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Technological developments to address climate change in South Africa and their potential economic impacts

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Technological developments to address climate change in South Africa and their potential economic impacts

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Abstract

This paper examines the risks and opportunities associated with technologies and technological developments relevant to South Africa's efforts to mitigate and adapt to the effects of climate change over the next decade (up to 2035). These technologies will make the energy sector cleaner while reducing the carbon intensity of energy demand and the energy intensity of gross domestic product. The paper focuses on 17 technologies and technological developments across four sectors: (1) energy; (2) industry; (3) mobility; and (4) agriculture and land use. The opportunities associated with these technologies far outweigh the risks, with some technologies significantly reducing the transition costs of carbon-intensive industries. In South Africa, removing regulatory hurdles and supporting faster development and adoption of new technologies can accelerate the climate transition, reduce costs and attract more investment.

JEL classification: E62, E63

Keywords: fiscal policy, policy mix, monetary policy, South Africa

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1. Introduction

The South African Reserve Bank (SARB) has a statutory mandate to enhance and protect financial stability in South Africa. Over the course of approximately the next decade (into 2030–2035), a range of technological developments are expected with implications for the South African economy. In some instances, climate change will be a motivating force for the adoption of new technologies or other changes in the conduct of economic activity. Mitigation of and adaptation to climate change will have broad economic implications, including for financial markets and central banks, through a variety of channels.[1] An understanding of the potential future landscape with respect to technological developments is an important step for limiting the risks faced by these financial institutions and central banks.

Therefore, this research study is undertaken to:

1. Identify global technological developments over the next decade that are likely to generate large transition risks for developing countries such as South Africa; and
2. Conduct a preliminary evaluation of the potential implications these may have for the South African economy and financial markets and institutions.

This research includes technological developments and related technologies that are likely to materialise in the foreseeable future (over the next 10 years, i.e. into 2030–2035).

The paper is made up of five parts, with Section 1 being this introductory section. Section 2 provides a brief background on climate risk within the specific South African context. In Section 3, identified priority technological developments and disruptive technologies are categorised, presented and described, while Section 4 offers an evaluation of the potential implications of these technological developments and disruptive technologies. Finally, Section 5 discusses key findings and synthesises takeaways.

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[1] C Arndt, C Loewald and K Makrelov, 'Climate change and its implications for central banks in emerging and developing economies', *South African Reserve Bank Working Paper Series No. WP/20/04*, June 2020. https://www.resbank.co.za/content/dam/sarb/publications/working-papers/2020/10001/WP-2004.pdf

2. Climate change risk in South Africa

2.1 UNFCC and the Paris Agreement

The United Nations Framework Convention on Climate Change (UNFCCC) came into effect in 1994 and is currently ratified by 197 countries (the parties to the UNFCCC) with the fundamental aim of preventing dangerous human interference with Earth's climate systems. The most recent landmark achievement of the UNFCCC was the 2015 Paris Agreement,[2] of which South Africa is a signatory.[3] Article 2 of the Paris Agreement proposes:[4]

> *"Holding the increase in the global average temperature to well below 2˚C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change".*

To strengthen the global response to climate change following the Paris Agreement, an Intergovernmental Panel on Climate Change (IPCC) special report was published in 2018,[5] which established that 0.8–1.2°C of global warming had already occurred. The special report also addressed carbon dioxide equivalent (CO_2eq) emissions requirements to limit average global temperature rise to 1.5°C and considered the impacts of a >1.5°C rise. The IPCC special report directly addresses specific technological developments required to effect this across sectors, including energy (specifically electricity), industry, mobility, agriculture and finance.

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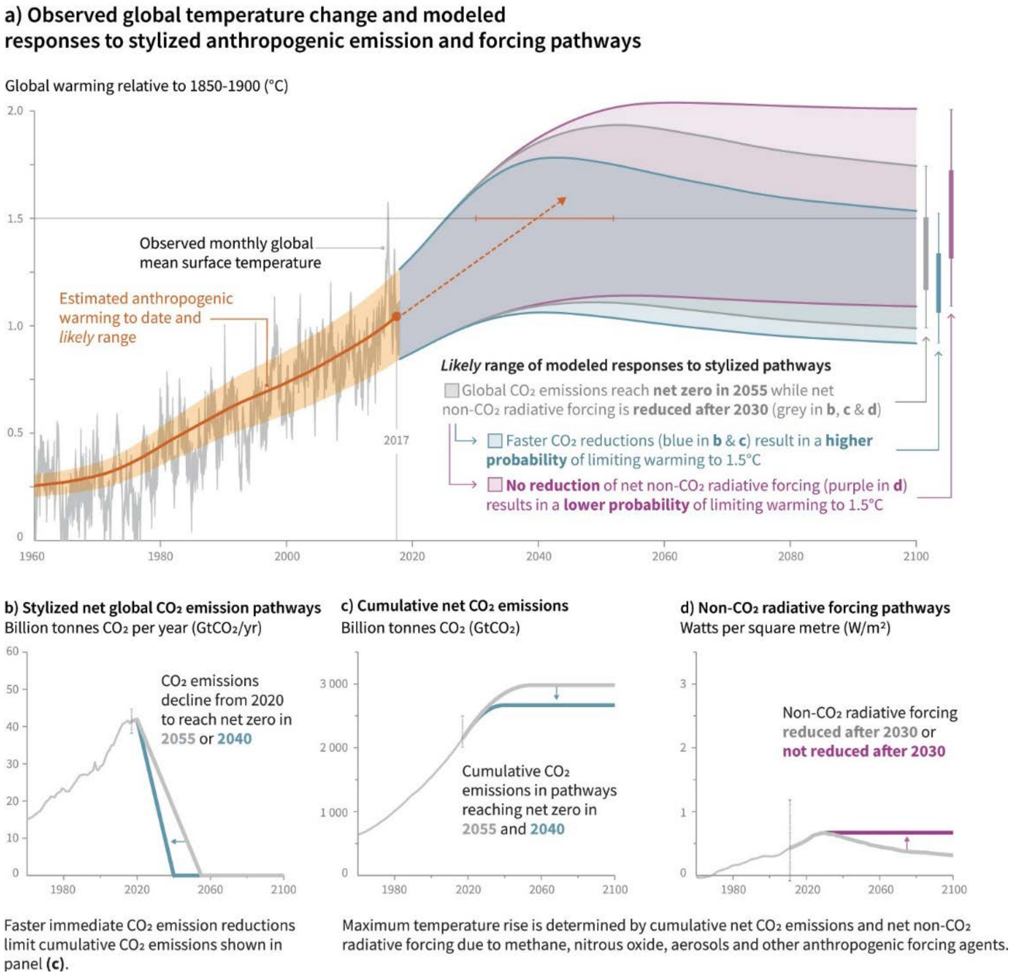
2 UNFCCC, 'The Paris Agreement', 2016. http://unfccc.int/ paris%5C_agreement/items/9485.php

3 Department of Environmental Affairs, 'South Africa signs Paris Agreement on Climate Change in New York'. Press release, 22 April 2016. https://www.environment.gov.za/mediarelease/southafricasignsparisagreementonclimate

4 UNFCCC, 'The Paris Agreement', 2016. http://unfccc.int/paris%5C_agreement/items/9485.php

5 IPCC, 'Global warming of 1.5°C. Summary for policymakers', 2018. https://www.ipcc.ch/sr15/chapter/spm/

Figure 1: Greenhouse gas (GHG) emissions and radiative forcing effects on global average temperature rise (specifically the 1.5°C limit in the Paris Agreement)[6]



Source: IPCC (2018)

The more recent IPCC Working Group I Sixth Assessment Report (AR6)[7] presents the physical science basis of climate change and established that 1.0–1.2°C of global warming has already occurred, and that human-caused global warming is unprecedented relative to the previous 2 000 years (see Figure 2).[8]

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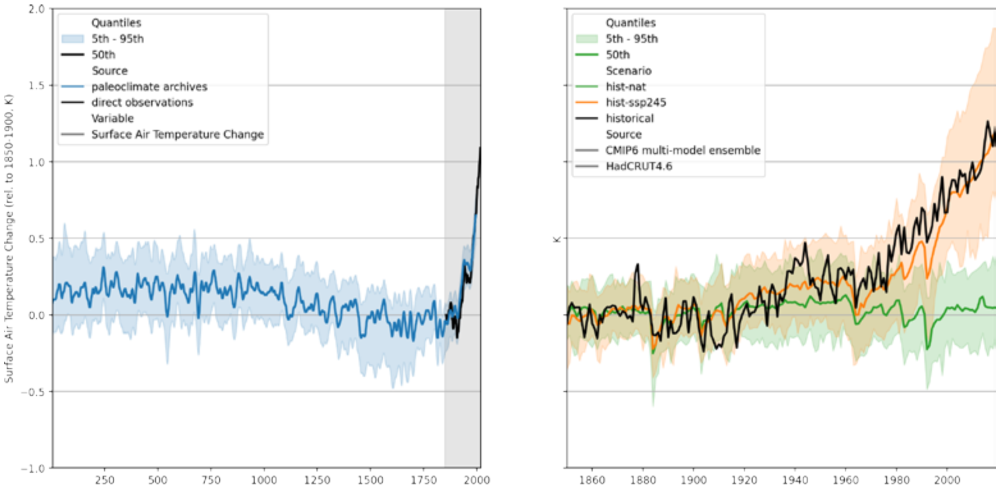
6 Ibid.

7 Working Group I contribution to the AR6 of the IPCC, 'AR climate change 2021: the physical science basis (Summary for policymakers)', 2021. https://www.ipcc.ch/report/ar6/wg1/#SPM

8 Thanks to Nicholls and Huppmann for developing the code to reproduce graphics from underlying data in the Working Group I contribution to the IPCC's AR6.

Figure 2: Changes in global surface temperature relative to 1850–1900: a) decadal average (1–2000); and b) annual average (1850–2020)[9]



a) Change in global surface temperature (decadal average) as reconstructed (1-2000) and observed (1850-2020)

b) Change in global surface temperature (annual average) as observed and simulated using human & natural and only natural factors (both 1850-2020)

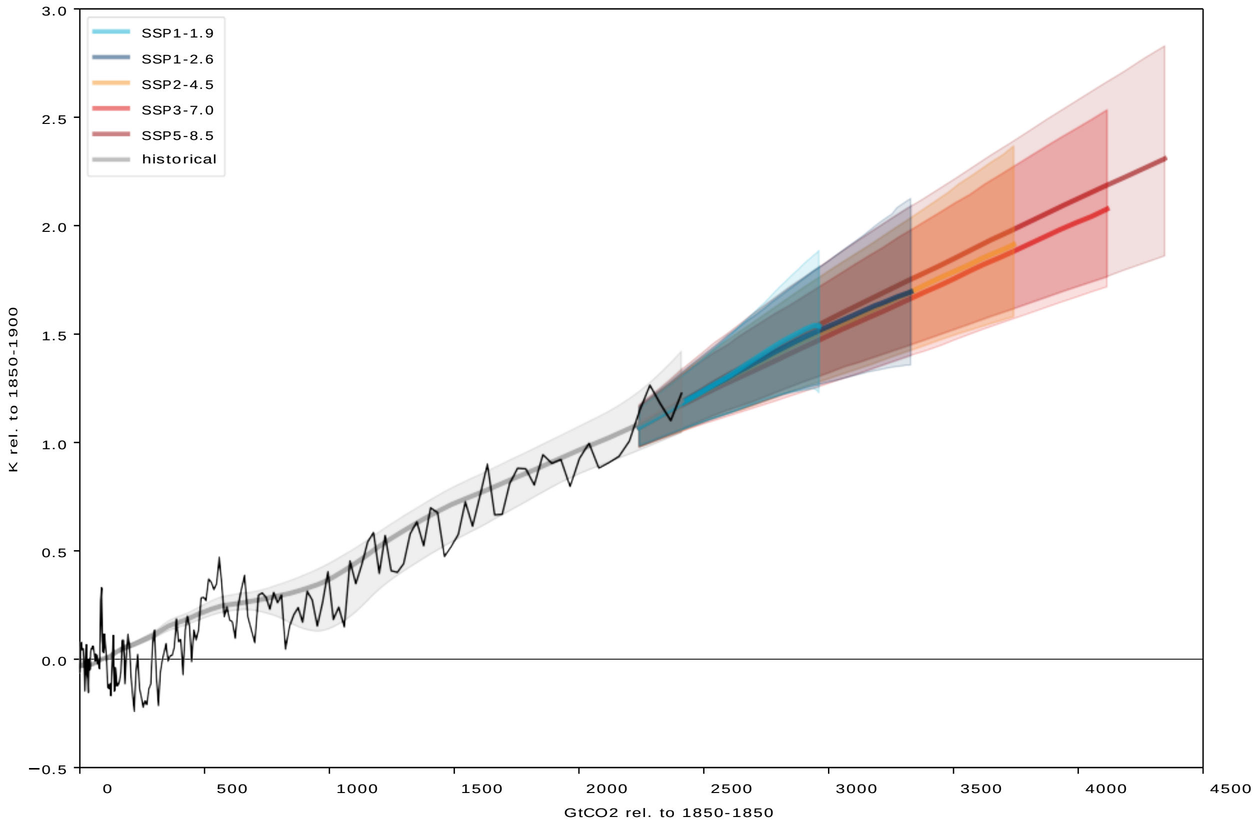
Source: IPCC (2021), and Z Nicholls and D Huppmann (2021)

