Position paper Systems Innovation Energy Hub

The permeating system of systems

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Preface

This positioning paper takes a stance on what we from the Si Energy Hub view as the context framing today's energy system; assess the current main challenges we are dealing with; review the current trends and transitions we believe are key to facilitate; and create a vision of a future energy system that we believe to be more just, sustainable, and prosperous to all other critical systems. The energy system permeates all systems and is therefore difficult to delimit. However, for the purposes of positioning ourselves, we demarcate the system as electricity generation and usage; energy used for space heating and industrial processes. We do not, however, exclude transportation, agriculture, forestry, society, climate, etc. But rather consider them as separate systems that energy has interdependencies with.

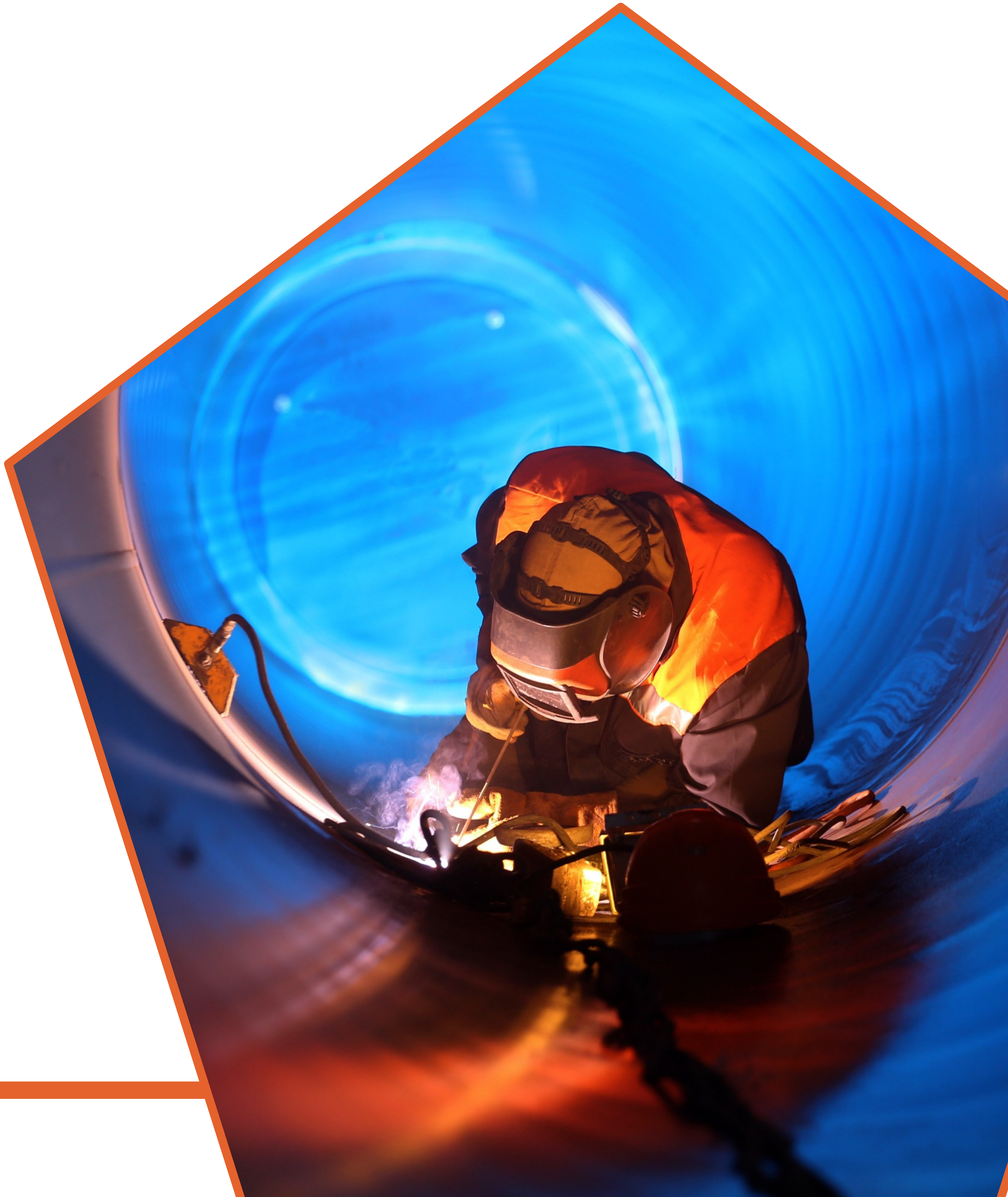
Energy Systems

Energy is the foundation of our economies, permeating every aspect of our lives such as food, transportation and communication. The energy system encompasses accessing, transferring, and converting energy from primary sources (biomass, geothermal, solar, wind, fossil fuels or other sources) into work (in the form of heat, light, sound and motion). It includes all the processes and all related components involved from the extraction of the energy resource to consumption.

The total amount of energy within the system is conserved due to the principle of energy conservation. However, certain primary resources are particularly valuable due to their higher energy density and versatility. During the transformation of these resources to perform the desired work, unintended dissipative processes occur, generating degraded forms of energy that are not efficiently used in our current energy system. The ratio between the energy used for the desired task and the resulting by-products is known as energy efficiency. Improvements to energy efficiency should be equally pursued on the system level as the component level.

Energy systems entail much more than transforming one energy form into another. They subsume natural resources, technological processes, economic and social institutions, and are central to economic progress. Societal development is linked to their energy systems, especially to energy abundance. Traditional energy systems limited premodern economies, but the industrial revolution changed this by using fossil fuels.

The industrial revolution is a direct consequence of a drastic change of the energy and technology availability to perform vital tasks in an automatised fashion.The associated sudden reduction of the relative energy cost led to a massive shift in the consumption made the energy more affordable and accessible. Consequently, the overall demand for the performance rose, leading to higher energy consumption. This so-called rebound effect is a consequence of changing technological components without including the interdependencies and feedback loops within the energy system.



