resources but rather create additional environmental harm and increase existing inequalities among nations (IPCC, 2022). This indicates that we remain in a dynamic divergent state, with economic growth and energy consumption continuing to grow beyond the capacity of our planet (CONVERGE Project, 2013). The enduring nature of these feedback loops indicates that there is still considerable misalignment in the global energy system concerning these objectives, therefore highlighting the magnitude of change that will be needed to achieve them.

Systemic barriers to the global energy transition

There are deeper structural barriers to the potential of meaningful transformation; while reinforcing feedback loops can account for continuing fossil fuel dependency and the divergent trajectory of the system, there are larger obstacles that exist within the energy system globally, which complicate the possibility for meaningful change. Systems thinking shows that the barriers to change are interrelated and self-reinforcing, providing stability to the current regime (Geels, 2011). Therefore, the transition to a more sustainable renewable energy source is constructively delayed because of the economic, political, infrastructural, and social elements that together build on the divergence from a more sustainable and equitable system.

Economic dependence

One of the major impediments to the energy transition is the path-dependency of the global economy. Historically, fossil fuels are the basis of growing economies, building industry, creating trade networks and developing consumption patterns. Because of this, many economies still have structural dependence on carbon-intensive industries for jobs and fiscal support. Research into carbon lock-in shows that an economy or economic system becomes established around the use of fossil fuels, and this makes transitioning away from fossil fuels costly and politically contentious (Unruh, 2000). In addition, there are still global capital flows that invest in fossil fuels, further entrenching existing market structures (International Energy Agency (IEA, 2023). The economic dependence results in a continuing divergence within our societies as short-term growth remains the priority over long-term sustainability.

Political and institutional lock-in

Fossil fuel dependence is entrenched even more so by political and institutional structures. Many governments receive revenue from fossil fuel industries and have a focus on energy security and economic stability. The combination of these competing interests creates obstacles to rapidly changing policies. Research on transition to sustainable development indicates that existing policy frameworks and governance systems tend to be biased in favour of existing industries, thus limiting the ability of new policies to address environmental issues (Geels, 2014). Furthermore, fossil fuel industries have a large amount of political power over the development of regulations and slow the speed at which efforts to reform take place (Newell

& Paterson, 2010). For instance, the United States has made commitments to tackle climate change but has nevertheless continued to permit new oil and gas extraction projects, primarily due to the actions of professional lobbying groups and politicians (Levi, 2019). These institutional dynamics operate as stabilising forces within the overall system that create a delay in reaching convergence, where equity and environmental limitations would be the basis of how policy decisions are made.