The specific physical climate risk for South Africa associated with continued climate change was also demonstrated in the Working Group I contribution to AR6, where increases in heat extremes, heavy precipitation and periods of drought have already been observed but will worsen with continued GHG emissions and a related increase in global average temperatures (Figures 3 and 4). As shown in Figure 3 and 4, the Shared Socio-economic Pathways (SSPs) are described in the form ‘SSPx-y’ where ‘x’ denotes socio-economic trends and ‘y’ the level of radiative forcing in the underlying scenario (for more information on these SSPs, the interested reader is referred to IPCC publications).[9] As a developing economy, South Africa is particularly vulnerable to the effects of climate change and structural changes related to mitigation and adaptation efforts.[10]

9 Based on the IPCC’s AR6 ‘AR climate change 2021: the physical science basis’, 2021; and Z Nicholls and D Huppmann, ‘Data compilation and figures from the IPCC AR6 WG1’ via GitHub (https://github.com/openscm/AR6-WG1-Data-Compilation), 2021.

10 C Arndt et al., ‘Climate change and its implications for central banks’, 2020.

Figure 3: Historical and projected global surface temperature rise and cumulative GHG emissions across selected shared socio-economic pathways (SSPs) showing a near-linear relationship[11]



Source: IPCC (2021), and Z Nicholls and D Huppmann (2021)

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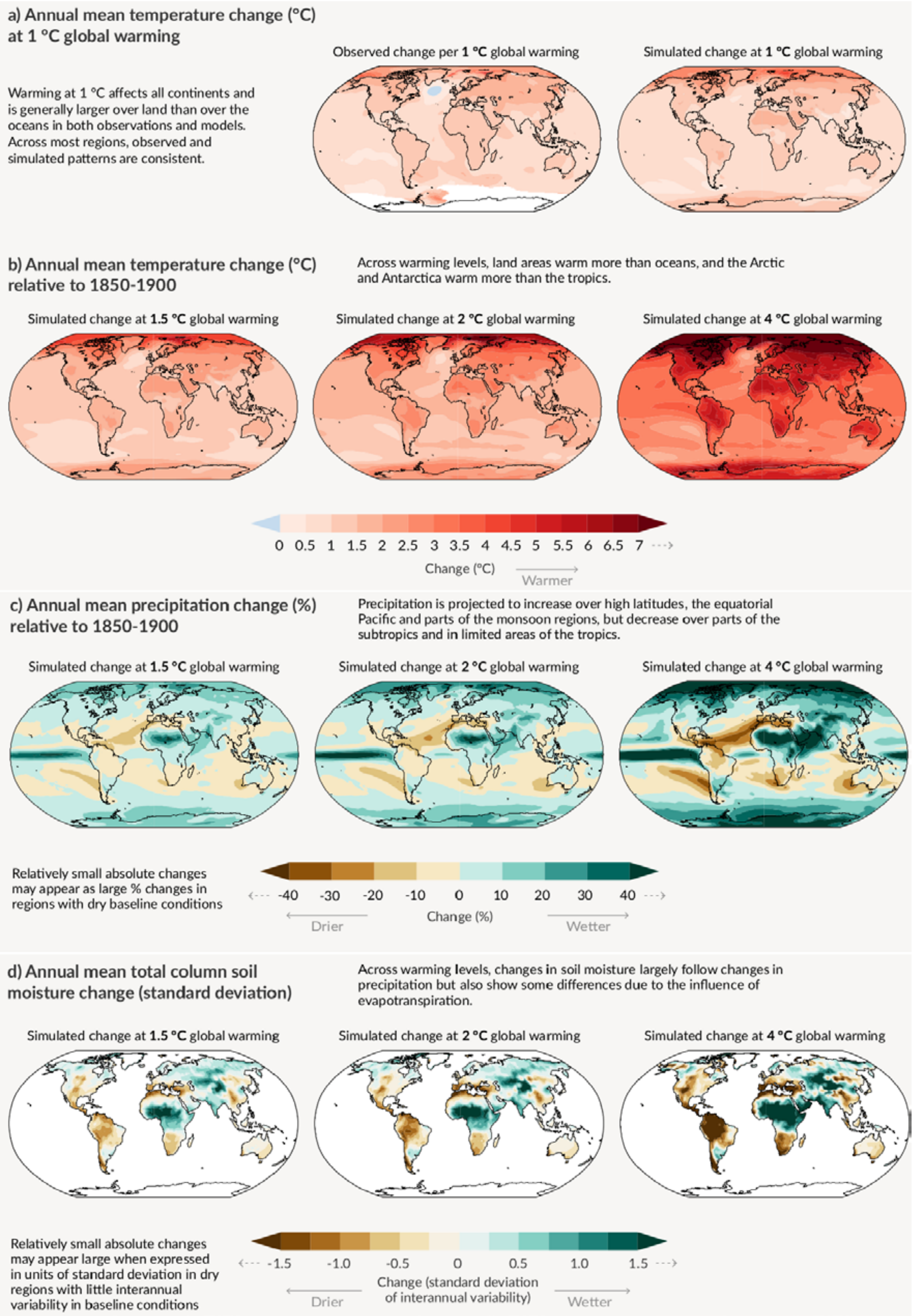
11 SSPs are defined by expected socio-economic trends and level of radiative forcing underlying the scenario as defined by the IPCC. IPCC's AR6, 'Climate change 2021: the physical science basis', 2021; and Z Nicholls and D Huppmann, 'Data compilation and figures from the IPCC AR6 WG1', 2021.

Figure 4: Maps of mean temperature, precipitation and soil moisture changes expected as average global temperature increases[12]



Source: IPCC (2021)

[12] IPCC's AR6, 'AR climate change 2021: the physical science basis', 2021.

2.2 South Africa's existing climate change response

South Africa's existing climate change response is characterised by the 2011 National Climate Change Response White Paper,[13] the 2016 Intended Nationally Determined Contribution (INDC),[14] which became South Africa's first Nationally Determined Contribution (NDC), and the 2021 Update as adopted by Cabinet and submitted to the UNFCCC NDC Registry.[15] These characterise South Africa's NDC for the period 2021–2025 (398–510 million tons of carbon dioxide equivalent, or $MtCO_2eq$) and 2026–2030 (398–440 $MtCO_2eq$) and is summarised from Winkler et al. in Figure 5. The updated NDC is based on extensive analysis and consultation by the national government (led by the Department of Forestry, Fisheries and the Environment) and includes notable contributions from the Presidential Climate Commission[16] informed by research undertaken by others, including University of Cape Town's Energy Systems Research Group,[17] the Council for Scientific and Industrial Research/Meridian Economics[18] and the National Business Initiative,[19] among others. There is also an intentional long-term journey towards net-zero as defined in the Low Emissions Development Strategy.[20]

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13 Department of Environmental Affairs, 'National climate change response white paper', 2011. https://www.gov.za/sites/default/files/gcis_document/201409/nationalclimatechangeresponsewhitepaper0.pdf

14 Department of Environmental Affairs, 'South Africa's Intended Nationally Determined Contribution (INDC)', 2016. https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/South%20Africa%20First/South%20Africa.pdf

15 Department of Forestry, Fisheries and the Environment, 'South Africa's first Nationally Determined Contribution under the Paris Agreement 2020/21 Update', 2021. https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/South%20Africa%20First/South%20Africa%20updated%20first%20NDC%20September%202021.pdf

16 Presidential Climate Commission, 'First report: recommendations on South Africa's updated Nationally Determined Contribution (NDC)', 2021. https://a9322a19-efe3-4459-9a6c-ab806fededa3.filesusr.com/ugd/1eb85a_896d0493b6284743b2ff3986b36be622.pdf

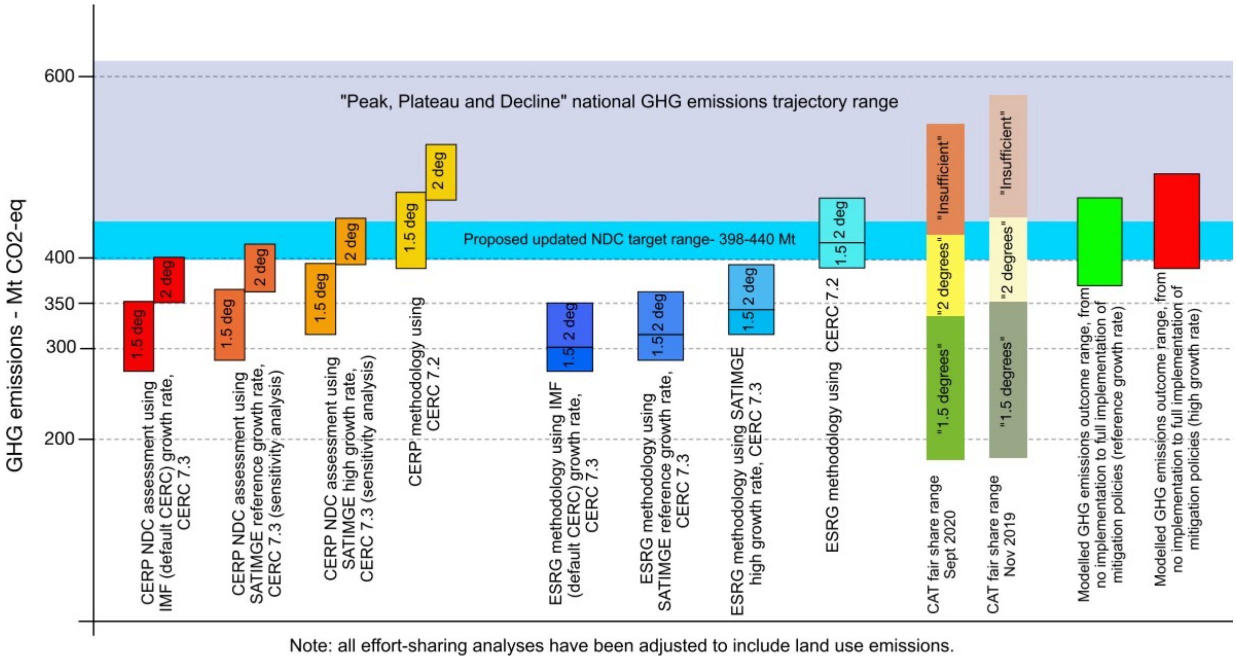
17 H Winkler, A Marquard, G Cunliffe and A Dane, 'South Africa's "fair share": mitigation targets in the updated first NDC in an international context', University of Cape Town, report, 2021. https://zivahub.uct.ac.za/articles/report/South_Africa_s_fair_share_mitigation_targets_in_the_updated_first_NDC_in_an_international_context_UCT_2021_/16691953