Over the past two centuries, the development of an industrial-age energy architecture transformed demographics, economy, and society. Fossil fuels played a crucial role, requiring extensive processing and large-scale operations. The energy system, including the energy infrastructure, is perfectly designed to meet the needs of these large-scale, cost-efficient operations. The fossil fuel industry became capital-intensive and integrated into capital markets. These centralised and regulated industrial energy systems were often associated with monopolies or oligopolies, with significant social, economic, and stakeholder interests.

Industrial-age energy systems still dominate the global energy architecture, with fossil fuels comprising around 80% of the energy global mix, and 60% of electricity generation. However, various factors indicate a profound change in energy systems. Awareness of the environmental impacts of fossil fuels, rising costs of fossil fuels, rising demand from emerging markets, and the scaling of distributed technologies are driving this change. Combined with information technology and new regulatory frameworks, they are reshaping the energy industry.


Current context

Sustainability

The traditional approach of solely focusing on meeting energy needs (that are in fact being facilitated by the cost-efficient availability of energy) without considering the environmental externalities is not in-line with a sustainable energy system. It does not ensure the well-being of current and future generations by balancing economic, environmental, and social factors. The combustion of fossil fuels which took millions of years to capture energy from light now releases high concentrations of greenhouse gases, mainly CO_2, causing human-made climate change. Over the last ten years, the drastic need to mitigate climate change has motivated actors to reduce these emissions and minimise the detrimental effect rising temperatures have on ecosystems, communities, and economies, especially in third world countries.

Clean technologies play a pivotal role in allowing a transition to a sustainable energy system. These technologies, such as solar power, wind turbines, hydropower, and geothermal systems, help reduce greenhouse gas emissions, improve air quality, and mitigate the environmental risks associated with energy production and consumption. These technologies however often require semiconducting materials, which have to be extracted from natural resources. To create sustainable energy, sustainable practices across the entire energy systems, from for example sustainable mining to waste disposal, have to be implemented.

Energy Accessibility

Energy accessibility is an important aspect of the energy system, aligning with SDG7's objective of affordable and reliable energy for all. It involves addressing the energy needs for the many and creating equitable and inclusive energy systems. Achieving affordable and accessible energy for everyone requires macro-level changes that empower communities and enable their active involvement in energy decision-making.

Localising energy systems allows communities to use local resources, develop tailored sustainable solutions, and enhance energy security. Decentralising power is crucial in improving energy accessibility by transitioning from centralised to decentralised models. This shift empowers communities, creates energy resilience, generates local employment opportunities, and expands energy access in remote areas.