Infrastructure inertia

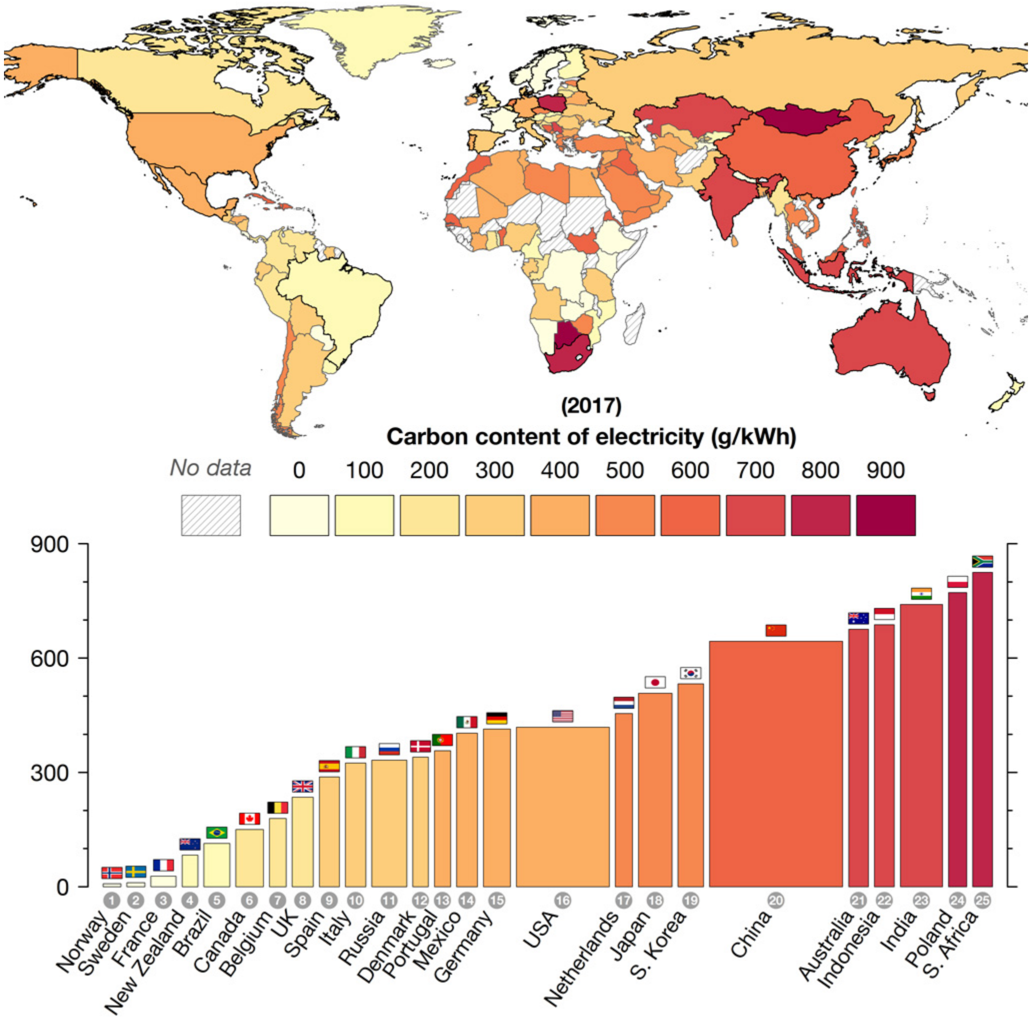
Another significant barrier to transformation is infrastructure. Long-lived, existing energy assets such as pipelines, oil refineries, coal mines and power plants were built to be operational for decades (Seto et al., 2016). Once these systems are established, there is pressure for them to continue to be productive and generate revenue due to the associated capital costs that have already been incurred, for example. The issuance of permits to build additional pipeline infrastructure, such as the Keystone XL Pipeline, serves to reinforce the ongoing reliance on fossil fuels (Hughes, 2016). Given that most fossil fuel activities in the world economy are perpetuated through existing physical structures, infrastructure ‘inertia’ ensures a continued reliance on fossil fuels and strengthens the divergent nature of the two-path trajectories.

Social norms and behaviour

Social and cultural factors are also a significant component of continued fossil fuel consumption. The energy we consume is closely associated with our lifestyles, consumption patterns, and society’s expectations regarding economic growth and development (Shove, 2010). For example, the way cities are designed to accommodate cars in the US leads to much greater levels of oil consumption than in other parts of the world that do not have such car-dominated urban environments. Figure 1 illustrates that the energy intensity from transportation per person is generally greater in low-density, car-dependent countries (including the US, Canada and Australia) than in those countries that are more compact and or have lower levels of vehicle ownership. Likewise, those countries that have lower car dependency and urban design have lower energy consumption based on transportation. The differences in energy consumption show that it is not just an outcome of choice but also a consequence of larger social and infrastructure systems (Newman & Kenworthy, 1999).

Consequently, these patterns maintain a difference due to continued reliance on unsustainable sources of energy; whereas more efficient energy systems will help create a world with convergence toward one another.

Figure 1: Energy intensity of transport (MWh per person) across countries (2017).



Source: Adapted from global transport energy datasets

The critique of global sustainability as portrayed by these patterns indicates that the present systems are not progressing towards equity and are exceeding the planet's limits (CONVERGE Project, 2013). These critiques emphasise the degree to which the present economic, political and social structures maintain divergence rather than convergence within the global energy system.

Leverage points for accelerating the energy transition

Systemic barriers help explain why society continues to rely on fossil fuels despite our current efforts to transition away from them, while system theory offers insight into how entrenched systems often include points of leverage where small changes can create large-scale, lasting change (Meadows, 2008). These points of leverage change the way that systems respond to feedback and also change the incentives that drive systems; in some cases, they will even transform the overall purpose of a system. If effectively utilised, points of leverage will create an environment that facilitates the transition to a sustainable global energy system while accelerating movement away from divergent to convergent sustainable systems.