18 J Wright and J Calitz, 'Systems analysis to support increasingly ambitious CO_2 emissions scenarios in the South African electricity system', 2020. https://researchspace.csir.co.za/dspace/handle/10204/11483; Meridian Economics, 'What might a Paris-aligned emissions profile look like for the South African power sector?' *Policy brief No. 2020/03.* 2020. https://meridianeconomics.co.za/wp-content/uploads/2020/08/Power-sector-carbon-budgets-2020-v1.1.pdf

19 National Business Initiative, 'Climate pathways and a just transition for South Africa', *webpage*, 2021. https://www.nbi.org.za/climate-pathways-and-a-just-transition-for-south-africa/

20 Department of Environment, Forestry and Fisheries, 'South Africa's low-emission development strategy 2050', February 2020. https://unfccc.int/sites/default/files/resource/South%20Africa%27s%20Low%20Emission%20Development%20Strategy.pdf

Figure 5: Comparison of fair share contributions for South Africa and proposed NDC range (South Africa adopted 398–510 $MtCO_2eq$ (2021–2025) and 398–440 $MtCO_2eq$ (2026–2030) as updated NDC in 2021)[21]



Source: Winkler et al. (2021)

2.3 Delineation of physical and transition risks

It is important to differentiate between weather and climate to understand the focus of this research paper as it relates to long-term climate change: weather pertains to short-term meteorological characteristics like temperature, rainfall, wind speed/direction and sunshine, while climate pertains to long-term average weather conditions.[22] As explained by the National Oceanic and Atmospheric Administration in the US, “Climate is what you expect, weather is what you get.”[23]

Within this context, the delineation between the physical risk and transition risk of climate change can be better understood by considering Figure 6, which utilises SSPs from AR6 to illustrate the impacts of physical risks and transition risks, depending on the level of mitigation. The SSPs present five narratives developed to compare baseline scenarios with climate policy scenarios that align with particular expected

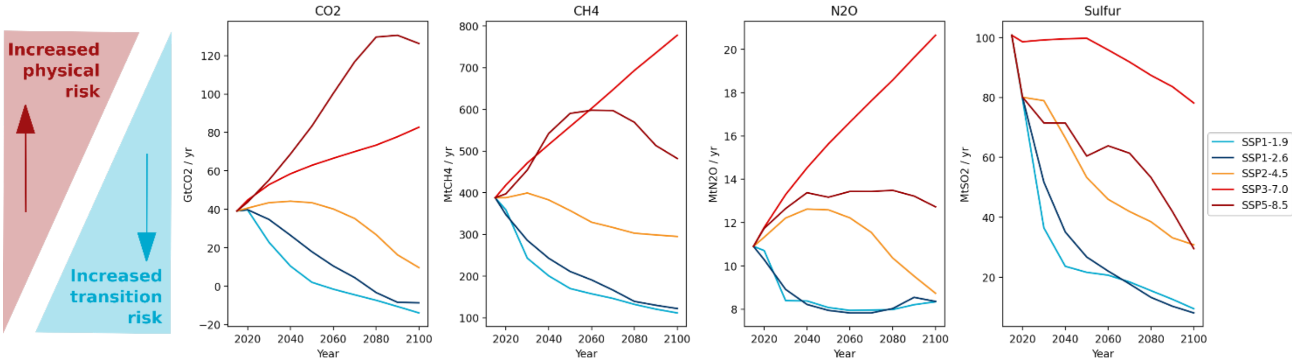
21 H Winkler et al., ‘South Africa’s “fair share”’, 2021.

22 V Krishnamurthy, ‘Predictability of weather and climate’, *Earth and Space Science* 6(7), 2019, pp 1043–1056.

23 National Oceanic and Atmospheric Administration, ‘What is the difference between weather and climate?’, 2021. https://oceanservice.noaa.gov/facts/weather_climate.html

socio-economic challenges for mitigation and adaptation.[24]

Figure 6: Illustration of physical and transition risk relative to GHG emissions trajectories[25]



Source: Author's illustration based on Z Nicholls and D Huppmann (2021)

Physical risks emanate from the interaction of climate events and trends with human and natural systems.[26] Transition risks emanate from the shift in adopted technologies and the economic dislocation and financial losses that are a consequence of shifting to lower-carbon economies.[27] For example, Welsby et al. argue that substantial transition risk exists as a result of the global need to mitigate GHG emissions (particularly from fossil fuels) and hence leave ≈90% of remaining coal reserves and ≈60% of remaining oil and natural gas reserves unextracted by 2050 to remain within the 1.5°C threshold.[28]

Physical risks and transition risks are mapped in Figure 7 with specific reference to impacts on the economy and financial systems, further demonstrating the negative feedback loop between the economy and financial systems.

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24 K Riahi, D P van Vuuren, E Kriegler, J Edmonds, B C O'Neill, S Fujimori, N Bauer, K Calvin, R Dellink, O Fricko, W Lutz, A Popp, J C Cuaresma, S KC, M Leimbach, L Jiang, T Kram, S Rao, J Emmerling, K Ebi, T Hasegawa, P Havlik, F Humpenöder, L A da Silva, S Smith, E Stehfest, V Bosetti, J Eom, D Gernaat, T Masui, J Rogelj, J Strefler, L Drouet, V Krey, G Luderer, M Harmsen, K Takahashi, L Baumstark, J C Doelman, M Kainuma, Z Klimont, G Marangoni, H Lotze-Campen, M Obersteiner, A Tabeau and M Tavoni, 'The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: an overview', *Global Environmental Change* 42, 2017, pp 153–168.

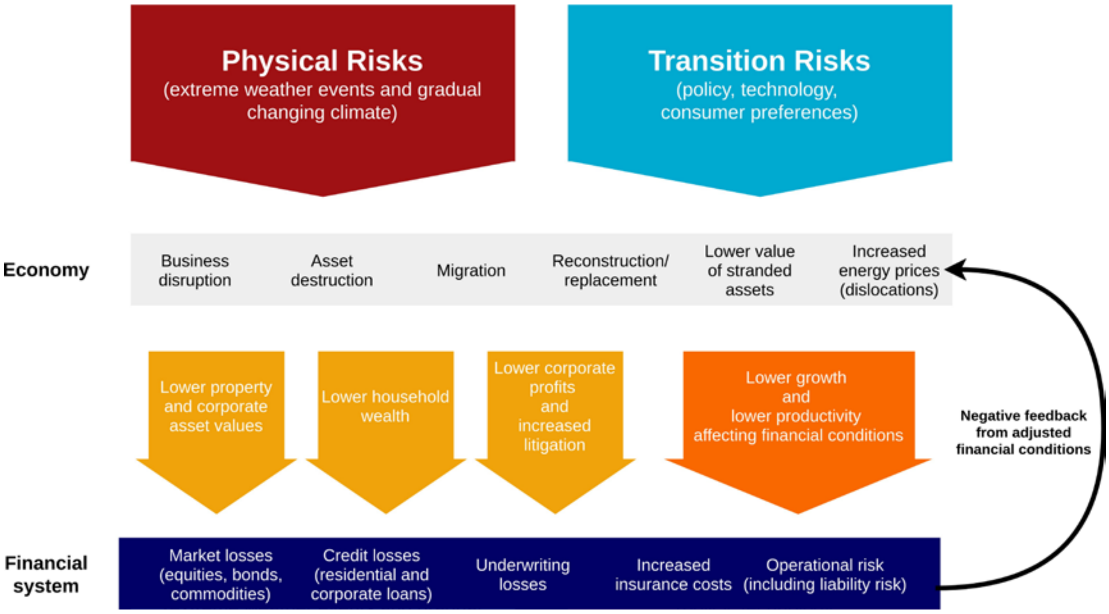
25 Selected SSPs are used as representative examples. SSPs are based on underlying socio-economic trends and levels of radiative forcing defined by the IPCC.

26 S Batten, R Sowerbutts and M Tanaka, 'Let's talk about the weather: the impact of climate change on central banks', *Bank of England Working Paper No. 603*, May 2016. https://www.bankofengland.co.uk/working-paper/2016/lets-talk-about-the-weather-the-impact-of-climate-change-on-central-banks

27 Ibid.

28 D Welsby, J Price, S Pye and P Ekins, 'Unextractable fossil fuels in a 1.5°C world', *Nature* 597(7875), Sep 2021, pp 230–234.

Figure 7: Two main channels of climate change risk affecting the economy and financial systems (including feedback mechanisms)[29]



Source: Author (based on P Grippa, J Schmittmann and F Suntheim (2019))

The focus of this research is on transition risks – the implications of technologies and technological developments specifically linked to climate change. The intentional focus is supported by the need to mitigate GHG emissions and transition from existing carbon-intensive methods of energy production and processing to low-carbon approaches, especially as part of economic recoveries post-COVID-19.[30] Although the focus of this research is on mitigation, future research should also address adaptation, and associated physical and transition risks.

2.4 Global climate-financing summary for developing countries

A summary of recent climate financing to developing economies by developed economies from all potential sources (including public and private)[31] up to 2019 is provided in the Organisation for Economic Co-operation and Development's 'Climate

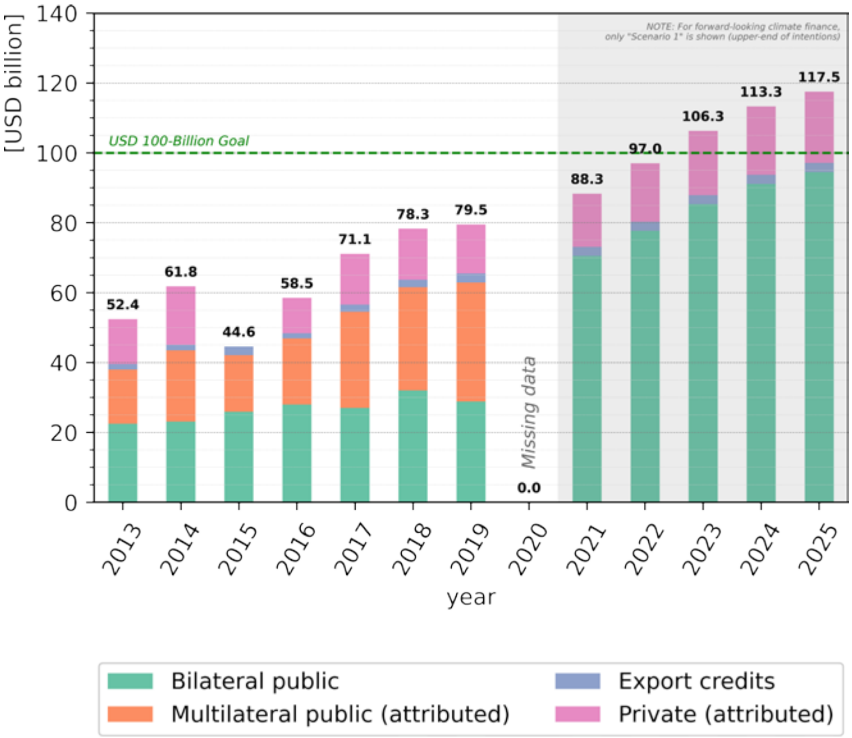
29 Adapted from P Grippa, J Schmittmann and F Suntheim, 'Climate change and financial risk', *Finance and Development*, December 2019. https://www.imf.org/external/pubs/ft/fandd/2019/12/climate-change-central-banks-and-financial-risk-grippa.htm

30 N Batini, G Melina, M di Serio and M Fragetta, 'Building back better: how big are green spending multipliers?', *IMF Working Paper No. 2021/087*, March 2021. https://www.imf.org/en/Publications/WP/Issues/2021/03/19/Building-Back-Better-How-Big-Are-Green-Spending-Multipliers-50264

31 Further information can be found in OECD, *Climate finance provided and mobilised by developed countries: aggregate trends updated with 2019 data*, Climate Finance and the USD 100 Billion Goal, Paris: OECD Publishing, 2021. https://doi.org/10.1787/03590fb7-en on the classification of "developed economies" and "developing economies".

finance provided and mobilised by developed countries: aggregate trends updated with 2019 data' (2021),[32] while an outlook to 2025 is provided in the same organisation's 'Forward-looking scenarios of climate finance provided and mobilised by developed countries in 2021–2025'.[33] These findings are summarised in Figure 8.

