New Frontiers:
Emerging Sustainable Technologies of the Next Decade

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INTRODUCTION

NEW FRONTIERS: EMERGING SUSTAINABLE TECHNOLOGIES OF THE NEXT DECADE

New technologies are emerging that improve sustainability – some in response to climate concerns, others as a result of unrelated lines of research or consumer trends.

Energy technologies are particularly important of course, from advanced solar cells and high-capacity batteries to hydrogen and nuclear fusion. Artificial intelligence and automation bring a wealth of possibilities, particularly for improved energy efficiency. Other novel sustainable systems cover remote sensing, food supply and transport.

What impacts could these technologies have? What is required to bring them to full-scale viability? And how should they be embedded in a wider system of sustainability?

Sustainability Report

This research paper is part of a 12-month series published by The Al-Attiyah Foundation every year. Each in-depth research paper focuses on a prevalent sustainable development topic that is of interest to The Foundation's members and partners. The 12 technical papers are distributed to members, partners, and universities, as well as made available online to all Foundation members.

EXECUTIVE SUMMARY

- Increasing concern over climate change, other environmental problems, and energy poverty has created increasing pressure for research and deployment of new sustainable technology across energy production, logistics and use.
- Adoption of new technologies is essential to achievement of the climate change mitigation pathways set by the Intergovernmental Panel on Climate Change's (IPCC) and the UN Sustainable Development Goals enshrined in the 2030 Agenda for Sustainable Development.
- In the energy sector, emerging technologies can meet demand with lower energy use. These include already quite mature technologies like renewable energies, electric vehicles, and hybrid technology, and in the near future, emerging ones like advanced biofuels, perovskite photovoltaics, and hydrogen transport.
- Broader sectors like mobility, AI, automation, 3D printing, remote sensing, biotech, and geoengineering are crucial to developing transformational energy innovations.
- Emerging technologies are fluid. In developing countries, they can adapt to support the development of energy and energy access systems for the poor, while in developed markets, they can encourage the creation of environmental monitoring systems and new products and services to support the energy transition.
- Emerging sustainable technologies are not simply pieces of equipment or code. They have to be embedded in business models, markets, regulatory frameworks, and social systems in order to be effective.

WHY NEW SUSTAINABLE TECHNOLOGIES ARE EMERGING

Technological change brought on by new sustainable technologies, or emerging technologies, or emerging green technologies (EGTs) is relevant for both developed and developing countries. An emerging technology is any technology that has already reached a certain technological maturity, but still has a comparatively low market share in the world or is still in a comparatively early stage of technological maturity[i] - but ready for deployment at the pilot or demonstration scale.

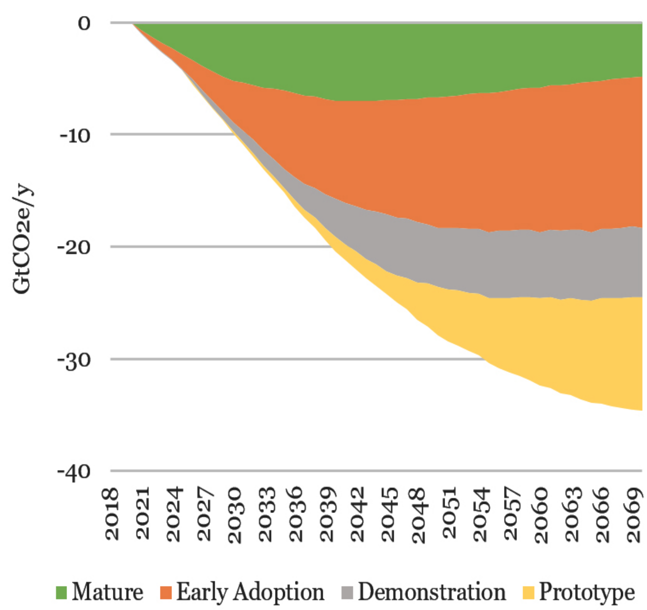
Growing interest in EGTs arises from a confluence of four factors:

- Ever-growing attention on the need to slow climate change and adapt to its impacts, leading to tightening national and corporate policies;
- Efforts to widen energy access and decrease energy poverty and insecurity, both in developing and developed countries;
- Improving performance of deployed green technologies, raising interest in new innovations and creating novel follow-on opportunities;
- Creation of new EGT possibilities by advances in wider fields of innovation, such as AI and biotech.

Rates of progress towards energy access, increased efficiency, decarbonisation, fuel diversity and lower pollutant emissions since the 2015 Paris Agreement and the UN's 2015 Sustainable Development Goals are still considered far from what is required to achieve the stated objectives of these two international treaties.

New technologies will therefore play a decisive role in fulfilling countries' nationally determined contributions (NDCs) while at the same time facilitating the decoupling of economic growth, energy demand, and environmental effects. Adoption of new technologies can contribute to the faster achievement of the climate change mitigation pathways set by the Intergovernmental Panel on Climate Change's (IPCC) and the 2030 Agenda for Sustainable Development, through several mechanisms. These include faster and wider deployment of novel solutions to economic, social, and environmental obstacles that operate as binding constraints on development; supporting more inclusive forms of participation in social and economic life; replacing environmentally costly modes of production with more sustainable ones; and giving policymakers powerful tools to design and plan development interventions.

Figure 1 Readiness of technologies to meet the IEA's Sustainable Development Scenario[ii]



Emerging technologies are fluid. In developing countries, they can adapt to support the development of energy and energy access systems for the poor, while in developed markets, they can encourage the creation of environmental monitoring systems and new

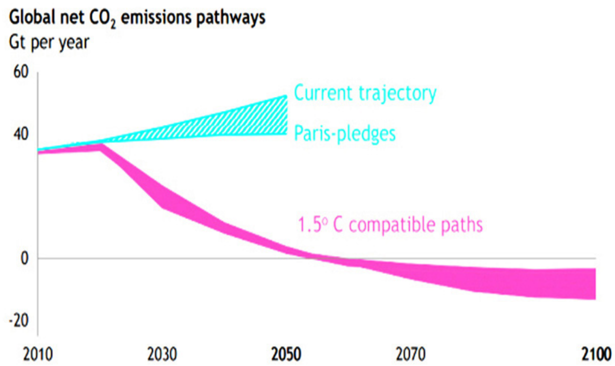
products and services to support the energy transition. They can also help in closing the science, technology, and innovation (STI) gap between developed and developing markets, meeting the transformative promise of "leave no one behind", which is the hallmark of the 2030 Agenda for Sustainable Development and its Sustainable Development Goals.