Economic and financial leverage points

One of the most immediate leverage points lies in restructuring financial incentives within the energy system. Fossil fuel subsidies and continued investment in carbonintensive industries reinforce existing feedback loops, whereas redirecting financial flows toward renewable energy can trigger self-reinforcing processes of innovation and cost reduction. For example, large-scale investment in renewable energy technologies has contributed to significant cost declines, making solar and wind energy increasingly competitive with fossil fuels (International Renewable Energy Agency, 2019). A prominent example is China, which has invested heavily in solar and battery supply chains, becoming the dominant global producer of renewable technologies and accelerating their global adoption (Bian et al., 2024). From a systems perspective, such financial shifts can create positive feedback loops that push the system toward convergence by aligning economic incentives with sustainability goals.

Policy and governance leverage points

The most significant opportunity for global energy transition is through policy interventions that can change the rules, incentives and overall direction of energy systems (Meadows, 2008). By regulating, taxing and planning infrastructure, governments can also transform existing feedback loops and accelerate the movement away from the use of fossil fuels to a sustainable alternative energy system. A notable example of this approach is Germany’s Energiewende (“energy transition”), where the ultimate goal was to decrease the country’s reliance on fossil fuels by providing support in the form of subsidies for developing renewable resources through investments, along with creating legally enforceable, binding targets for reducing greenhouse gas emissions. Since then, Germany has successfully grown and expanded its renewable energy sector within the country’s electricity market, demonstrating the impact that eTective coordination of various forms of policies can have on overall market characteristics and the associated investment trends.

Research on sustainability transitions suggests that long-term policy consistency is essential for enabling systematic change and encouraging innovation (Geels, 2011). In addition, carbon pricing policies also illustrate how governance can influence system behaviour by increasing the cost of carbon-intensive activities and incentivising cleaner alternatives. For instance, Sweden’s carbon tax has led to significant emission reductions since its introduction in 1991, alongside continued economic growth (Andersson, 2019). This challenges the notion that decarbonization negatively affects economic performance and further demonstrates how the policy can be used to steer market behaviour towards environmentally friendly options. Another noteworthy case is the rapid decline in electricity generation from coal in the UK. The sharp decrease in coal’s share of the UK electricity generation has been largely due to a combination of carbon pricing, renewable energy growth and policy instruments aimed at phasing out coal.

The decline of coal-fired power generation shows how coordination efforts across multiple levels of government can accelerate energy structural transitions by making carbon-based fuels progressively less viable from an economic perspective. International agreements on climate change, especially the Paris Agreement, show how important it is for countries to act together to address climate change. While there is still an insufficient amount of implementation being done, the agreement has stated that the world's nations understand it is not enough to implement their own national policy to solve their country's climate problems (Falkner, 2016). From a systems theory perspective, countries cooperate to work together because the world is interconnected through environmental and economic systems. Despite this benefit from governance, there are many factors that impede good governance interventions, including political opposition, short electoral cycles, and competing economic interests. Some countries have continued to foster fossil fuel growth through government endorsement even when the government has made climate promises, thereby limiting the impact of policy reform.

Regardless of these constraints, governance continues to be one of the most effective levers that will create much of the context under which economic and technological systems and social systems function. As a result, effective policy offers the potential to shift the global energy system to a more equitable and sustainable future.

Technological innovation and positive tipping points

To accelerate the global shift to a low-carbon economy, technology represents a third main way to use existing systems (fossil fuels) for technological disruption and adoption of low-carbon alternatives. Technological changes act as positive feedback in the larger system when they produce self-reinforcing feedback loops that change the behaviour of that system (Meadows, 2008). As renewable technology becomes more affordable, more accessible, and increasingly used, it increasingly challenges the dominance of fossil fuels and provides the global energy system with a more convergent and sustainable future.

A clear example of how the technological learning effect works is seen in the dramatic reduction in costs associated with renewable energy technologies over the past twenty years. The International Renewable Energy Agency (IRENA) published research in 2023 that shows the cost of solar photovoltaic (PV) electricity has dropped significantly, based on three main factors: economies of scale, technological learning and global deployment of the technology. Similar trends have been observed with wind and battery storage technologies (IEA, 2023). These trends demonstrate a positive feedback loop where greater use leads to technological advancements and decreased costs, and therefore greater adoption of the technologies.

Nemet (2006) suggests that part of the reason that technological learning has played such a major role in accelerating energy transition is that, as industries grow, innovation becomes more efficient. The rapid development of electric vehicles (EVs) is an example of how technological advances can lead to changes across systems. As EV technology advances and the necessary infrastructure develops, consumers show increased adoption and higher confidence in purchasing EVs, which creates an ongoing cycle of increased investment in and innovation of EVs (Geels et al., 2017). Norway, as a good representative of this pattern, has created government incentives, provided financial support for developing necessary infrastructure and facilitated the adoption of EVs in the last few years. As a result, EVs now make up most new cars sold in Norway (Figenbaum, 2017). Norway's experience demonstrates that technological advances will have significantly greater results when they are supported by policy and social acceptance.