Energy Resilience

Following recent global events, the need for resilient energy systems has become widely apparent and on everyone's agenda. Resilience typically means to rebound after a disturbance; however, it can also be seen as an evolving process. Meaning that for each hit that the system takes, it adapts to tackle future disturbances better. This in turn allows the system to be secure over time, as the environment changes. This also means that the energy system must always be reliable, affordable to everyone and that long-term investments are pursued in time. A resilient energy system encircles more than only its technical components, it applies to the social, economic, and technological system which is energy.

Information Technologies & Technological Advancement

Information technology (IT) plays a catalytic role in transforming the energy system, facilitating sustainable practices in the energy production, distribution and consumption. Through smart data analytics and machine learning, information technology enables the collection and analysis of data from distributed energy sources, interdependently optimising energy generation, distribution, and consumption. This empowers us to align consumption patterns with variable energy resources. New technology enables peer-to-peer energy trading, grid management, and secure billing, fostering local energy generation and energy resilience. Real-time energy data and visualisations empower consumers to make informed decisions, implement energy-saving measures, and participate in demand response programs.

Shifting the focus from availability dictating consumption to the other way around. Furthermore, IT enables the development of innovative business models such as virtual power plants, revolutionising energy trading and demand response. These technological advancements disrupt the traditional top-down, centralised energy system, promoting distributed energy generation, consumer empowerment, and new market structures. The energy system is thereby transitioning towards a collaborative, dynamic, and sustainable paradigm.

Energy Market

Energy markets were developed more than 20 years ago to support the unbundling of foremost state-owned generation, grid and distribution entities. The design of these markets has been based on predominantly fossil fuel and nuclear-powered plants. With the heavily increasing integration of renewable generation (wind, solar, water, biomass) and the shift into a multifaceted decentralised generation landscape, the system of how to buy and sell energy needs to be adapted to the new circumstances to support a fast decarbonisation of the whole international energy system.

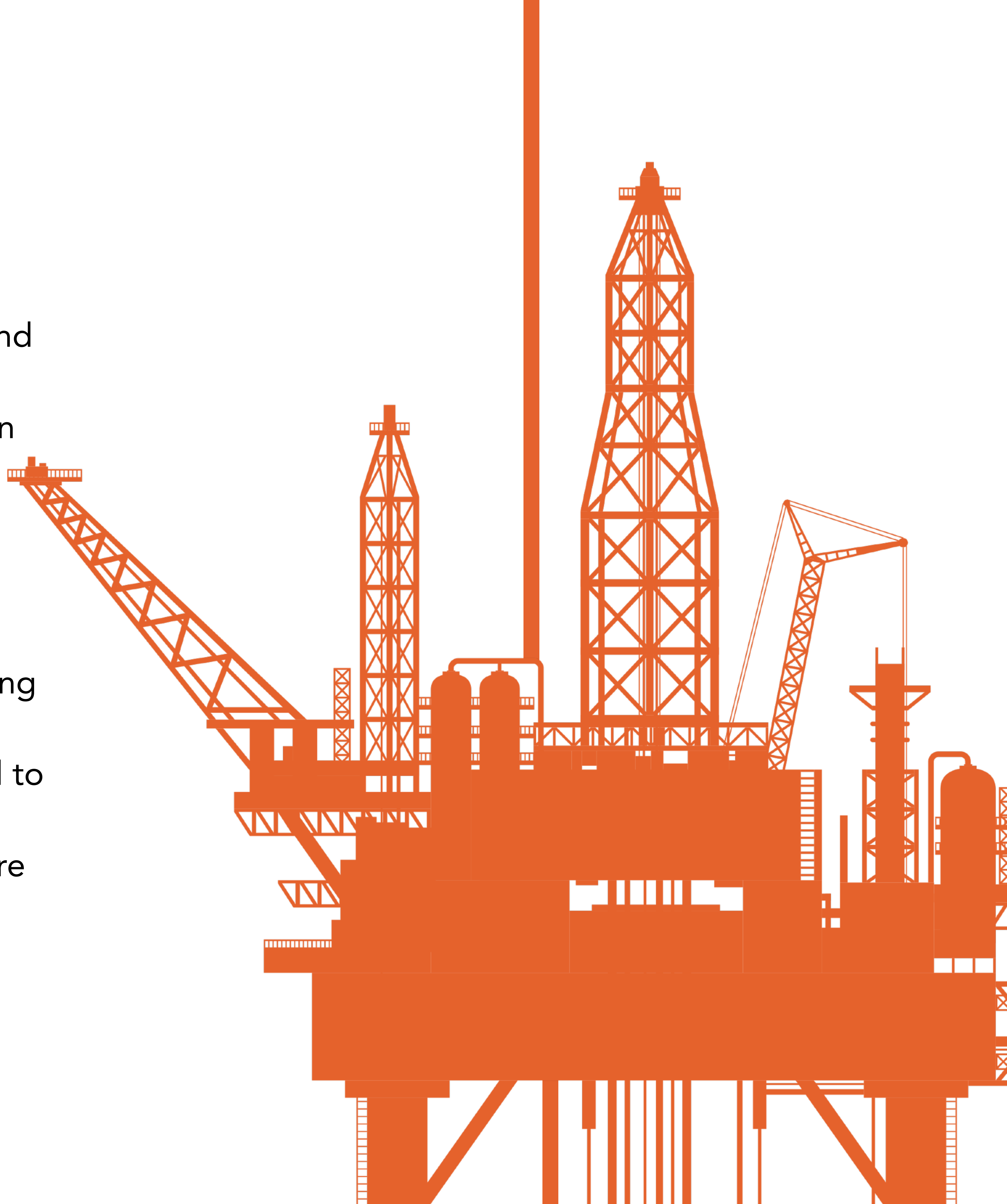
In addition to changing the market design of the energy markets, new environmental products will be added to the energy markets to manage the ecological value of renewable energy assets. These certificates need to be integrated with the international financial markets and need to be part of financial reporting systems to ensure that a triple bottom line is maintained. Continuous improvements in technology will also shape the design and operating model of the energy markets of the future. They will become more globally connected to be an integral part of the fight against carbon emissions and climate change.