Developed countries are often characterised by large, well-established energy systems and infrastructure, mostly developed on traditional hydrocarbons, which can be challenging to adapt to new sustainable technologies without extensive retrofitting and overhaul. These changes also could have damaging socio-political consequences. Developing countries, especially least developed countries (LDCs) often have very limited access to energy and energy systems. Developed markets, therefore, may be able to assist these countries in embarking on their sustainable development by bypassing traditional, more-polluting forms of energy through modern, emerging sustainable technologies for energy security. Hence, EGTs offer unique opportunities for closer collaboration between developed and developing countries, in pursuit of the needed transition of the global energy system.

AREAS OF NEW TECHNOLOGICAL ADVANCE

Advancements in the digital sphere, like Artificial Intelligence (AI), Big Data, remote sensing, robotics, and Internet-enabled tech, has resulted in applications that can enable higher efficiency and decarbonisation across the entire energy value chain. They can also create, measure, develop and monitor the effectiveness of development programmes and progress towards climate and sustainability goals.

Figure 2 Global CO_2 emissions pathways[iii]



Emerging technologies in renewable energy could target higher efficiency or improved reliability or wider availability at a fraction of the cost of current approaches. These include advanced solar and wind, new renewables (such as tidal energy, wave energy, and ocean thermal), advanced batteries to support renewable energy, and superconductors. Research into nuclear fusion is also growing, but it remains technologically enormously challenging[iv], which reduces its likelihood to contribute effectively to the energy transition in the near-term.

Table 1 Key Emerging Technologies of the Decade

Technology	Impacts	Maturity
Advanced batteries	• Supporting deployment of renewable energy • Supporting power demand of electric vehicles	Early commercial
Electric ground vehicles	• Decarbonises road transport • Increased power demand	Early commercial
3D printing	• Improved fabrication of renewable energy systems • Lowers energy use in manufacturing • Improved maintenance for energy installations	Early commercial
Artificial Intelligence, Automation, Internet of Things (IoT) & Big Data	• More efficient energy use, e.g. 'smart homes' • Demand management for renewable energy integration • Better design and operations of mining operations	Early commercial
Cloud computing	• Efficient resource appraisal • Faster and intelligent decision making	Early commercial
Engineered geothermal	• Low-cost, near-zero carbon dispatchable power and heat, available in most locations	Early commercial
Advanced nuclear fission power	• Dispatchable near-zero carbon power to lower gas and coal demand	Demonstration
Low-cost carbon capture, use, and storage (CCUS)	• Lowers CO2 emissions • Supports production of low-carbon hydrogen and ammonia	Demonstration
Direct air capture (DAC)	• Reduction of atmospheric CO2 • Sustainable provision of CO2 for industrial uses	Demonstration
Self-driving vehicles	• Increased travel, increasing energy demand • Potentially higher efficiency and lower congestion • Synergies with electric vehicles	Pilot
Block chain	• Peer-to-peer renewable energy trading	Pilot
Optimised Biotech	• AI for the manufacture of biofuels and synthetic fuels for ground, marine, and air transport	Pilot
Electric aviation	• Zero-carbon short-range air travel	Pilot
Hydrogen aviation	• Zero-carbon air travel	R&D
Nuclear fusion	• High-power zero-carbon energy	R&D

Some examples of important EGTs are:

- Vehicular automation, that involves the use of mechatronics, AI, and multi-agent systems that can navigate road transport and scope energy-resource rich fields without the need of an operator;
- Autonomous mining systems that can enable more efficient extraction of minerals, critical materials, and rare earth elements (REEs) to support the manufacture and deployment of clean energy systems (such as panels for solar photovoltaic, and electrolysers for zero-carbon hydrogen);
- AI for more optimised agriculture and biotech, with parallels for the manufacture of biofuels and synthetic fuels for ground, marine, and air transport;
- Cloud and high-performance computing for more efficient resource appraisal;
- Additive manufacturing ('3D printing') to cut material waste, lower logistics and maintenance expenses, and produce more efficient or, in some cases, completely novel energy system components;
- Predictive maintenance.

Other emerging technologies address energy supply through low-cost, higher-efficiency, low- or zero-carbon sources. These include carbon capture, use, and storage (CCUS), hydrogen for power and industry, ammonia for transportation and heavy industry, battery storage systems to support renewable variability and power demand in electric vehicles, and other renewables, including geothermal and ocean energy.

These technologies can support the energy transition in a variety of ways, such as facilitating greater integration of clean energy into power systems, grid flexibility, faster and intelligent decision making to optimise operating and capital costs for energy systems, refined system operations, and implementation of new market designs for more sustainable energy systems.

EGTS: TWO CASE STUDIES

The two case studies presented below, relate to emerging technologies that can increase the deployment rates of low-carbon sources of energy, particularly in end-use sectors like transport, industry, and residential and commercial buildings. They are advanced CCUS (with direct air capture (DAC)), and hydrogen. DAC has the advantage of contributing to a circular form of emissions by leveraging fossil fuel-fired power generation sources in favour of renewables, while hydrogen (in both blue and green forms), will play an essential role in decarbonisation of heavy industry and long-distance transport.

Advanced CCUS and Direct Air Capture (DAC)

How does DAC work?

DAC tackles legacy and ongoing/residual emissions by removing CO2 directly from the atmosphere. Although relatively expensive, it will be required in many 'overshooting' trajectories of emissions to achieve 1.5°/2°c goals. It may also be cheaper than directly decarbonising the most difficult remaining sectors. On its own, DAC could assist in meeting CO2 removal goals by becoming part of a larger portfolio of decarbonisation efforts.

Solid sorbent systems, which require significantly less heat than liquid solvent systems (80°c, compared to 900°c), can utilise heat generated from waste (another sustainable technology) to release captured CO2 into permanent storage, or for use in various products and applications. Both systems can be powered by renewable energy, or, as in the case of the solid sorbent system, by recovering waste heat, significantly reducing lifecycle emissions. The main technological challenges are to scale up DAC and reduce its costs via manufacturing-type processes.

Where is it being established?