The interaction among technology, governance and consumer behaviour creates positive feedback loops on a systematic level in such a way as to accelerate broader systematic transformation. Technological innovation also has the potential to trigger what systems theorists describe as “positive tipping points,” where relatively small changes initiate rapid and large-scale transformation across an entire system. Otto et al. (2020) argue that once low-carbon technologies become economically and socially dominant, transitions can accelerate non-linearly as fossil fuel systems become increasingly uncompetitive. This can already be observed in global renewable energy markets, where declining costs have led to significant increases in renewable investment and deployment (IRENA, 2023). In this sense, technological innovation does not merely support transition but can fundamentally alter the trajectory of the global energy system itself.

The complete energy transition may be largely unachievable through technological innovation alone, but structural changes will be necessary. The research conducted on sustainability transitions supports this view by noting that, given the political, economic, and social systems that exist around much of the current technology, numerous systems of support exist to facilitate expansion, while others will act as impediments to this expansion (Geels, 2011). For example, without appropriate infrastructure to support renewable energy technologies, they will likely continue to suffer from the lack of support from government policies and from subsidies for fossil fuels.

Additionally, the continued large disparity in availability for technologies between the Global North and Global South also presents the possibility of reinforcing divergence between countries rather than allowing for the opportunity for them to converge. This clearly shows that for technological innovation to happen; it will need to be combined with broader institutional and societal change. While technological innovations are only one component of an energy transition, they will be of great significance as they will have the ability to simultaneously alter markets, consumer behaviour and energy systems. Technological innovations combined with supportive regulations and long-term investments can lead to the creation of a self-enforcing process that will help speed up the movement away from fossil fuels to a more sustainable and convergent global system.

Global equity and a just energy transition

Although technological innovation and policy reform are crucial for accelerating decarbonization, systems thinking demonstrates that the global energy transition cannot be deemed as successful unless it produces and perpetuates existing social and economic inequalities. The energy transition is happening in an extremely unequal global system, characterised by great discrepancies in wealth, historical emissions, and adaptive capability (IPCC, 2022). Therefore, the challenge lies not only in reducing carbon emissions but also in ensuring that the transition occurs in a way that is both socially and economically just. One of the biggest problems relating to climate governance is the uneven allocation of historical responsibility for emissions.

Developed countries, like the United States and several European nations, have taken advantage of fossil-fuel-based industrialisation throughout their histories, leading them to produce a greater share of global greenhouse gas (GHG) emissions than less developed nations (Meyer and Roser 2010). On the contrary, developing countries continue to depend on lower-cost fossil fuel resources to facilitate industrialisation and alleviate poverty. As a result of this, the current global energy transition creates a conflict between developing and developed countries by putting pressure on lower-income nations to decarbonise, despite having contributed much less than developed countries to the current climate crisis.

These inequalities reaffirm that from a systems perspective the world is becoming more divergent as a result of capitalist exploitation, including the advantages of economically developed nations regarding financial resources, technological capabilities and institutional capacity to make the transition to renewable sources of energy and at the expense of less developed nations that are experiencing significant energy access challenges (Newell & Mulvaney, 2013). Most Sub-Saharan African countries continue to face severe energy access challenges, even though their emissions are extremely low compared to other parts of the world (IEA, 2022). Therefore, the pathways to transition to renewable sources of energy will be experienced differently among different regions of the world. The concept of "Just Transition" was created as an important idea in climate policies.

Just Transition is concerned about ensuring that there is a fair distribution of the social and economic costs relating to de-carbonising polices and that special consideration is given to workers and communities that are dependent upon for fossil fuel industries (Heffron and McCauley, 2018). For context, the European Union's Just Transition Mechanism is an example of a tool used to support regions that rely heavily on coal and carbon-intensive industries to transition towards climate neutrality. International Cooperation between countries is critical in achieving a common goal of transitioning to cleaner energy sources around the world. Financing, transferring technology and providing funding for climate-related initiatives are all generally considered necessary for developing countries to achieve a low-carbon future (UNDP, 2022).