Current Challenges

Decarbonisation

Awareness of the environmental impacts of fossil fuels has led to a significant shift towards renewable and carbon-free technologies, particularly in electricity generation through photovoltaic energy and wind power. However, decarbonisation of other energy sectors, particularly heat and mobility, still poses considerable challenges. In such cases, electrification becomes a viable strategy for reducing carbon emissions in these sectors.

Nonetheless, the process of decarbonisation often encounters obstacles due to carbon lock-in, which refers to the self-perpetuating inertia created by entrenched fossil fuel-based energy systems, hindering the adoption of alternative energy technologies. Related to the concept of technological lock-in, the concept is most used in relation to the challenge of altering the current energy infrastructure to respond to global climate change. Consequently, industries that prove difficult to decarbonise, such as the maritime and aviation sectors, are actively exploring sustainable fuel technologies like hydrogen and ammonia as potential solutions.



Integration of Renewables

While the costs of renewable energy technologies have been decreasing over time, the decentralised nature of renewables requires a large upfront investment and does not benefit from economies of scale to the same extent as fossil fuel. In addition, the intermittent nature of the energy sources necessitates the development and implementation of large and long-time energy storage systems. The integration of renewable energy sources into the existing grid, which has historically been designed to distribute energy from large, controllable, centralised power plants through a transmission grid to end users, poses numerous technological and regulatory challenges.

This is primarily due to the fundamental differences in design criteria for the grid between conventional power plants (large, centralised, controllable) and distributed energy resources (small, non-controllable, decentralised). Long-term integration of renewables necessitates the extension and updating of distribution systems, potentially resulting in grid overcapacity. However, these extensions do not necessarily solve emergent challenges associated with the increased penetration of renewables, such as grid stability, reliability, forecasting, predictability, load management, and flexibility. Solving the challenges related to the integration of renewables into the grid requires fundamentally different approaches than those employed for conventional power plants.

New Service Models

The transition from a commodity-based to a service-based energy system requires the alignment of interests of energy producers and consumers, overcoming stakeholder barriers, managing resistance from influential actors, and ensuring high-quality service provision. This transformative process involves redefining energy as a tailored service that caters to the specific needs and preferences of consumers.