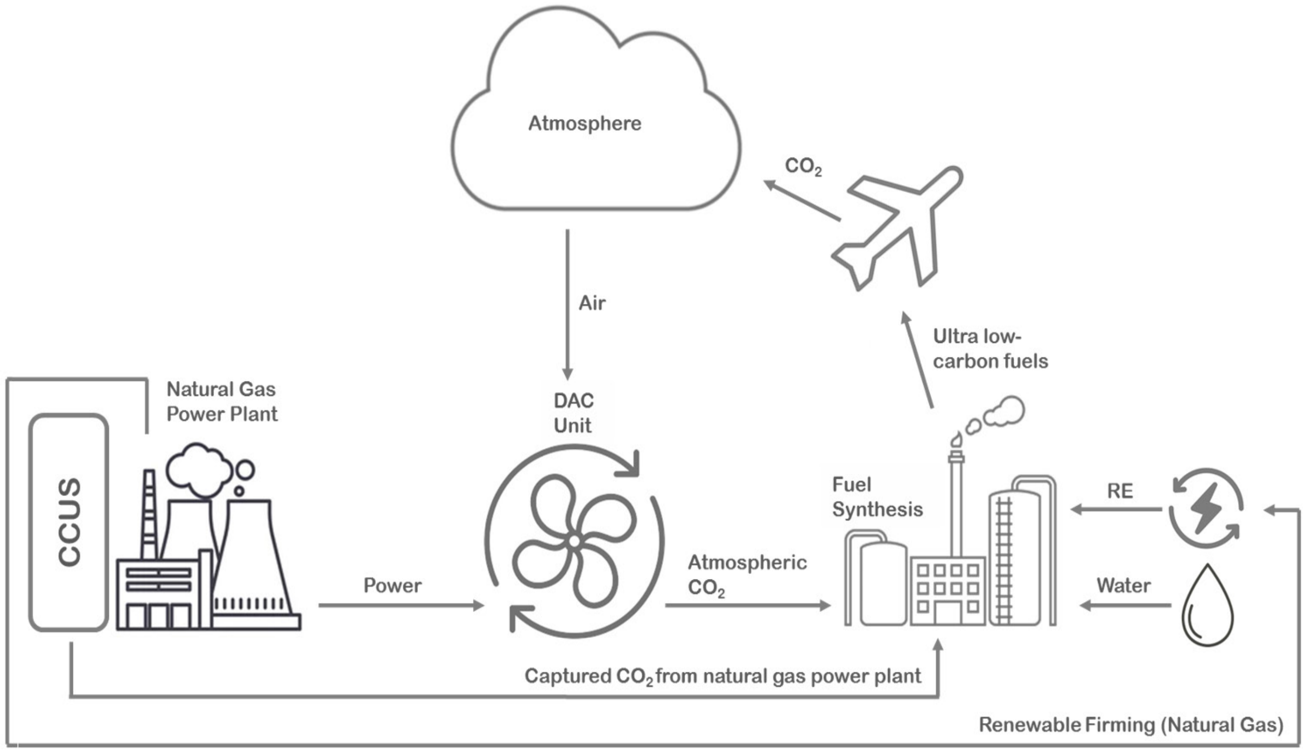
In north-east Scotland, Europe is establishing its first large-scale CO2 DAC facility which will help remove between 0.5-1 Mtpa of CO2 from the atmosphere to help achieve the net-zero emissions target of 2050. Captured CO2 will be stored deep below the seabed in Scotland's extensive offshore storage sites. In Iceland, the Orca project recently began capturing 3000 tonnes/year of CO2 and storing it in basalt where it is expected to react to form solid minerals. However, storage is not always feasible, requiring alternate offtake arrangements. In countries with oil and gas resources, captured CO2 could be used for enhanced oil recovery (EOR) to boost hydrocarbon export security, although lifecycle emissions would not decrease substantially due to the utilisation of that oil and gas elsewhere. Using the CO2 in construction material and plastics can provide a long-term storage solution spanning decades, or even centuries, especially if such products are biodegradable.

How can it contribute to a circular system of emissions?

From an energy supply perspective, there is an opportunity to power DAC through leveraging natural gas power plants that would otherwise be retired before the end of their lifetimes in favour of renewable energy sources. This strategy would involve converting some portion of the natural gas fleet into combined heat and power plants coupled with CCUS to power DAC. This arrangement could provide power to the grid during times of peak demand when renewable intermittency and variability limit renewable generation, and during non-peak hours, when excess renewable energy is produced, that renewable energy could power DAC.

Then, the captured CO2 through DAC could be processed into synthetic crude, which can be turned into petrol, diesel, and jet fuel for sectors where electrification remains a challenge, such as marine and air travel. This process adds little to no new emissions to the atmosphere, compared to traditional fuels. The fuels release the captured CO2 when they're burned, returning levels to where they were, or, if the CO2 is recaptured, result in a circular system of emissions. With this strategy, DAC could not only make use of surplus renewable electricity but contribute to a circular system of emissions.

Figure 3 Illustration depicting how direct air capture can leverage natural gas power in favour of renewables and support the creation of synthetic crude[v]



Hydrogen

How can hydrogen support the energy transition?

As the future use of oil and gas will be constrained by climate limits, fossil fuels need to embark on smart decarbonisation solutions that can help secure their role in the future. Blue hydrogen, which can be produced from natural gas in combination with CCUS, is one such solution, and one that has gained significant traction in the Middle East hydrocarbon producing countries recently.

To align with decarbonisation targets and measures such as an EU carbon border tariff, hydrogen can be used to produce derivatives (such as steel and ammonia) which can be exported. These materials would be easier to transport globally than native hydrogen. Another approach would be to export a fuel such as liquefied petroleum gas (LPG) or ammonia, which would be reformed into hydrogen in the destination market or used as blend stock, then receive back a shipment of CO2 for storage.