The Paris Agreement acknowledges that there is a variance in how much nations can contribute to efforts aimed at reducing their impact on climate change or contributing toward helping reduce impacts on climate change (Falkner, 2016). Critics believe the current structure of climate governance still reflects the priorities of wealthier countries and could continue to lead to differing levels of support across nations with a lower level of development (Ciplet, Robert & Khan, 2015). Ultimately, systems thinking demonstrates that the global energy transition is not solely an environmental or technological issue but also a question of justice and equity. Achieving convergence, therefore, requires restructuring global systems in ways that allow sustainability, equitable development and long-term environmental stability to coexist.

Author's perspective: rethinking the energy transition

From my perspective, a major barrier to the transition to renewable energy is the perception of climate change as a technical issue rather than a systemic one. Political and public views tend to focus mostly on finding replacements for fossil fuels (e.g., solar and wind). However, systems thinking tells us that fossil fuel dependence is an outcome of our political/economic system and social structures, not simply a technical issue. Until societies prioritise short-term growth and high consumption over long-term sustainable practices, meaningful change will be hard to accomplish. In my opinion, the persistence of fossil fuel dependence demonstrates that the current global system remains structurally divergent rather than convergent. Despite increasing climate awareness and technological progress, global energy consumption and carbon emissions continue to rise in many regions.

This suggests that technological innovation alone is, however, insufficient if wider systems continue to incentivise unsustainable production and consumption patterns. The transition, therefore, requires not only cleaner technologies but also a reconsideration of the assumptions that underpin modern economic systems and societal definitions of progress. The purpose of systems thinking is to provide a lens through which to see global challenges as most intertwined with other areas of our lives. In the case of energy systems, we can observe that energy systems are deeply related to systems of transportation, urban design, political institutions, and consumer behaviour; thus, isolated policies are usually unable to create transformational change.

Systems thinking provides an optimistic viewpoint through the concept of leverage points, whereby targeted interventions may create large-scale systemic change (Meadows, 2008). This is evidence with the recent rapid decline in renewable energy and growth in the volume of EVs. Systems will often experience rapid change when a reinforcing feedback loop begins favouring change over stability. Nonetheless, one of the primary obstacles for the future is ensuring that as we transition away from fossil fuels, the gap between developed and developing economic systems does not continue to grow.

While developed countries have a much greater ability (both financial and technological) to move toward less carbon-intensive power generation, many developing nations are still primarily reliant on fossil fuels for their economic growth and energy needs. If we do not develop an effective system of global cooperation and equity in the distribution of resources, we will only perpetuate the existing divergence between developed and developing economic systems and will do so without moving toward the hope of creating a fair global economy.

Ultimately, I believe the move away from fossil fuels is about more than just dealing with the environment; it is a way to see if we can change the way we do things so that sustainability, equity, and resiliency are built in. To be successful in this energy transition, we will need to make changes to current governance, economic policy, and society's values in addition to using new technology.

Conclusion

When applying systems thinking to analysing the worldwide move from fossil fuels, the fact that there is still a need for fossil fuels can't just be explained by politics or technology failures on their own, but rather, by many interconnected loops of feedback, institutions that are resistant to change, physical inertia of localities and long-held social and economic structures supporting the older energy system.

These factors also explain why the global energy systems have shown a great deal of divergence despite more awareness about climate change and commitment to reducing reliance on carbon-based fuels. At the same time, systems thinking also shows that there are many means through which we can leverage change from within even the most established systems. Policy, technology, finance, and international cooperation are all examples of interventions that, if done together and in a cohesive manner, can propel a system towards a more sustainable and converging future. For instance, the transformation of the energy system in Germany (called the Energiewende), the transition to electric vehicles in Norway, and the expansion of global renewable energy are three examples demonstrating that it is possible to create a system that favours low carbon through the positive feedback loops established to support those efforts.

Additionally, research shows that moving away from fossil fuels isn't just about environmental concerns or technology - it is an issue of justice and equity on a global level. Historical emissions responsibility and different capacities to adjust and adapt all require that the transition to cleaner energy will be achieved by addressing the broader structural inequalities related to climate change, in conjunction with the decarbonisation process. If this does not happen, the energy transition risks creating more divergence than convergence in the global system.

The shift from fossil fuels is part of a large-scale restructuring of the global systems toward sustainability, resilience and long-term equity. Systems thinking as a framework for understanding complexity emphasises the interconnectivity of our environmental, political, economic and social systems. The future of the energy transition will depend on progress in technology and progress in our ability as humans to radically rethink the systems and priorities that sustain our dependence on fossil fuels.

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