Figure 8: Summary of climate finance from developed to developing economies



Source: Organisation for Economic Co-operation and Development

Across 2019/2020, global climate finance averaged USD632 billion per year, meaning ≈12.5% of global climate financing went to developing economies (excluding self-sourced financing). According to the Climate Policy Initiative, climate financing requirements are projected to be more than six times this amount by 2030 (USD4.13 trillion).[34] With respect to technologies and technological development, it is clear that a scale-up in overall funding, technology transfer and capacity building to

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32 OECD, *Climate finance provided and mobilised by developed countries: aggregate trends updated with 2019 data*, Climate Finance and the USD 100 Billion Goal, Paris: OECD Publishing, 2021.

33 OECD, *Forward-looking scenarios of climate finance provided and mobilised by developed countries in 2021-2025: technical note*, Climate Finance and the USD 100 Billion Goal, Paris: OECD Publishing, 2021. https://doi.org/10.1787/5f1f4182-en

34 B Naran, P Fernandes, R Padmanabh, P Rosane, M Solomon, S Stout, C Strinati, R Tolentino, E Wakaba, Y Zhu and B Buchner, 'Global landscape of climate finance 2021', Climate Policy Initiative, Nov 2019. https://www.climatepolicyinitiative.org/wp-content/uploads/2021/10/Global-Landscape-of-Climate-Finance-2021.pdf; J Timperley, 'How to fix the broken promises of climate finance', *Nature* 598, 2021, pp 400–402.

developing economies is required to meet NDC mitigation and adaptation commitments. South African climate finance is dominated by the private sector, which contributed 57% of the total R63.1 billion (USD4.75 billion, averaged over 2017/2018), while the public sector contributed 3% (the remainder being blended finance).[35]

2.5 Carbon pricing mechanisms

Global consensus is increasingly to price CO_2 emissions (as the dominant GHG contributor) appropriately, even as perspectives on mechanisms, pricing levels and sector inclusion vary.[36] The map of global carbon pricing mechanisms (Figure 9) illustrates the range of carbon pricing mechanisms adopted in a number of major global economies (including China's emissions trading system in 2021 – the largest carbon pricing market in the world at 4 000 $MtCO_2eq$/year). In 2021, only 21.5% of global GHG emissions fell under any form of pricing mechanism, and <4% of these were above 40–80 USD/tCO_2eq (deemed necessary to meet the Paris Agreement 2°C goal).[37] As countries become more ambitious (via their NDCs), carbon pricing instruments and their pricing are expected to become similarly ambitious.

South Africa has high carbon intensity across a range of export products and services, so it is important for South Africa to carefully consider large trade partners like the European Union (EU) potentially ratcheting up domestic carbon pricing, such as carbon border adjustment mechanisms.

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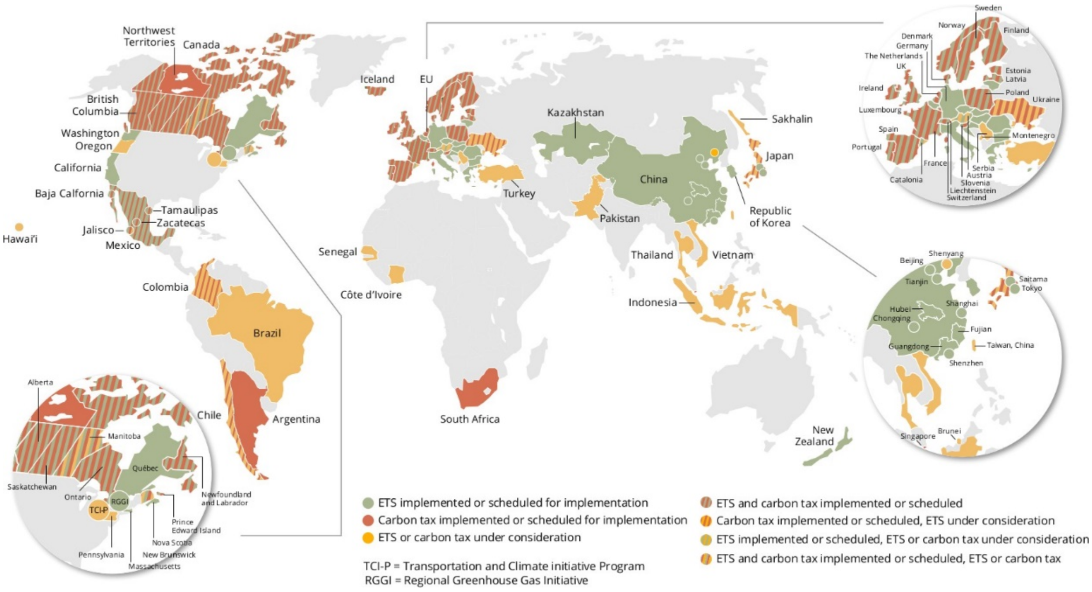
35 A Cassim, J-V Radmore, N Dinham and S McCallum, 'South African climate finance landscape 2020', 2021. https://www.climatepolicyinitiative.org/wp-content/uploads/2021/01/South-African-Climate-Finance-Landscape-January-2021.pdf

36 World Bank, 'State and trends of carbon pricing 2021', 2021. Washington, DC: World Bank. https://openknowledge.worldbank.org/bitstream/handle/10986/35620/9781464817281.pdf

37 Carbon Pricing Leadership Coalition (World Bank), 'Report of the high-level commission on carbon pricing and competitiveness', 2019. Washington, DC: World Bank. https://openknowledge.worldbank.org/bitstream/handle/10986/32419/141917.pdf

Figure 9: Carbon pricing map (2021)[38]



Source: Carbon Pricing Leadership Coalition

2.6 Exponential technological development

The primary motivation to understand modern technological risks specifically linked to climate change is their potential for exponential adoption and related tipping points – that is, tipping points for both climate change and technological adoption. As hypothesised and explored in Azhar's *The exponential age* (2021), the chasm between linear thinking/institutional arrangements[39] and technological development/adoption creates an exponential gap between societies and institutions (Figure 10).[40]

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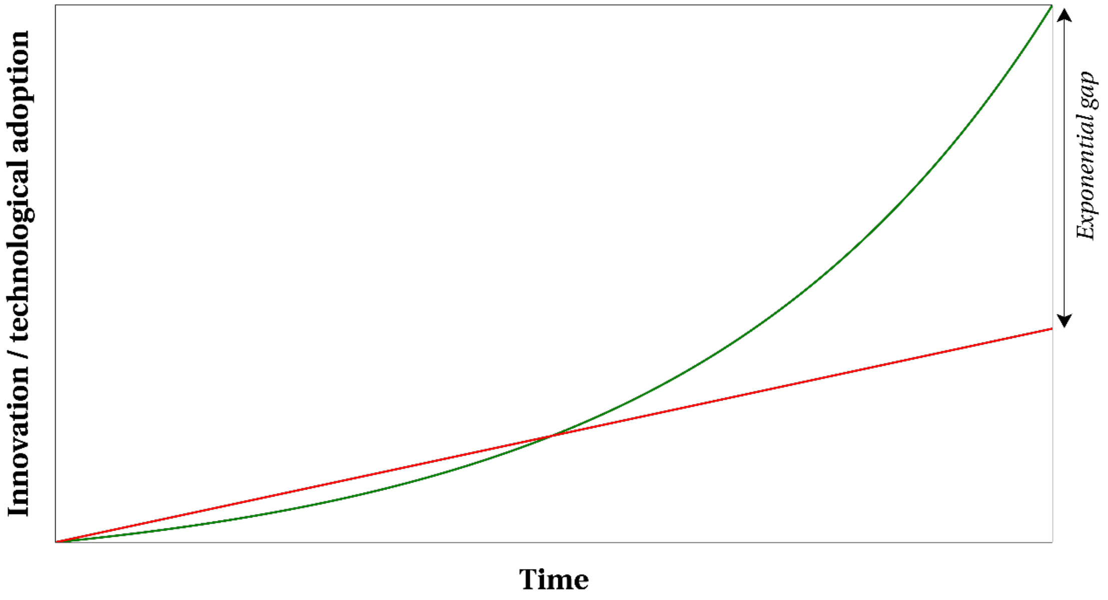
38 Ibid.

39 Specifically, how technological change and adoption take decades when incumbents choose to exploit and adjust to technologies at a self-determined pace. See R Nelson and S Winter, *An evolutionary theory of economic change*, Cambridge: Harvard University Press, 1982.

40 S Cunningham, 'Framing the concepts that underpin discontinuous technological change, technological capability and absorptive capacity', *TIPS research report for Department of Trade and Industry*, November 2018. https://www.tips.org.za/research-archive/trade-and-industry/trade-and-industry/item/download/1721_83368b23d40c511328ac1f1102b10153

Figure 10: Illustration of the exponential gap, with specific reference to innovation and subsequent technology adoption[41]



Source: Azhar (2021)

3. Priority technological developments and disruptive technologies

The intentional focus is on priority technological developments to address climate change that will generate large transition risks for the South African economy.[42] Sectors are categorised and characterised in the sub-sections that follow, being:

- energy (section 3.1);
- industry (section 3.2);
- mobility (section 3.3); and
- agriculture and land use (section 3.4).

Implicitly linked to technological developments, this research incorporates the broader topic of techno-optimism and the limits to long-term growth. Meadows et al.'s seminal *The limits to growth* is a clear reference in this respect,[43] while more optimistic perspectives are provided by the likes of Browne[44] and others. For the purposes of this research, the question of whether technological developments can or will prove

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41 A Azhar, *The exponential age*, New York: Diversion Books, 2021.

42 Although true artificial general intelligence is intensely debated as a hypothetical point at which no further technological developments will be necessary, it is not considered within the scope of this research.

43 D H Meadows, D L Meadows, J Randers and W W Behrens, The limits to growth: a report for the Club of Rome's project on the predicament of mankind, New York: Universe Books, 1972.

44 J Browne, Make, think, imagine: engineering and the future of civilisation, Berkeley: Pegasus Books, 2021.

sufficient to address the impacts of climate change (in terms of both mitigation and adaptation) is not addressed. Instead, the expected technological developments are characterised (this section) and their potential implications are assessed (section 4). The nature of deep decarbonisation (mitigation) requires temporal and spatial transformation that is daunting and unprecedented.[45] Considering the disruptive nature of technological developments in an 'exponential age', it is feasible that technological developments over a short period of time will contribute significantly to the shifts in decarbonisation required to address climate change. Although not explored as part of this research, the related co-benefits of this are becoming increasingly clear in a number of sectors (as employment opportunities, reduced localised pollution, health benefits and technology transfers).[46]

3.1 Energy

The manner in which GHG emissions can be reduced is easily understood by the four factors in the well-known Kaya identity:[47]

$$GHG = P.\frac{Y}{P}.\frac{E}{Y}\frac{GHG}{E}$$

Where:

GHG	: greenhouse gas emissions
P	: population
$\frac{Y}{P}$	: gross domestic product (GDP) per capita
$\frac{E}{Y}$	: energy intensity of GDP
$\frac{GHG}{E}$	: GHG emissions intensity of energy demand.

Of the four factors that can mitigate GHG emissions, technological interventions in the energy sector are critical – that is, minimise energy intensity $(\frac{E}{Y})$[48] and reduce GHG

45 National Academies of Sciences Engineering and Medicine, 'Deployment of deep decarbonization technologies: proceedings of a workshop', 2019. Washington, DC: The National Academies Press. https://www.nap.edu/cart/download.cgi?record_id=25656

46 International Finance Corporation, 'CTRL-ALT-DEL: a green reboot for emerging markets', 2021. Washington, DC: International Finance Corporation. https://www.ifc.org/wps/wcm/connect/topics_ext_content/ifc_external_corporate_site/climate+business/resources/a+green+reboot+for+emerging+markets

47 Y Kaya and K Yokobori, *Environment, energy, and economy: strategies for sustainability*, Tokyo: United Nations University Press, 1997.