Green hydrogen can be the final pathway to a net-zero portfolio

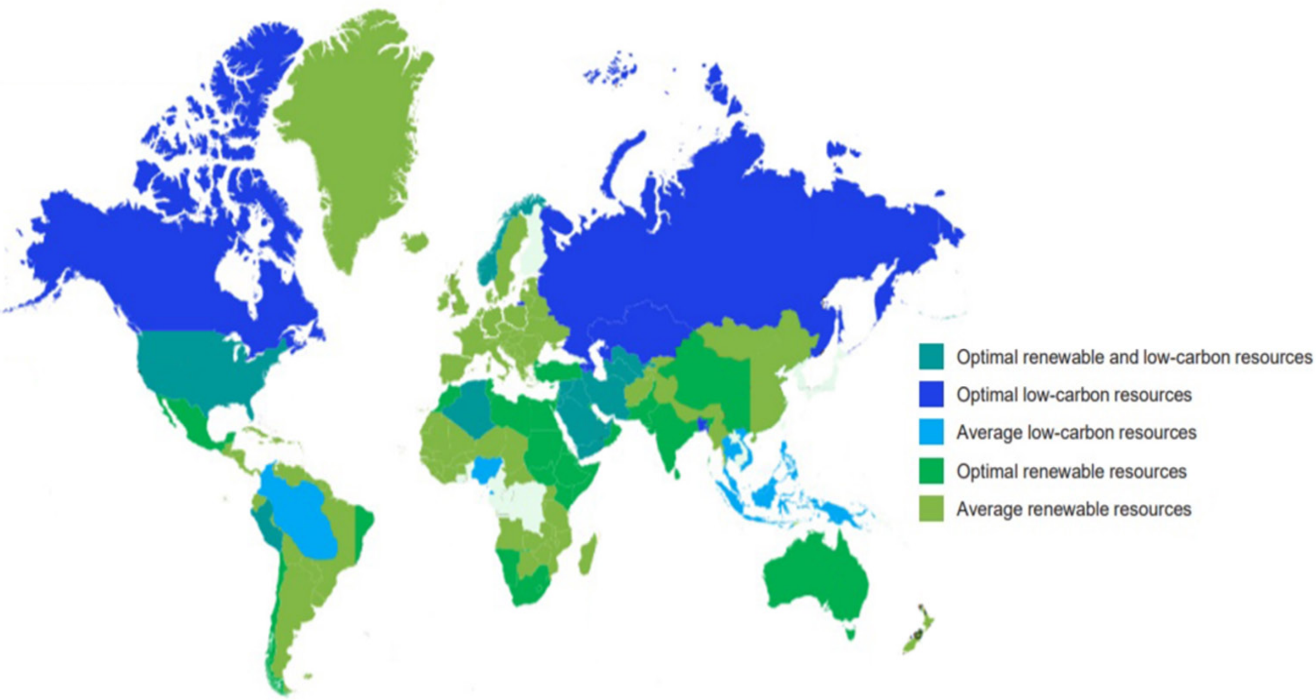
Green hydrogen can be the final pathway to a net-zero portfolio for hydrocarbon producing countries that are also endowed with renewable sources. In areas with ample solar and wind power, electrolysers can be powered with zero-carbon energy to produce green hydrogen. Currently, green hydrogen is still expensive compared to grey and blue. The cost of hydrogen from electrolysis depends on the technology used and its efficiency, its costs (primarily capital, with operating costs less important), the cost of input electricity, the lifetime of the electrolyser, and its load factor (how much is used relative to maximum capacity).

How will it become cost-competitive?

To become cost-competitive, low-carbon electrolytic hydrogen needs to be produced from renewables and/or other clean energy with high availability and low costs, possibly a combination of solar PV, off-peak nuclear, concentrated solar thermal power (CSP) and batteries. The Middle East, US, Australia, and certain parts of South America are best suited to take advantage of their favourable renewable resources to become leading producers of green hydrogen. Until green hydrogen becomes economically viable, these countries, which are also significant producers of hydrocarbons, can utilise their fossil fuel wealth to produce blue hydrogen, by integrating it with CCUS systems.

Key technological needs for blue hydrogen are low-cost capture with high capture rates (95%+). Autothermal reformers look more likely to achieve this than the commoner steam methane reformers. For green hydrogen, key technological needs are reducing electrolyser costs by scaling up and streamlining manufacturing and reducing the need for precious metal inputs. Solid oxide electrolysers are currently expensive and require high temperatures but have a promising technological path to reduce costs, improve efficiency and make use of waste heat.

Figure 4 Illustration depicting geographies with favourable blue hydrogen and green hydrogen production conditions[vi]



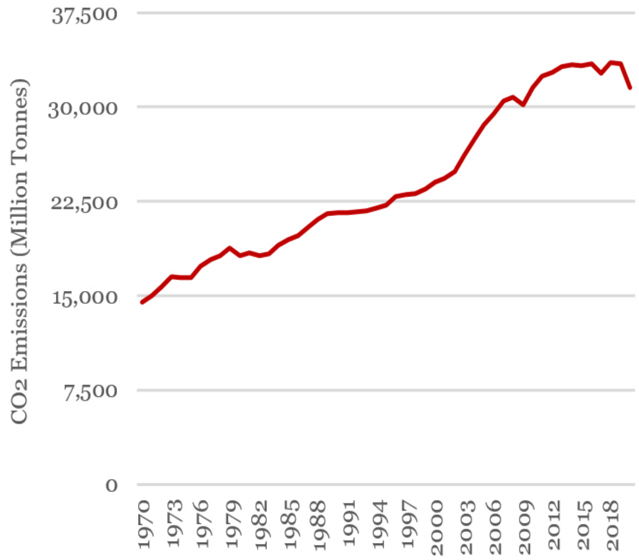
EGTS CAN ACCELERATE ACTION ON THE IPCC'S GHG EMISSIONS PATHWAYS

Emerging technologies are potentially the world's most powerful influencer to accelerate action on the Intergovernmental Panel on Climate Change's (IPCC) GHG emissions pathways limiting global warming to 2°c/1.5°c. Increased efficiency via sustainable technologies can play a central role not only in tackling climate change and assisting world governments achieve emission mitigation targets as outlined under their NDCs, but also crucial sustainable development goals.

Efficiency as a result of technology advances has helped constrain recent growth in emissions. The benefit of internet-enabled tech was most pronounced during the height of the coronavirus pandemic in 2020, when remote work applications, teleconferencing, and remote sensing replaced traditional mobile-based activities, particularly road transportation/commute for work and education, air travel for business and leisure, and workforces at energy, construction, manufacturing, and industrial sites.