Unlike delivering a physical product, the shift requires the constant delivery of advanced services with efficient treatment of energy. If the service is poorly designed, it can become costly for the energy provider rather than the consumer, unlike the current scenario. Effectively addressing resistance coming from the producers and managing the transition necessitates strategic communication, stakeholder engagement, and the development of robust service models to avoid actors hindering the ongoing transition due to conflicting interests.

Maintaining Resilience During Transitions

Resilience and transitions are two forces in direct opposition of one another. A resilient system is one which retains its current form and function, and the energy transition is imposing deliberate changes that affect energy systems' ability to maintain their function. However, to ensure long-term resilience, the system must adapt to changing circumstances and therefore be able to maintain its function whilst undergoing change.

Therefore, we need to manage the challenge of maintaining resilience now and in the future as the system becomes renewable, but variable. Simultaneously, the strategy for decarbonisation of other sectors such as mobility and industry, is realised through electrification. Thus, putting a larger strain on the electricity grid and reducing the overall redundancy of the energy system by not being able to revert back to other types of energies. As such, the overall energy system needs to account for how to retain this resilience as more and more systems rely solely on that of electricity.

Energy Accessibility for 8 Billion People

Energy is all around us, yet access to clean and reliable energy remains a key challenge around the globe. Securing the energy transition for all parts of the world becomes a challenge as demand for critical materials increases. Different countries have different geographical prerequisites for local production; varying political states that govern how international trade may unfold; and varying local capabilities and technologies.

Therefore, there is no one solution that can be implemented anywhere to solve all energy problems. However, ensuring that these solutions are implemented across the board is elementary to achieve a just and sustainable transition on a global scale. Shifting cooking and heating energy sources towards local and clean ones provides a tremendous opportunity for decarbonization.

Carbon Capture

Photosynthesis naturally captures carbon by converting CO_2 into organic matter using sunlight. Fossil fuels are derived from ancient plant and animal remains that stored carbon through photosynthesis over a period millions of years. However, our excessive use of fossil fuels has accelerated this carbon cycle, resulting in increased CO_2 emissions. To mitigate these impacts, carbon-capture methods have become vital.

Carbon capture reduces CO_2 emissions, mimics a natural accelerated carbon cycle and fosters a circular use of materials, and enables recycling and usage of captured CO_2 in industries such as enhanced oil recovery and other processes. By integrating carbon capture into material lifecycles, we can address emissions, promote resource recycling, and transition to a sustainable and efficient energy system.


Transitions

From Centralised to Decentralised

The transition from centralised to decentralised energy systems involves shifting to user-generated systems like (rooftop) solar panels, small-scale wind turbines, and utilising waste heat from local industrial parks. One way to distinguish between centralised and decentralised systems is by examining how energy is injected into the grid. In the case of electricity, decentralised resources refer to energy resources that directly connect energy into the distribution grid. These can include rooftop solar panels and small-scale wind turbines, among others.

Decentralisation enables individuals, communities, and businesses to be both energy producers and consumers, leveraging nearby industrial waste heat. These decentralised solutions can be tailored to local communities, considering social, environmental, and cultural factors, rather than solely prioritising economic optimisation. Localising energy resources and incorporating waste heat recovery allows communities to capitalise on unique energy generation opportunities, reducing reliance on distant power plants and promoting self-sufficiency. Concurrently, these smaller actors can leverage their position of higher agility and shorter lead times, to achieve more rapid change and adaptability.

Energy-as-a-Service

Energy-as-a-Service (EaaS) introduces novel business models and value propositions that are important for systems innovation in the energy sector. One key aspect is the shift from the traditional energy supply model to pay-for-performance models. Consumers pay for desired energy services or performance levels rather than the quantity of energy consumed, promoting energy efficiency and sustainability on both the consumer and the producer side.

Additionally, EaaS enables flexibility and scalability by accommodating diverse customer profiles and adapting to changing energy landscapes. It promotes collaboration among different stakeholders, including energy providers, technology developers, financiers, real estate owners and consumers. By fostering partnerships and knowledge sharing, EaaS drives innovation and accelerates the adoption of sustainable energy solutions.