48 Energy efficiency interventions are also a key enabler in this respect but are not considered disruptive for the purposes of this research.

intensity of energy demand ($\frac{GHG}{E}$). The technological developments considered are provided in the sub-sections that follow but are listed here for ease of reference:[49]

- scaled-up variable renewable energy (VRE) technologies;
- electrical energy storage;
- carbon capture and storage (CCS) for electricity production;
- electrolytic hydrogen;
- nuclear fission – small modular reactors; and
- digitalisation.

3.1.1 Scaled up VRE technologies

Notable technology cost declines in two particular VRE technologies (≈-90% for solar PV and ≈-50–70% for onshore wind) have occurred over the past 10 years (Figures 11 and 12),[50] resulting in new capacity deployment at an increased scale in recent years (including in developing economies).

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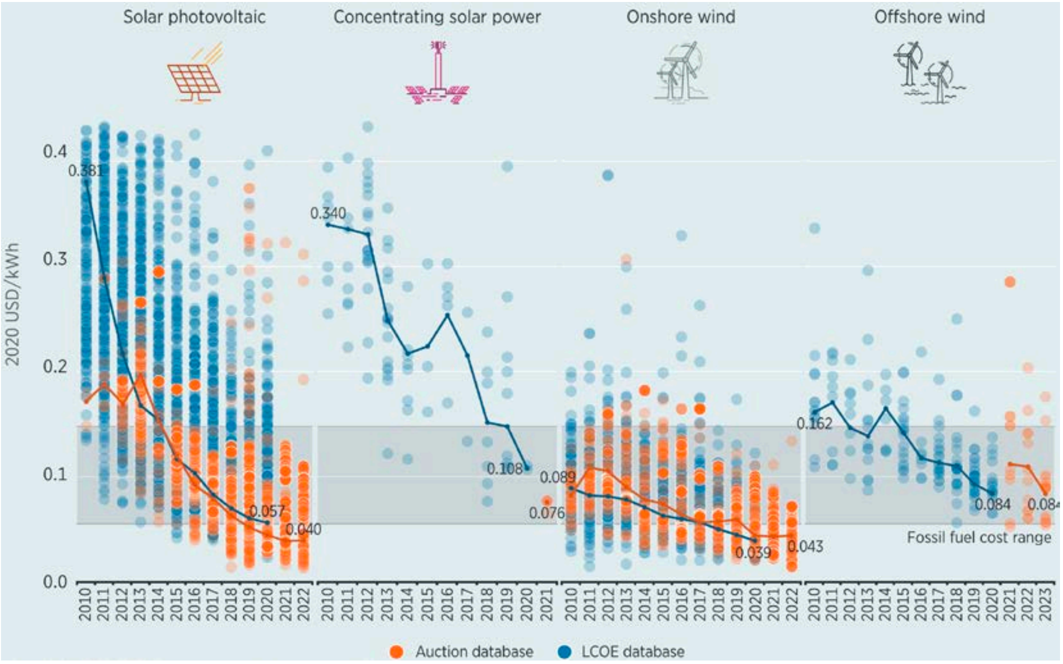
[49] Other enabling technologies considered ancillary at this stage include grid-forming inverter-based resources and ultra-high-voltage transmission networks (ultra-high-voltage alternating current/high-voltage direct current).

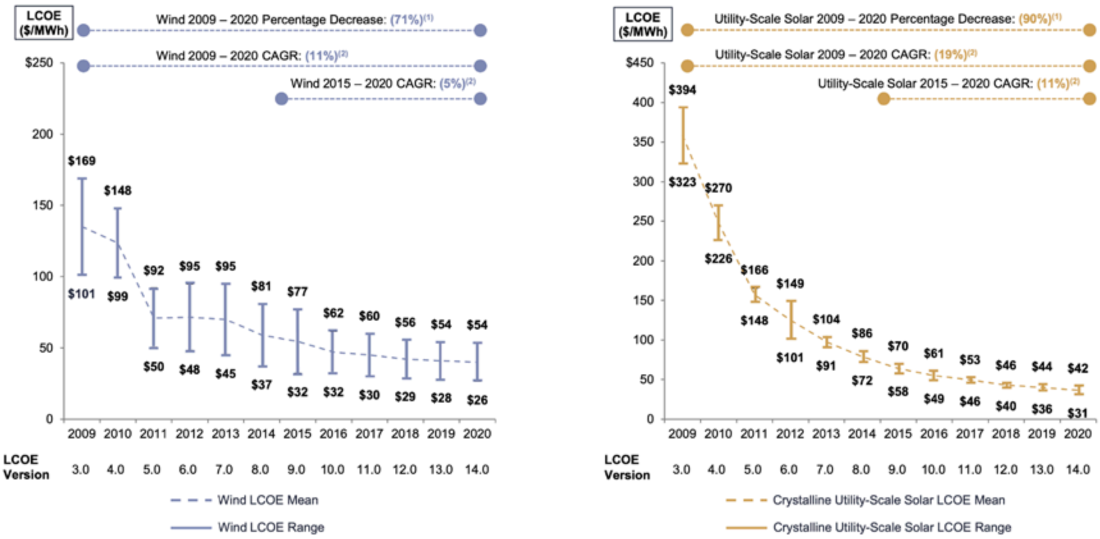
[50] Encouraging cost trends for solar thermal applications are also noted globally but to date lack global adoption

Figure 11: Project-weighted global average levelised cost of energy for auctions and power purchase agreements for solar photovoltaics, solar thermal applications and wind (onshore/offshore)[51]



Source: International Renewable Energy Agency (IRENA)

Figure 12: Historical levelised cost of energy of onshore wind and solar photovoltaics revealing substantive growth in capacity and decreasing LCOE[52]



CAGR – Compound Annual Growth Rate

LCOE – Levelised Cost of Electricity

Source: Lazard (2020)

51 International Renewable Energy Agency (IRENA), ‘Renewable power generation costs in 2020’, 2021. https://www.irena.org/publications/2021/Jun/Renewable-Power-Costs-in-2020

52 Lazard, ‘Lazard’s levelized cost of energy analysis – version 14.0’, 2020. https://www.lazard.com/media/451419/lazards-levelized-cost-of-energy-version-140.pdf

Investment costs for these technologies are also expected to continue to decline as deployment scales. Expectations for further cost reductions are -45% to -55% for utility-scale solar photovoltaics[53] (conservatively -35% to -40%, according to IEA),[54] -20% to -30% for onshore wind[55] (-10% according to IEA),[56] and -40% to -50% for offshore wind[57] (particularly floating offshore wind where South Africa would likely focus as a result of a relatively deep near-shore coastline).[58]

As a result, the trade-off between power-sector cost and decarbonisation (especially in South Africa) no longer exists. Indeed, VRE technologies require complementary technologies to ensure system adequacy, but bulk energy provision from these relatively inexpensive energy providers is a critical part of a least-cost trajectory for South Africa's energy mix.[59]

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53 National Renewable Energy Laboratory (NREL), '2021 Electricity ATB technologies and data overview', 2021. https://atb.nrel.gov/electricity/2021/index

54 International Energy Agency (IEA), 'World energy outlook 2021', 2021. Paris: IEA. https://iea.blob.core.windows.net/assets/88dec0c7-3a11-4d3b-99dc-8323ebfb388b/WorldEnergyOutlook2021.pdf

55 National Renewable Energy Laboratory (NREL), '2021 Electricity ATB technologies and data overview', 2021. https://atb.nrel.gov/electricity/2021/index

56 Ibid.

57 Ibid.

58 Energy Sector Management Assistance Program (World Bank), 'Going global: expanding offshore wind to emerging markets', 2019. Washington, DC: World Bank. http://documents1.worldbank.org/curated/en/716891572457609829/pdf/Going-Global-Expanding-Offshore-Wind-To-Emerging-Markets.pdf; World Forum Offshore Wind, 'Global offshore wind report', 2020. New York: World Forum Offshore Wind; World Bank Group, 'Offshore wind technical potential in South Africa', 2020. Washington, DC: World Bank. http://documents1.worldbank.org/curated/en/337531586894229468/pdf/Technical-Potential-for-Offshore-Wind-in-South-Africa-Map.pdf

59 J G Wright, J Calitz, N Ntuli, R Fourie, M Rampokanyo and P Kamera, 'Formal comments on the Draft Integrated Resource Plan (IRP) 2018 (Report) v1.2', Council for Scientific and Industrial Research (CSIR), 2018. https://researchspace.csir.co.za/dspace/handle/10204/10492; 'Integrated resource plan 2018, Technical report, 2018. http://www.energy.gov.za/IRP/irp-update-draft-report2018/ IRP-Update-2018-Draft-for-Comments.pdf.

Department of Mineral Resources and Energy, 'Integrated resource Plan (IRP 2019)', technical report, 2019. http://www.energy.gov.za/IRP/2019/IRP-2019.pdf.

B Mccall, J Burton, A Marquard, F Hartley, F Ahjum, G Ireland and B Merven, 'Least-cost integrated resource planning and cost-optimal climate change mitigation policy: alternatives for the South African electricity system', *Southern Africa – Towards Inclusive Economic Development Working Paper #29, 2019.* https://sa-tied.wider.unu.edu/article/least-cost-integrated-resource-planning-and-cost-optimal-climate-change-mitigation-policy-%E2%80%94

3.1.2 Electrical energy storage

At high VRE penetration levels (>50% demand met by VRE), energy storage emerges as a notable value-adding technology (contributing >20% and up to 80% relative to peak demand).[60] Applications can range from utility-scale and distributed grid-connected applications to specific stand-alone applications. Value-stacking for energy storage offers particular utility, for example energy arbitrage, seasonal storage, system services (frequency regulation), VRE support, black start and network deferral.

Storage can take the form of various technologies but in South Africa will predominantly be through short- to medium-duration energy storage technologies like battery energy storage systems (1–6 hours, lithium-ion as a likely technology), possibly combined with flow batteries (6–12 hours, vanadium redox flow being the most likely technology),[61] as illustrated in Figures 13 and 14 respectively. Costs for lithium-ion battery energy storage systems in particular have dropped substantially over the past 10 years[62] and are expected to continue to do so over the coming decade (≈-60% to -70% by 2030).[63]

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60 I Staffell, M Jansen, R Green, R Gross, T Green and O Schmidt, 'Drax Electric Insights Quarterly – Q3 2019', technical report, 2019. https://www.drax.com/wp-content/uploads/2019/12/191202_Drax_Q3_Report.pdf

61 US Trade and Development Agency, 'South Africa energy storage technology and market assessment', 2017. https://www.crses.sun.ac.za/files/research/publications/technical-reports/USTDA_Public+Version+1.pdf

62 A Eller and D Gauntlett, 'Energy storage trends and opportunities in emerging markets', International Finance Corporation (IFC), 2017. https://www.esmap.org/sites/default/files/esmap-files/7151-IFC-EnergyStorage-report.pdf; Lazard, 'Lazard's levelized cost of storage analysis – version 6.0', 2020. https://www.lazard.com/media/451418/lazards-levelized-cost-of-storage-version-60.pdf

63 W Cole, A W Frazier and C Augustine, 'Cost projections for utility-scale battery storage: 2021 update', *NREL technical report*, June 2021. https://www.nrel.gov/docs/fy21osti/79236.pdf; IRENA, 'Electricity storage and renewables: costs and markets to 2030', 2017. http://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Oct/IRENA_Electricity_Storage_Costs_2017.pdf

Figure 13: Utility-scale battery energy storage system used primarily for frequency regulation (and some energy arbitrage) at Hornsdale Power Reserve (100 MW/129 MWh – Australia)

Source: AEMO

Figure 14: Vanadium redox flow batteries at commercial scale (2 MW/8 MWh – Seattle, USA)

Source: UET

Novel long-duration energy storage technologies, including new thermal storage materials and media (particularly for solar thermal applications), gravitational storage (Energy Vault[64] (Figure 15)) and thermal storage (Carnot batteries[65] (Figure 16)) could also have future applications in South Africa, particularly as the existing coal fleet is re-purposed.