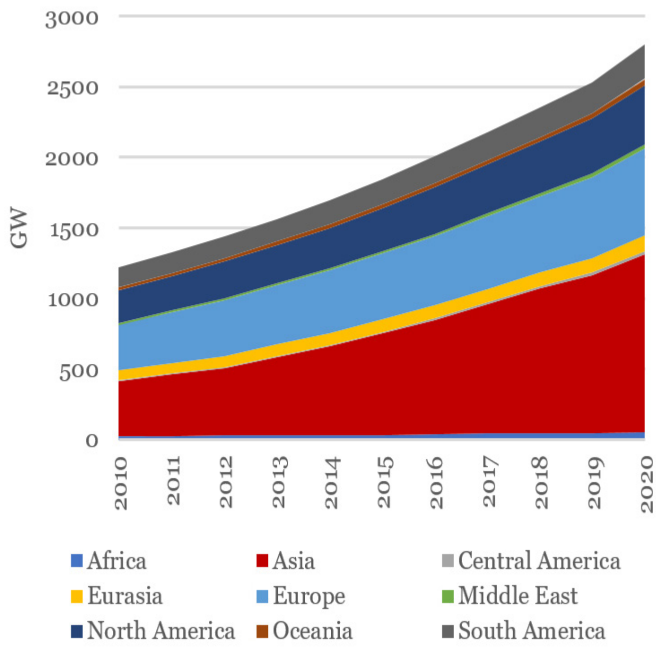
While fossil fuel consumption fell by record amounts for most of the year, renewables and electric vehicles, meanwhile, two of the main building blocks of the energy transition, remained largely immune to the effects of the pandemic[vii]. In the case of electric vehicles, this was mainly due to policy support in the EU and stimulus measures in China, encouraging adoption of technologies to support the transition.

Figure 5 Drop in CO_2 emissions in 2020[viii]



Renewable electricity was the main gainer, especially in Asian and African geographies. Countries whose economic activity and mobility was hardest hit as a result of the pandemic, particularly China and the US, completed a record amount of renewable energy capacity in 2020, on the back of policy support, resulting in higher renewable energy generation in early 2021.

Figure 6 Renewable energy capacity growth, 2010-2020[ix]



EGTS OFFER DISTINCT ADVANTAGES BUT FACE MANY CHALLENGES

Key emerging technologies can trigger revolutionary innovation leaps beyond the confines of individual economic sectors, but to do so requires raw materials and technological devices to guarantee competitiveness. Batteries, high-power motors, capacitors, electrolytes, circuits, transistors, and semiconductors (all used in the manufacturing of modern technologies and technological products) require critical minerals and metals. Apart from raw material needs, emerging technologies also need to be backed by improved developments in material science concerning their manufacture, with issues such as tensile strength, heat resistance or conduction, strength to weight ratios, rigidity, etc. being key to modern R&D. The recent post-pandemic unlocking has strained supply chains, at least temporarily halted progress in falling renewable energy costs, and given a foretaste of the challenge of supplying sufficient raw materials and intermediate components for the mass deployment of systems such as electric vehicles.

Table 2 Key emerging technologies in the renewable and clean energy space

Technology	How does it work?	Sectors best suited for	Advantages over conventional technology	Key materials needed for technology	Countries leading R&D	Maturity
Perovskite Solar Cells	Perovskite is combined with bifacial crystalline silicon solar cells[x] to enable higher power conversion efficiency as one cell is optimised for high energy photons, and the other for low energy particles. Solar cells can thus better capture light on their front and rear sides by responding to the variability of incident light	Rooftop solar PV panels; low-power wireless IoT applications; specialised solar solutions (solar blinds)	Predicted efficiency of 35% in 3-5 years, surpassing efficiency of monofacial silicon solar cells and conventional bifacials; More efficient and uniform solar generation; Perovskite-silicon cells are same shape and size as silicon cells and can easily slot into panels for solar farms and rooftop arrays	Perovskite materials, such as methylammonium lead halides and all-inorganic caesium lead halide; Cheap to produce and simple to manufacture	China, US, South Korea, UK, Poland, Switzerland, Netherlands	Pilot

Wind Kites	Wind kite turbines are operated in periodic pumping cycles, alternating between reel-out and reel-in of the kite tether to create a high traction force which is converted into electricity, providing a basis for a highly mobile wind energy system[xi]	High-efficiency wind power generation, particularly in deep-water offshore deployment	Minimises structural forces of conventional wind turbines; Super light weight; Removes need for bending-resistant foundations; Accesses altitudes far beyond the limit of conventional wind turbines (200 m); Wind is stronger and steady at these altitudes, which increases capacity factors of wind kites to 60% (conventional wind turbines are 20-35%)	Carbon fibre	US, Italy, Germany[xii]	Pilot
Lithium-Air Battery	A lithium-air (Li-air) battery uses oxidation of lithium at the anode and reduction of oxygen at the cathode to induce a current flow, theoretically leading to electromechanical cells with the highest possible specific energy	Automotive industry, particularly electric vehicles; electrification of heavy vehicles; efficient energy storage applications	Estimated to hold up to 5x more energy than conventional li-ions	Hybrid electrolyte – ionic liquid and dimethyl sulfoxide		Pilot

Non Li-ion Batteries	Rechargeable batteries based on alternative metal elements (Na, K, Mg, Ca, Zn, Al, etc.) that can provide relatively high power and energy density using abundant, low-cost materials[xiii]	Energy storage applications	Zinc-ion batteries are currently the only non-lithium technology that can adopt Li-ion's manufacturing process to make an attractive solution for RE storage [xiv]; Do not require formation cycling enabling supply chain security; Safe due to use of water as electrolyte			Early Commercial
Nuclear Fusion	Fuel plasma nuclei are heated to collide and create fusion at high temperatures, either through inertial confinement or magnetic confinement	Zero-carbon, inexhaustible power generation	Long-term, sustainable, economic and safe energy source for electricity generation; Doesn't generate long-lived unstable nuclei unlike nuclear fission	Hydrogen-deuterium-tritium fuel mix; Deuterium can be easily extracted from ordinary water, but tritium does not exist in nature and decays radioactively	EU, North America, Japan, Russia, China, South Korea	Early commercial

OTHER AREAS OF EMERGING SUSTAINABLE TECHNOLOGIES

Emerging sustainable technologies are not limited to applications in the energy sector. Conversely, advances in broader technologies can be found to have energy-related applications. The transition to a low-carbon future requires technical and progressive innovations in sectors that share cross-cutting themes with energy.

Sectors like mobility, AI, automation, 3D printing, remote sensing, biotech, and geoengineering are all examples of sectors developing technological innovations to support the energy transformation. Table 5 summarises such key emerging technologies. It can be seen that several of them are cross sectors, for instance the synergies of AI and remote sensing, automation and EVs.