From Static to Dynamic Systems

Energy in many parts of the developed world is seen as an abundant commodity. In recent times, power generation plants function by adjusting their rate of production to meet the fluctuations in demand. However, in a future of more variable energy production, the users of electricity will need to adjust their usage following fluctuations in how electricity is generated and available. This is today steered by corresponding prices which in turn steer users' inclination to consume. Smarter integration of home appliances allows them to automatically adjust their usage according to price. Our future energy system will need to be more adaptive and faster to evolve than the prior inert system. This becomes possible by leveraging the shorter lead times and acceptance of decentralised solutions.

Electricity consumption has been a historically stagnant metric since the advent of modern electricity, as improved efficiency has been met by growing demand. However, this historical trend is expected to turn for many nation-states, towards a rapid increase in electricity consumption. Meeting this growth of demand cannot, the system's current state, be met by expansions of grids and large-scale power generation as they are an immensely expensive and challenging feat, whereas incorporating smaller and smarter solutions have a lower activation barrier. Thus we need to do more than upscale the system of today for the demand of tomorrow, but we need to make the current system work better as a whole, to better suit the context of tomorrow. Transitioning to something new and being positive to change across all levels of the system.

Regenerative System

Turning the energy system from one which is destructive towards one that is regenerative. Idyllic as it may sound, the energy system houses the ability to produce more good than harm with the right regulatory mandates and economic incentives. Today, an abundance of energy is used for overconsumption and the production of goods and services at low prices. Simultaneously, an increasingly renewable energy system creates more times of abundance and equally, more times of scarcity. Therefore, the system needs to foremost accommodate for these fluctuations through energy storage; secondly, the system needs to use this capacity of overproduction for regenerative purposes such as carbon capture and storage (CCS) or desalination.

Using renewable energy for CCS as long as there are coal- and oil power plants, is ill advised as the renewable energy should rather be used to offset the need for coal and oil in the first place. However, in times of abundance, where societal needs are saturated, the case for using renewable energy for CCS becomes much more attractive. However, this would require the CCS facilities to become an integrative part of large scale renewable energy production such that this abundance can circumvent market forces and the rebound effect. This would form a truly additive carbon offset which can be sold as certificates or turn renewable energy sources' CO_2e footprint into the negatives.

Outlook

Future Energy Systems

Combined, these transitions provide us with several avenues to design and envision more sustainable and prosperous energy systems. However, getting there is no easy feat and will constitute a transition on its own. Laid out hereinafter, is the accumulation of the overarching trends shaping the energy system along with the transitions that we view as critical to fuel a sustainable energy transition. Together, they come to describe an energy system that is clean, accessible, and reliable in the many years to come, for the many people. Without proponing any particular energy source, we advocate for the right technology in the right place and a generally diverse energy mix. We emphasise the need for a systems thinking approach to these challenges that consider the interdependencies of components and long-term feedback loops that need to shape policies going forward. A future sustainable society requires us to design it such that its components are laid out to reduce excessive transportation and transmission losses. Rather than claiming the right to offset emissions by purchasing certificates of renewable energy production on the other side of the world, we need more granular energy certificates that can take us from net-zero, towards gross-zero.

Businesses in this system, especially energy and utility companies, need to be purpose-driven rather than profit-driven. Incentives should lie in conserving primary energy, reducing waste heat where possible, and improving efficiency throughout all facets of society. These changes must be vertically integrated, such that stakeholders on all levels benefit from decreased energy consumption. Through this, we can continue to achieve societal prosperity without continuously increasing our consumption. Our support systems that today maintain the hair-thin balance of maintaining a functional electricity system, need to be turned to more regenerative purposes such as storage and CCS rather than fueling industrial processes.

Just as how the industrial revolution was fueled by coal and the steam engine, further advances in how we generate and manage our energy can significantly transform the future of society. We acknowledge that future energy security needs to be ensured against hazardous weather events and trends; sabotage and weaponization; fluctuation in generation and consumption. Challenges that can be met through anticipation and preparation. Further than that we may envision better scenarios, but they are only ideas until we can collaborate together on a better future. We will leave this chapter to let you decide, how we might envision our future, start thinking beyond and share your ideas with the world through systems innovation.

"The energy equation today is not working if we want to meet our goals in terms of dealing with climate change and sustainable development. We are going to have to rethink the energy system"

- Scott Foster, UNECE

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