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64 Energy Vault, ‘Energy vault’, 2021. https://www.energyvault.com/

65 Siemens Gamesa, ‘Electric thermal energy storage (ETES): industrial decarbonisation’, 2021. https://www.siemensgamesa.com/en-int/-/media/siemensgamesa/downloads/en/products-and-services/hybrid-power-and-storage/etes/siemens-gamesa-etes-ad-teaser-industrial-decarbonization.pdf

Figure 15: Energy Vault (EV1) gravitational storage demonstration (Switzerland)

Source: Energy Vault

Figure 16: Electric thermal energy storage demonstration plant (130 MWh – Germany)

Source: Siemens

Although not disruptive, other classical long-duration hydroelectric energy storage technologies, like pumped hydro storage and the substantial regional reservoir storage available in the Southern African Power Pool, could be strategically utilised or marginally expanded.[66] Pumped hydro storage is limited as a result of limited remaining appropriate locations in South Africa,[67] while climatic variability and

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66 J Wright and J van Coller, 'Long-term system adequacy in the Southern African Power Pool (SAPP) based on a review of historical capacity balances and electricity trade: a case for capacity mechanisms', *Journal of Energy in Southern Africa*, 29(4), 2018. http://dx.doi.org/10.17159/2413-3051/2018/v29i4a5581;

IRENA, 'Southern African Power Pool: planning and prospects for renewable energy', technical report, 2013. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2013/SAPP.pdf

67 Eskom, 'Peaking power stations', *webpage*, 2021. https://www.eskom.co.za/eskom-

consequent hydrologic conditions require careful planning consideration for Southern African Power Pool hydro reservoirs.

3.1.3 Carbon capture and storage for electricity production

Considering South Africa's significant energy mix dependence on coal generation (and consequent carbon emissions intensity),[68] the potential utilisation of CCS technologies (pre-combustion and post-combustion) could play a role in transitioning the electrical energy mix.[69]

There are currently no applications of CCS at coal power stations in South Africa (mostly due to economic considerations). Globally, one of the largest power stations to apply post-combustion CCS is Petra Nova (240 MW) in the US (Figure 17), but wide-scale deployment has not yet occurred (mostly due to a combination of technological and economic challenges). Pre-combustion CCS technologies separate CO_2 to create fuels for utilisation in a power station (coal-to-gas integrated gasification combined cycle) but have achieved limited global commercial success.

Figure 17: Post-combustion CCS at Petra Nova (240 MW – USA)

Source: Petra Nova

divisions/gx/peaking-power-stations/

68 J R Calitz and J G Wright, 'Statistics of utility-scale power generation in South Africa in 2020', Council for Scientific and Industrial Research, 2021. http://hdl.handle.net/10204/11865

69 B Page, G Turan, A Zapantis, L Beck, C Consoli, I Havercroft, H Liu, P Loria, A Schneider, E Tamme, A Townsend, L Temple-Smith, D Rassool and T Zhang, 'Global status of CCS, targeting climate change 2019', Global CCS Institute, Technical report, 2020. https://www.globalccsinstitute.com/wp-content/uploads/2019/12/GCC_GLOBAL_STATUS_REPORT_2019.pdf

National Energy Technologies Laboratory (NETL), 'Post-combustion CO_2 capture', 2021.

NETL, 'Pre-combustion CO_2 capture', 2021.

The utilisation of bioenergy with carbon capture and storage is also considered a potentially transformative technology.[70] Drax power station in the UK (Figure 18) applies this negative emissions technology at scale,[71] but concerns around a set of unproven negative emissions technologies and biomass availability/sustainability remain.[72]

Figure 18: Bioenergy with carbon capture and storage at Drax power station (UK)

Source: Drax

Generally speaking, financing risk for CCS technologies and related projects has been highlighted as a challenge in developing economies especially in the power sector where limited global application has been seen.[73]

3.1.4 Electrolytic hydrogen

As power systems transition towards increasing amounts of VRE, dispatchable and flexible generation capacity that is not energy constrained will be required. In most countries this is predominantly provided by fossil fuels like natural gas, but generation

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70 B Page et al. 'Global status of CCS, targeting climate change 2019'.

71 Drax, 'BECCS and negative emissions', *webpage*, 2021. https://www.drax.com/about-us/our-projects/bioenergy-carbon-capture-use-and-storage-beccs/

72 S Fuss, J G Canadell, G P Peters, M Tavoni, R M Andrew, P Ciais, R B Jackson, C D Jones, F Kraxner, N Nakicenovic, C Le Quéré, M R Raupach, A Sharifi, P Smith and Y Yamagata, 'Commentary: betting on negative emissions', *Nature Climate Change* 4(10), 2014, pp 850–853; M Fajardy, A Koberle, N MacDowell and A Fantuzzi, 'BECCS deployment: a reality check', *Grantham Institute (Imperial College London) briefing paper No. 28*, December 2018. https://www.imperial.ac.uk/grantham/publications/briefing-papers/beccs-deployment-a-reality-check.php

73 D Rassool and I Havercroft, 'Financing CCS in developing countries', Global CCS Institute, 2021. https://www.globalccsinstitute.com/wp-content/uploads/2021/04/Financing-CCS-In-Developing-Countries-V2-1.pdf

technologies utilising natural gas[74] can be retrofitted or intentionally designed to be dual-fuelled to be driven by blends of zero-carbon fuels like hydrogen or ammonia.[75] Fuel cells utilising hydrogen can play a similar role as a source of power.[76]

The source of low-carbon or green hydrogen (and its derivatives, like ammonia) is expected to be produced by electrolyser technologies (alkali electrolyser cells, proton exchange membranes and, potentially, solid-oxide electrolytic cells) – that is, through electrolytic hydrogen production (see Figure 19 for an industrial scale example of this). Although still nascent as a result of underlying issues of economics and performance relative to competitor technologies (hydrogen via steam methane reforming), its viability has improved in recent years and is expected to continue to do so over the next 10 years,[77] largely driven by continued cost reductions, performance improvements in renewable energy and electrolyser technologies as well as the inclusion of carbon pricing in investment decisions.[78]

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74 Open-cycle gas turbines, closed-cycle gas turbines and internal combustion engines.

75 J Goldmeer, 'Ammonia as a gas turbine fuel', *General Electric PowerPoint presentation*, 2021; A Valera-Medina, S Morris, J Runyon, D G Pugh, R Marsh, P Beasley and T Hughes, 'Ammonia, methane and hydrogen for gas turbines', *Energy Procedia* 75, pp 118–123, August 2015.

76 I Staffell, D Scamman, A V Abad, P Balcombe, P E Dodds, P Ekins, N Shah and K R Ward, 'The role of hydrogen and fuel cells in the global energy system', *Energy and Environmental Science* 12(2), 2019, pp 463–491; D Hart, F Lehner, S Jones, J Lewis and M Klippenstein, 'The Review Industry Fuel Cell 2018', technical report, 2018. https://fuelcellindustryreview.com/archive/TheFuelCellIndustryReview2018.pdf

77 International Energy Agency (IEA), 'The future of hydrogen: seizing today's opportunities', *technology report*, 2019. https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf; World Energy Council (WEC), 'Hydrogen demand and cost dynamics', Working paper, 2021. https://www.worldenergy.org/publications/entry/working-paper-hydrogen-demand-and-cost-dynamics; WEC, 'Inputs from senior leaders on hydrogen', Working paper, 2021. https://www.worldenergy.org/publications/entry/working-paper-inputs-from-senior-leaders-on-hydrogen-developments; WEC, 'National hydrogen strategies,' Working paper, 2021. https://www.worldenergy.org/publications/entry/working-paper-hydrogen-on-the-horizon-national-hydrogen-strategies

78 Primary electrolyser technologies include alkali electrolyser cells, proton exchange membranes and solid-oxide electrolytic cells.

Figure 19: Industrial-scale proton exchange membrane electrolyser (20 MW & 3000 t/year – Becancur, Canada)

Source: Air Liquide

In sectors where GHG emissions are hard to abate (refineries, chemicals (ammonia, methanol), fertilisers, cement, iron/steel – direct reduced iron and potential green steel production), the use of low-carbon hydrogen or zero-carbon hydrogen (including blue hydrogen) will likely become necessary (electrolytic hydrogen is more likely to be appropriate for South Africa).

3.1.5 Nuclear fission (small modular reactors)[79]

As a zero-carbon source of energy, nuclear fission can play a critical supplemental role as part of mitigation efforts where existing nuclear generation capacity exists.[80] In South Africa, large pressurised water reactors may not be economical, but they have been included in long-term planning for now.[81] The deployment of small modular reactors entering commercial operations in South Africa – like NuScale, among others (see Figure 20) – is feasible but, considering the nascent nature of the technology,

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79 Nuclear fusion is another potentially disruptive technology but has been faced with seemingly endless engineering challenges. Despite this, there are estimated to be 30 private nuclear fusion firms across the globe. Funding has been and continues to be substantial, so technological development continues – for example, private enterprises like TAE Technologies, Helion Energy, General Fusion, Tokomak Energy, Commonwealth Fusion Systems and public- or state-funded efforts like the International Thermonuclear Experimental Reactor and Chinese Fusion Engineering Test Reactor.

80 J D Jenkins, Z Zhou, R Ponciroli, R B Vilim, F Ganda, F de Sisternes and A Botterud, 'The benefits of nuclear flexibility in power system operations with renewable energy', *Applied Energy* 222, 15 July 2018, pp 872–884; D K Gattie, J L Darnell and J N Massey, 'The role of US nuclear power in the 21st century', *Electricity Journal* 31(10), 2018, pp 1–5.

81 J G Wright et al., 'Formal comments on the Draft Integrated Resource Plan (IRP) 2018', CSIR, 2018; Department of Energy, 'Integrated Resource Plan 2018', Technical report, 2018.

Department of Mineral Resources and Energy, 'Integrated Resource Plan (IRP 2019)', 2019.

B McCall et al. 'Least-cost integrated resource planning and cost-optimal climate change mitigation policy: alternatives for the South African electricity system', 2019.

definitively needs global commercial deployment (likely in the US initially) and related cost reductions.

Figure 20: NuScale small modular reactor (77 MW) – artist's impression

Source: NuScale (2021)

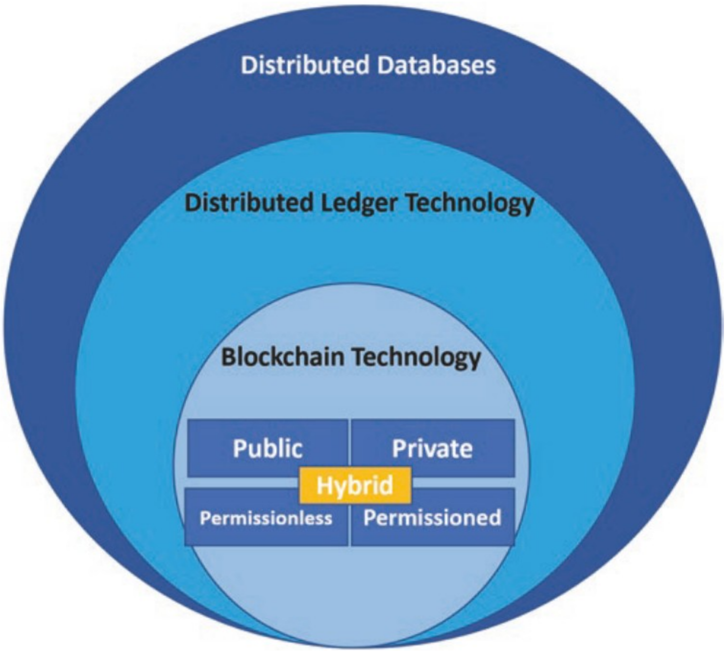
3.1.6 Digitalisation

The digitalisation layer in the energy sector that combines data, analytics and connectivity is envisioned as an enabler in future energy systems that will integrate new technologies and allow customers, utilities and other market participants increased levels of flexibility. This is specifically applicable to the proliferation of VRE technologies like solar photovoltaics and wind, where measurement, control and management are distributed via digitally enabled tools and platforms for system operators, utilities, private enterprises and customers themselves.