Table 3 Other areas of emerging sustainable technologies

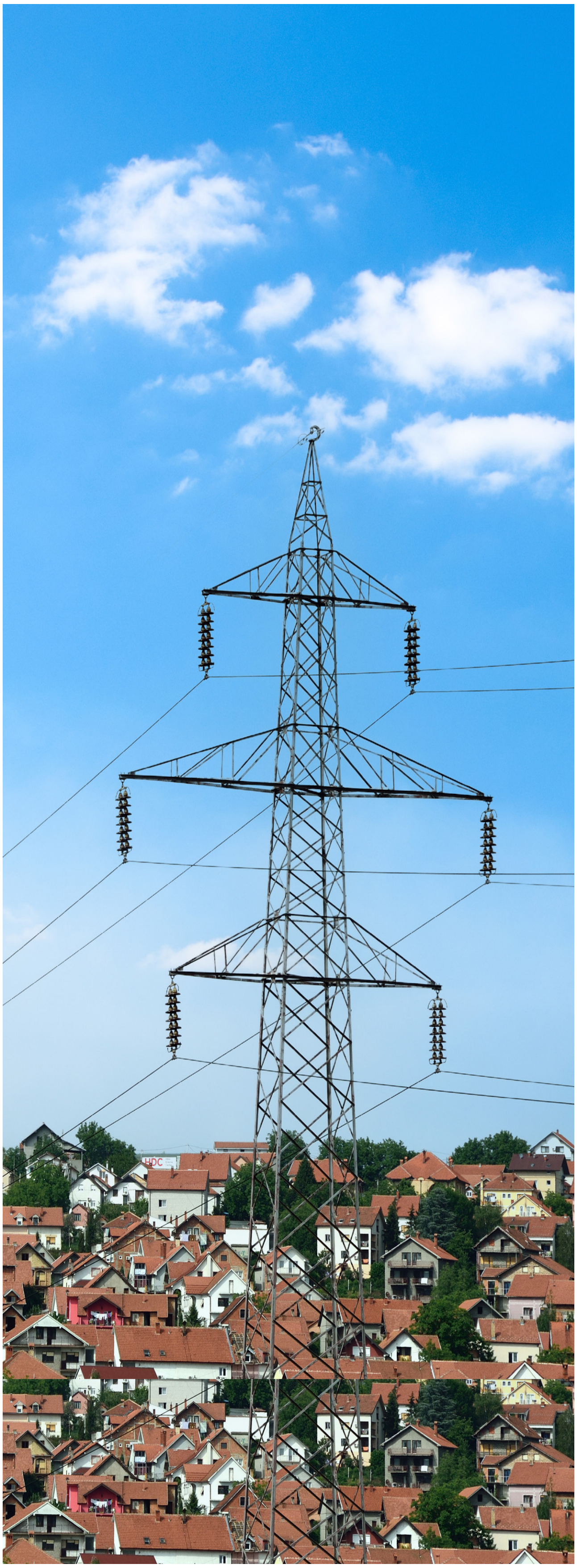
Sector		Emerging Technologies
Mobility	Electric Vehicles	• Bidirectional charging allowing energy to flow from grid to EV, and from EV to the grid or to homes[xv] • Autonomous vehicles that can find a charging point
	Hydrogen Vehicles	• Hydrogen fuel cell cars • Hydrogen fuel for air mobility • Fuel-cell heavy duty transport
	Super-fast Travel	• Hyperloop[ii] (ultra-high-speed ground transport) powered by solar panels placed on the top of travel tubes
	New ICE	• Homogeneous charge compression ignition (HCCI)[xv] • Pre-mix charge compression ignition (PCCI)[xv] • Reactivity-controlled compression ignition (RCCI)[xv]
	Advanced Aviation, Missile & Weapons	• Hypersonic (military and passenger aircraft, missiles, rockets, and spacecraft that can reach speeds through the atmosphere faster than Mach 5)
	Autonomous Mining	• Autonomous drilling, charging, blasting, loading and trucking • Undersea autonomous mining • Remote mining
Automation	Recycling	• Quick learning to identify and separate materials at super-human speeds • Infrared lasers for sorting plastics • Pyrolysis
	IoT	• Internet-enabled devices (smart EV charging, smart homes, smart meters, smart cities, smart grids) • Internet-enabled sensors and actuators
	Climate Modelling	• Open data labs • Next generation modelling • Data Cloud and Application Programming Interfaces • Extreme weather attribution • Long-range and small-scale forecasting for adaptation and for renewable output prediction
	Additive Manufacturing	• 3D Printing • Microfabrication
Remote Sensing	GHG detection & Pollution	• Satellite and drone detection for methane leakage • GHG sensors developed from carbon nano-particles • Agricultural optimisation for carbon storage, methane and nitrous oxide reduction
	Advanced Agriculture	• Agricultural robotics • Closed ecological systems • Vertical farming systems
Biotech	Artificial life	• Artificial photosynthesis • Immersive virtual reality, reducing travel demand • Artificial brain • Advanced biofuels • Non-animal meat, reducing land use change and GHGs
	Waste remediation	• Automatic variable filtration (AVF) • Advanced oxidation processes (AOP) • UV irradiation • Plasma
	Non-animal meat	• Artificial meat • Food extrusion machines
	Biomaterials	• Gene therapy • Scaffold fabrication • Tissue engineering
Climate	Geoengineering	• Solar geoengineering[xix]/ Solar radiation management • Carbon dioxide removal • Weather modification and cloud-seeding

THE IMPACT OF EMERGING SUSTAINABLE TECHNOLOGIES

Higher adoption of renewable energy technologies can encourage interaction with other frontier emerging technologies like big data and AI technologies. For example, in countries with ambitious renewable energy expansion plans, machine-learning algorithms can be used to predict the output of solar (and/or wind) farms, allowing scheduled energy delivery to the grid. Convergence of renewable energy systems with digital technologies can also help renewables' costs to fall further. This can encourage uptake of new materials and processes in the manufacture of renewable energy technologies, and in the distribution of renewable power, making them increasingly competitive with fossil fuel power generation, particularly in countries that have limited access to energy. For example, coupling big data with energy distribution allows households to feed surplus energy back into the electricity grid, transforming into a potential source of income for poorer households.

AI, meanwhile, when combined with innovative storage technologies, and new battery types, can help address the intermittency of renewable energy better through dynamic adjustment of supply and demand. Newer battery and/or storage methods may have better affinity to new materials being researched for the manufacture of renewable energy systems to improve their efficiency. This can facilitate wider and more far-reaching deployment of renewable energy technologies, especially in countries which have a natural resource base of such materials.

Advances in battery and storage technologies can also improve the performance of electric vehicles. When supported by proactive policies, as in the EU, such advances result not in only in a significant growth in market share, but also in improvements in R&D and scaling, which can benefit overall GHG emissions reduction.