Specific applications that could leverage digitalisation are those in aggregated demand side response resources to increase system flexibility and improve system integration. Two specific cases most relevant to the South African context are automatic electric water heaters for domestic applications (residential households) and smart charging/discharging of electric vehicles.

Specific digital technologies with a significant anticipated impact include advanced metering infrastructure to enable various potential demand-side response applications, remote monitoring/control and industrial automation. Among other capabilities, distributed ledger technology and blockchain platforms can scale distributed energy trading (including aggregation) and intelligent mobility.[82] Considering their inherent decentralised nature, distributed ledger technology and blockchain more specifically have wide-ranging energy-system applications (Figure 21) as a result of their inherent secure, distributed and flexible nature.

Figure 21: Graphical illustration of how blockchain is a subset of distributed ledger technologies and distributed databases more generally[83]



Source: Cali et al. (2021)

Specific applications of artificial intelligence and machine learning in the energy sector that contribute to the broader suite of fourth industrial revolution technologies might also include generator preventative maintenance, system reliability (adequacy and security) and transmission line design and monitoring.[84]

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82 CIGRE WG C5.30 (TB 824), *The role of blockchain technologies in power markets*, 2020. https://e-cigre.org/publication/824-the-role-of-blockchain-technologies-in-power-markets;
IEA, 'Digitalization and energy', Paris: IEA, 2017. https://iea.blob.core.windows.net/assets/b1e6600c-4e40-4d9c-809d-1d1724c763d5/DigitalizationandEnergy3.pdf

83 U Cali, M Kuzlu, M Pipattanasomporn, J Kempf and L Bai, *Digitalization of power markets and systems using energy informatics.* Cham: Springer, 2021.

84 T Marwala, *Closing the gap*. Johannesburg: Pan Macmillan, 2021.

3.2 Industry

3.2.1 Blue hydrogen

Approximately 98% of current global hydrogen consumption (mostly for refining and ammonia production) is produced by steam methane reforming of fossil-based fuels like natural gas (grey hydrogen), making significant contributions to global GHG emissions.[85] Low-carbon hydrogen can be produced, that is blue hydrogen, by utilising CCS technologies to capture CO_2 from the steam methane reforming process.

The production and utilisation of hydrogen as an energy carrier and feedstock is expected to dramatically increase as part of net-zero future economies (+130% by 2030 and +480% by 2050).[86] This will require a range of low-carbon or zero-carbon sources of hydrogen (including blue hydrogen) for hard-to-abate industrial sectors like refineries, chemicals (ammonia, methanol), fertilisers and iron/steel manufacture. In hard-to-abate sectors, the use of large-scale CCS technologies (like blue hydrogen) may be the most efficient method of mitigation.[87]

South Africa is uniquely placed in this respect, with substantial existing infrastructure and capacity at Sasol and PetroSA, where large volumes of fossil-based hydrogen are currently produced (from coal and natural gas) for synthetic fuel production and diesel desulphurisation. There is thus significant potential to mitigate GHG emissions from these processes with blue hydrogen. However, as shown in Figure 22 (in South Africa) and Figure 23 (globally), limited proven large-scale geological storage formations may limit CCS deployment at scale (theoretical storage of 150 Gt is almost all offshore in the Outeniqua, Orange, Durban and Zululand basins).

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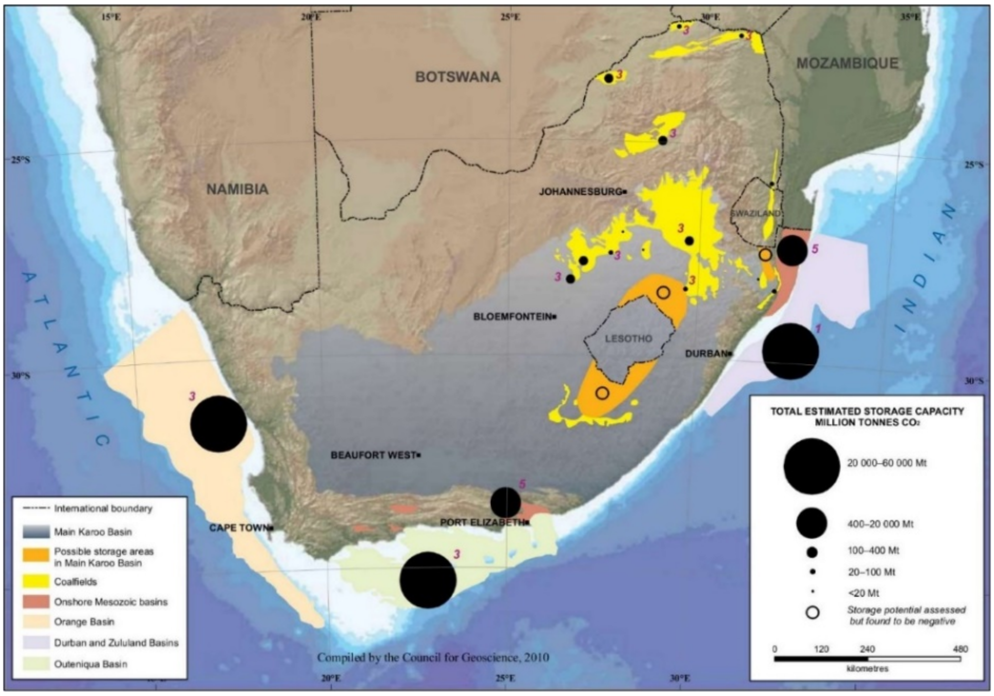
85 Global CCS Institute, 'Blue hydrogen', 2021. https://www.globalccsinstitute.com/wp-content/uploads/2021/04/CCE-Blue-Hydrogen.pdf

86 IEA, 'World energy outlook 2021', 2021. Paris: IEA. https://www.iea.org/reports/world-energy-outlook-2021; IEA, 'Net zero by 2050: a roadmap for the global energy sector', technical report, 2021. Paris: IEA. https://iea.blob. core.windows.net/assets/4719e321-6d3d-41a2-bd6b-461ad2f850a8/ NetZeroby2050-ARoadmapfortheGlobalEnergySector.pdf

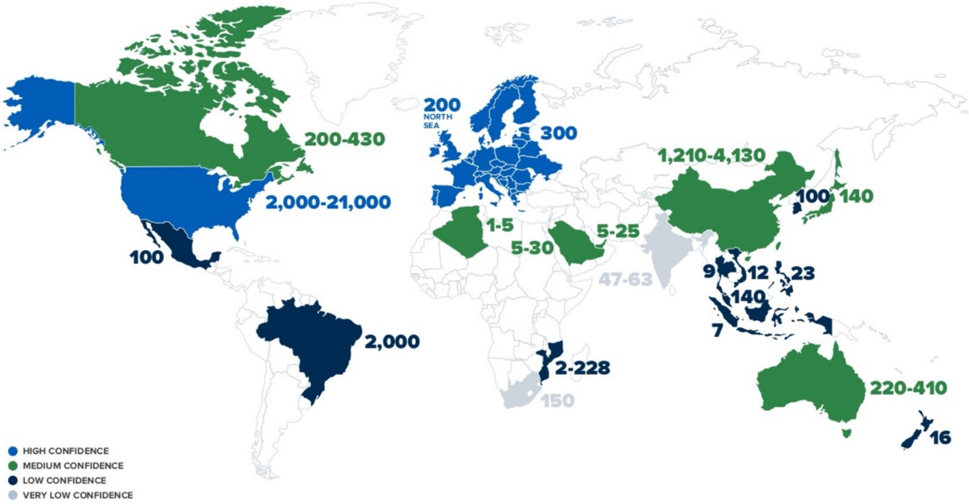
87 S Paltsev, J Morris, H Kheshgi and H Herzog, 'Hard-to-abate sectors: the role of industrial carbon capture and storage (CCS) in emission mitigation', *Applied Energy* 300, Oct 2021, p 117322.

Figure 22: Estimated South African CO_2 storage resources[88]



Source: J Glazewski, A Gilder and E Swanepoel (2012); Cloete (2010)

Figure 23: Estimated global storage resources (gigatonne)[89]



Source: B Page et al (2020)

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88 J Glazewski, A Gilder and E Swanepoel, 'Carbon capture and storage (CCS): towards a regulatory and legal regime in South Africa', Institute of Marine and Environmental Law and African Climate and Development Initiative, 2012, http://www.imel.uct.ac.za/usr/law/imel/downloads/CCS_Report.pdf.

M Cloete, 'Atlas on geological storage of carbon dioxide in South Africa', Council for Geoscience, Pretoria, 2010.

89 B Page et al., 'Global status of CCS, targeting climate change 2019', Global CCS Institute, 2020.

As a result of this limited storage at scale and CO_2 utilisation, a prioritisation of the industrial demand of electrolytic hydrogen production for the remaining CO_2 is more likely (carbon capture, utilisation and storage would not be sufficient to avoid the requirement to store large amounts of CO_2 in known geological formations).

3.2.2 Direct air carbon capture and storage

Direct air carbon capture and storage (DACCS) is an enabling negative emissions technology that uses chemical processes to capture CO_2 directly from the atmosphere and store it (typically in geological storage reservoirs). It is still in the early stages of development, relatively expensive and exhibits scaling challenges,[90] and to date the only large-scale DACCS project is Orca's Climeworks in Iceland (Figure 24). The use of large-scale CCS technologies (like DACCS) is expected to become a viable and efficient method to mitigate CO_2 in the long term.[91]

DACCS technologies can be water and energy intensive and thus must be based on zero-carbon electricity and heat while ensuring net-negative emissions are part of their deployments.

If not storing captured CO_2, utilisation of DACCS facilities for particular applications could also be considered, for example carbon capture, utilisation and storage. Particular applications could include enhanced oil recovery, the production of synthetic fuels (powerfuels/Power-to-X (PtX)), fertilisers, beverages, building materials/aggregates and chemicals production.[92]

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90 D W Keith, G Holmes, D St Angelo and K Heidel, 'A process for capturing CO_2 from the atmosphere', *Joule* 2(8), 2018, pp 1573–1594;

J C Minx, W F Lamb, M W Callaghan, S Fuss, J Hilaire, F Creutzig, T Amann, T Beringer, W De Oliveira Garcia, J Hartmann, T Khanna, D Lenzi, G Luderer, G F Nemet, J Rogelj, P Smith, J L Vicente, J Wilcox and M Del Mar Zamora Dominguez, 'Negative emissions - Part 1: Research landscape and synthesis' *Environmental Research Letters*, 2018, 13(6);

S Fuss, W F Lamb, M W Callaghan, J Hilaire, F Creutzig, T Amann, T Beringer, W De Oliveira Garcia, J Hartmann, T Khanna, G Luderer, G F Nemet, J Rogelj, P Smith, J V Vicente, J Wilcox, M Del Mar Zamora Dominguez and J. C. Minx, 'Negative emissions - Part 2: Costs, potentials and side effects', *Environmental Research Letters*, 2018, 13(6).