A larger share of renewables in a country's overall generation mix improves the climate impact of vehicle electrification. It also offers synergies with storage and managing intermittency challenges, via smart grid technologies. EVs could be used to supply power to the grid through bidirectional charging, making it possible to reduce demand for electricity during peak consumption periods, or to sell back stored power to utilities.

Beyond transportation and power, decarbonisation of industry, such as cement, iron, steel, and chemicals, through technologies like CCUS, electrification of industrial heat, and hydrogen can facilitate innovation and advanced low-carbon production routes for key industrial products. After energy efficiency and materials efficiency, CCUS is the third most-important lever for emissions reductions in industry.

Figure 7 CO_2 emissions from EVs compared to diesel vehicles in Europe[xx]

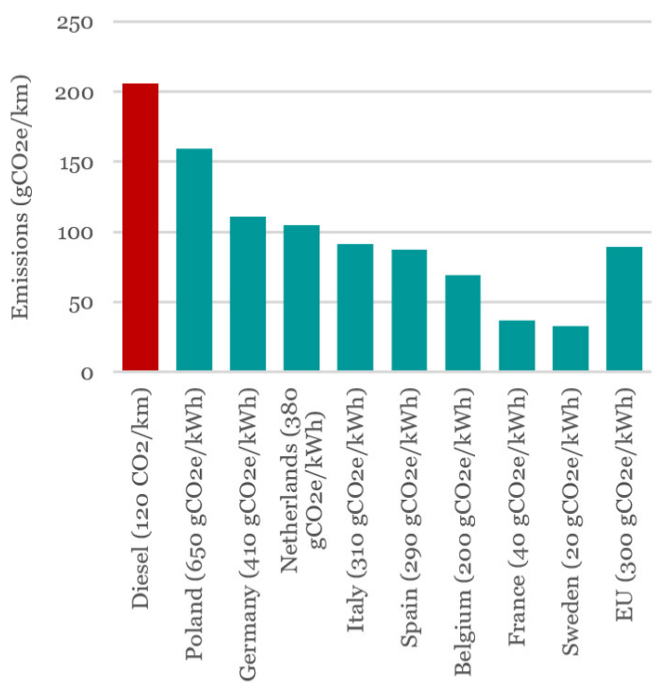
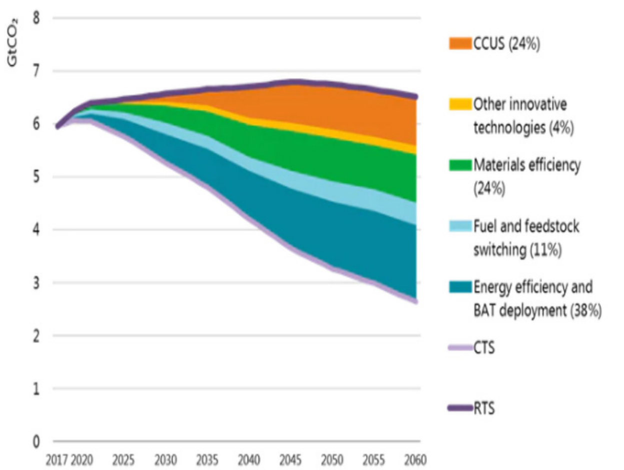


Figure 8 Emissions reductions for key industry subsectors (cement, iron and steel, chemicals) by mitigation strategy, CTS compared with RTS, 2017-60[xxi]



The IEA's Reference Technology Scenario (RTS) is the baseline scenario that takes into account existing energy and climate related commitments by countries, including the NDCs pledged under the Paris Agreement to combat climate change, limit emissions, and improve energy efficiency. Under the RTS, the share of emissions from industry will rise significantly, if CCUS is not deployed on a large scale. The Clean Technology Scenario (CTS), which lays out an energy system pathway and a CO_2 emissions trajectory in which CO_2 emissions related to the energy sector are reduced by around three-quarters from today's levels by 2060, shows that CCUS can contribute nearly 30% of the cumulative emissions reductions compared to the Reference Technology Scenario.

Other innovative technologies in industry, especially digitalisation, will also play an important role in transitioning the sector to a low-carbon future. Advanced materials and robotics can reduce costs of emissions reduction technologies like CCUS. The greatest potential for reducing costs lies in the application of AI and internet-enabled tech in predictive maintenance and automation, particularly in carbon storage.

Emerging technologies are also helping to pave the way to a greenhouse gas-neutral future in other sectors of the economy, including agriculture, aerospace, construction, finance, materials and textile science, electronics, IT and communications, medicine, biotech, neuroscience, military, space, robotics, transportation, and mobility. They can enable new forms of transparency, control and collaboration, and can provide the data for better informed production and consumption decisions, providing new tools for environmental policies.

The World Economic Forum's Exponential Climate Action Roadmap argues that digital technologies alone can help reduce global emissions by 15% by 2030[xxii], particularly through exponential technologies (technologies whose output per dollar or size is consistently accelerating), like 5G, cloud computing, first-generation industrial automation, and drones.

INTEGRATING EGTS INTO THE BROADER SUSTAINABLE ECONOMY AND SOCIETY

EGTs on their own cannot drive the energy transition. They require innovation in enabling infrastructure, in business models, in systems operation, in market design, and in government action to create integrated solutions that assist in decarbonising end-use sectors. The transformation towards EGTs within the scope of sustainable production and consumption patterns requires action across several levels.

- EGTs as part of production processes across the entire value chain of an economy requires the acquisition of technical skills. This will require actors in the energy, manufacturing, industry, and construction sectors to familiarise themselves with successful concepts for the introduction of EGTs as well as with the competitive advantages these technologies can provide for their companies.
- Businesses need to reflect on corporate strategies and their effectiveness with respect to new and evolving technological contexts. They can define newer business models, new implementation modalities, and new tools to adapt to an EGT-driven transition. For traditional hydrocarbon businesses, automation, connection, and aggregation through big data analytics, and AI can be helpful in building a low-carbon business ecosystem with concrete benefits.

INTEGRATING EGTS INTO THE BROADER SUSTAINABLE ECONOMY AND SOCIETY

- Developing sustainable materials turnover can help in the development of advanced science and technology concepts with potential synergies critical for future materials cycles. Examples of possible changes to patterns of materials cycles in materials turnover are hybrid value-adding, green chemistry, bionic process concepts, personalised value-added chains, cross-sectoral recyclable materials symbioses (such as net-zero industrial parks), and usage-centred business models.
- Governments embracing EGTs for a sustainable ecosystem can be the primary drivers of green consumerism (a state in which end-users demand products and services that have undergone a low-carbon and/or eco-friendly production process) by committing to environmental upgrades. These include policies for the judicial allocation of natural resources, waste reduction, and the maintenance of an ecological balance.
- Regulatory bodies and policymakers can target the integration of emerging sustainable technologies into industry by providing solutions for the standardisation of systems, platforms, protocols, digital skill sets, and security. This can encourage a shift from legacy business models underpinning industry in favour of more-digitised, sustainable models.
- Public and private investment in innovation needs to grow significantly, and innovation support must be coordinated across national governments and international initiatives, and with the private sector. As a first step, governments should fund research that will create a continuous pipeline of innovations, which can then be refined by the private sector and bought to market.
- International partnerships can assist and amplify efforts to integrate EGTs into society. They can add value by informing decision-makers on shared innovation needs and building a consensus on shared priorities; enabling cross-border R&D programmes; connecting policymakers, investors, experts and innovators from different countries; tracking levels of investments; developing collaborative strategies by convening expertise from different countries; and encouraging good practice.

IMPLICATIONS FOR MAJOR OIL AND GAS PRODUCERS

Emerging technologies are the future of the energy transition. Mature technologies like renewables will encourage the bulk of initial progress towards a net-zero future, but it will be the technologies in early adoption (like CCUS and hydrogen, automation and digitalisation) that will drive fuller decarbonisation, especially of more challenging sectors.

EGTs will have a significant impact on global demand for oil and gas by transforming the hydrocarbon value chain. Exports of oil and gas will transform into exports of embedded oil and gas products with applicable carbon regulations, so that large hydrocarbon producers continue to enjoy export markets in geographies with stringent climate controls.

Leading hydrocarbon producers can play an active and important role in developing and integrating new EGTs to transform their businesses into low carbon. They can define new implementation modalities, and new tools to adapt to an EGT-driven transition.

A major opportunity lies in the drawdown of atmospheric CO_2 for net-zero ambitions. Hydrocarbon producers can partner with developers of direct air capture projects to leverage natural gas power plants in synergy with renewable energy sources and output new fuels like synthetic crude for transport.

MENA oil and gas producers can convert EGTs like DAC into business opportunities by utilising their subsurface reservoir expertise to offer safe CO_2 disposal as a service. This can encourage collaboration and partnership with international governments and R&D organisations and will encourage policy mechanisms that reward carbon-abatement ETGs.

Technologies like internet enabled-tech, drones, AI, big data, and electronic monitoring can enable safer and more optimised oil and gas production activities in areas with complex geologies.

CONCLUSION

Technological innovation will continue to be the critical enabler of progress towards the energy transformation. However, for EGTs to drive decarbonisation of all end-use sectors of the economy, innovation priorities need to be refreshed to encourage integration of higher shares of EGTs into the broader sustainable economy and society.

Innovation in EGTs needs to be broader than just R&D, and must be accompanied by innovations in business models, policies, processes, and market designs. Initially, this can accelerate the integration of a higher share of mature EGTs like renewable energy into the value chain, which is key to decarbonising end-use sectors like buildings and transport.

In the medium- to long-term, EGTs can enable affordable decarbonisation of industrial activities such as iron and steel making, cement production, chemical and petrochemical production, along with marine and air transport.

International collaboration can foster the adoption of EGTs in developing markets and help in narrowing the developmental gap between developing and developed markets. Government to Government partnerships will play a crucial role in this regard, as they can be the precursor to private sector investments. They can do this through clear signalling of EGT innovation priorities, addressing policy barriers, providing enabling infrastructure, convening different actors to move projects forward, and co-investing, where required, to minimise financial risks.

APPENDIX

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xv. EV Technology, "9 Leading EV Influencers Discuss the Innovations that will Shape the Future of Electric Cars", https://blog.wallbox.com/9-leading-ev-influencers-discuss-the-innovations-that-will-shape-the-future-of-electric-cars/
xvi. An HCCI engine burns gasoline, but uses compression ignition—like a diesel engine—rather than a spark plug. In theory, that provides the efficiency of a diesel, without the soot and high levels of nitrogen-oxide (NOx) emissions
xvii. A PCCI engine is a "middle ground" between diesel-engine compression ignition and HCCI, because it injects some fuel early to let it mix with air in the combustion chamber, and then injecting more fuel later. That provides more control over ignition timing than HCCI, but can also create pockets of unburned hydrocarbon by-products, which is bad for emissions
xviii. An RCCI engine uses two fuels: a low-reactivity fuel (like gasoline) that is port injected, and a high-reactivity fuel (like diesel) that is direct injected. "Reactivity" refers to a fuel's tendency to ignite under compression. This method leads to big efficiency gains, but still with fairly high emissions
xix. Solar geoengineering refers to a set of emerging technologies that could alter the Earth's radiative balance—perhaps through injecting aerosols into the stratosphere, where they would reflect a small fraction of sunlight back into space—reducing the amount of climate change caused by greenhouse gases
xx. Chart shows the CO_2 emissions of EVs in Europe. Even when powered with the "dirtiest" electricity (such as in Poland), emissions from EVs are considerably lower than fossil fuel-powered vehicles
xxi. IEA, "Transforming Industry through CCUS", May 2019, https://www.iea.org/reports/transforming-industry-through-ccus
xxii. World Economic Forum, "Digital Technology can cut global emissions by 15%. Here's How", January 2019, https://www.weforum.org/agenda/2019/01/why-digitalization-is-the-key-to-exponential-climate-action/

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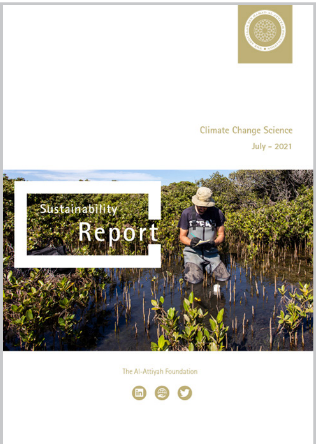

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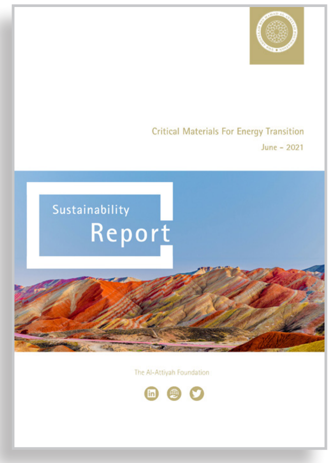

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