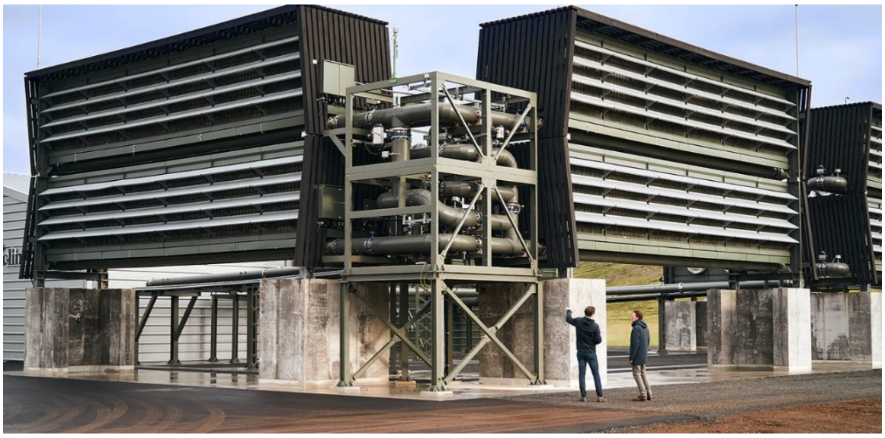
G F Nemet, M W Callaghan, F Creutzig, S Fuss, J Hartmann, J Hilaire, W F Lamb, J C Minx, S Rogers and P Smith, 'Negative emissions - Part 3: Innovation and upscaling', *Environmental Research Letters*,2018, 13(6).

91 S Paltsev et al. 'Hard-to-abate sectors', *Applied Energy* 300, Oct 2021.

92 B Page et al., 'Global status of CCS, targeting climate change 2019', Global CCS Institute, 2020.

As discussed in section 3.2.1, the need to store large amounts of CO_2 may still pose significant challenges to the deployment of DACCS in the South African context.

Figure 24: Orca's Climeworks is the first large-scale DACCS facility in the world (≈4 kt CO_2/year – Iceland)[93]



Source: Climeworks

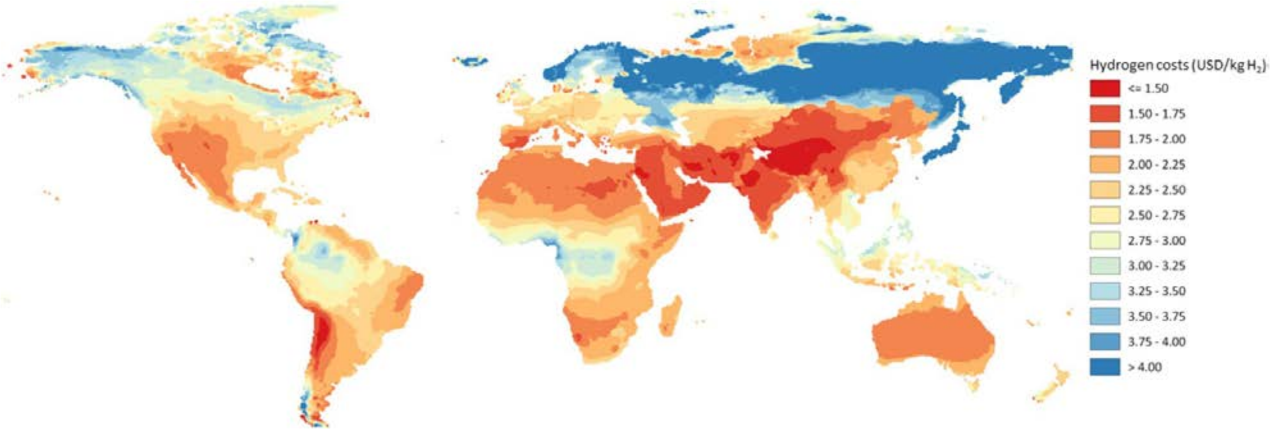
3.2.3 Electrolytic hydrogen (export focus)

Although not explicitly a technological development in itself, the underlying technologies comprising domestic electrolytic hydrogen production in South Africa for export directly impacts the South African economy. As described in Section 3.1.4, the production of low-carbon or zero-carbon hydrogen (electrolytically) is expected to become competitive in the next 10 years.[94] This is particularly important for South Africa as a potential exporter to large economies like Japan, South Korea and a number of EU countries (see Figure 25). In the long term, electrolytic hydrogen utilisation in hard-to-abate industrial sectors offers an opportunity for further domestic decarbonisation while simultaneously ensuring decarbonised exports as countries consider carbon-pricing mechanisms like carbon border adjustment mechanisms.

93 Climeworks, 'Orca: the first large-scale plant'. https://climeworks.com/roadmap/orca

94 T Roos and J Wright, 'Powerfuels and green hydrogen', *EU-South Africa Partners for Growth report*, 2021. https://www.researchgate.net/publication/349140439_Powerfuels_and_Green_Hydrogen_public_version

Figure 25: Estimated hydrogen production cost from hybrid solar photovoltaic and wind systems in 2030[95]



Source: International Energy Agency

3.3 Mobility

3.3.1 Electrification of mobility (direct)

The direct electrification of mobility via the adoption of electric vehicles can be a major contributor to mitigation efforts as electricity mixes decarbonise. The adoption of electric vehicles is likely to be most applicable to private transportation (passenger vehicles) and particular areas of public transportation (rail, buses), electric light-duty vehicles and some medium-duty vehicles (for goods and passenger transportation). As lithium-ion battery storage packs comprise the dominant cost component of electric vehicles, their historical cost trajectory over the past decade clearly demonstrates why adoption at scale is inevitable (Figure 26).

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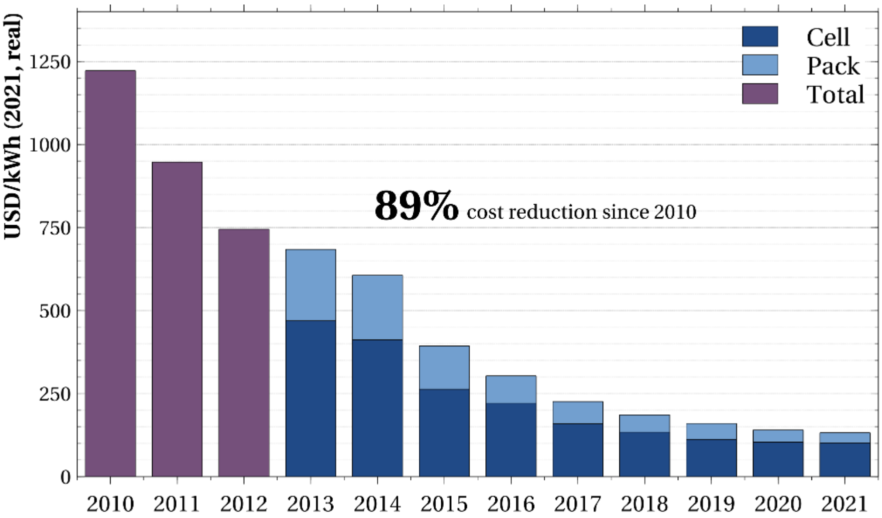
95 IEA, ‘Global hydrogen review 2021’, Paris: IEA, 2021. https://iea.blob.core.windows.net/assets/e57fd1ee-aac7-494d-a351-f2a4024909b4/GlobalHydrogenReview2021.pdf

Figure 26: Battery pack costs trajectory (2010–2021)[96]



Source: Bloomberg New Energy Finance (2017)

Mobility electrification is likely to reduce South Africa's significant dependence on imported oil and liquid fuels (to improve national energy security) and increasingly diversify the country's energy mix towards cleaner mechanisms of electricity production (dominated by VRE technologies).

3.3.2 Hydrogen mobility

Where the direct electrification of mobility is not technically or economically feasible, indirect electrification via fuel cell electric vehicles (fuelled with electrolytic hydrogen) for public transportation (buses) and long-haul goods transportation could become viable for medium- and heavy-duty vehicles.[97] Minor existing gas network infrastructure in South Africa may prove challenging for the necessary scale to make costs competitive with existing alternative energy carriers.

As with the electrification of mobility, the utilisation of domestically produced hydrogen could contribute to a substantial reduction in CO_2 emissions and an increase in national

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96 Based on Bloomberg New Energy Finance, 'Battery pack prices fall to an average of $132/kwh, but rising commodity prices start to bite', 2021. https://about.bnef.com/blog/battery-pack-prices-fall-to-an-average-of-132-kwh-but-rising-commodity-prices-start-to-bite/; and C Curry, 'Lithium-ion battery costs and market', Bloomberg New Energy Finance, 2017. https://data.bloomberglp.com/bnef/sites/14/2017/07/BNEF-Lithium-ion-battery-costs-and-market.pdf

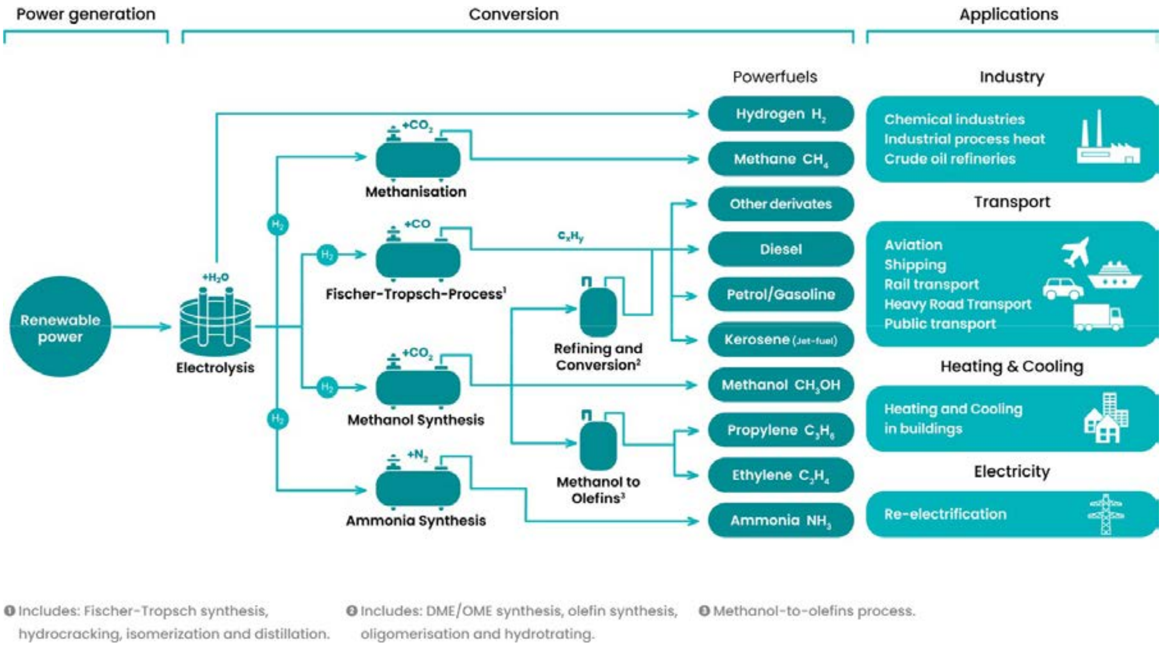
97 Although not indirect electrification, fuel cell electric vehicles can also utilise low-carbon hydrogen (like blue hydrogen).

energy security (substantively reduced oil and liquid fuel imports).

3.3.3 Powerfuels

As summarised in Figure 27, powerfuels (or PtX technological developments) are synthetic gaseous or liquid fuels based on electrolytic hydrogen. In other mobility sectors where direct electrification or hydrogen may not be technically or economically viable and existing liquid/gaseous fuels may still be required (shipping, aviation), the utilisation of powerfuels could contribute significantly to mitigation. An example of this is shown in Figure 28, a PtX plant in Germany producing aviation fuel (e-kerosene).

Figure 27: Range of powerfuel applications – all based on electrolytic hydrogen production (processes, products and applications)[98]



Source: Crone et al (2019)

98 Global Alliance Powerfuels – German Energy Agency, 'Powerfuels: missing link to a successful global energy transition', technical report, 2021. https://www.powerfuels.org/fileadmin/gap/Publikationen/Green_Paper/Global_Alliance_Powerfuels_Powerfuels-A_missing_link_to_a_successful_global_energy_transition.PDF

Figure 28: Existing Ineratec PtX plant (≈350 000 kg/year – Germany)[99]

Source: Ineratec (2021)

Domestic off-take in South Africa is unlikely in the short to medium term. Instead, international exports of hydrogen, hydrogen-based derivatives and/or synthetically produced PtX powerfuels could be a new economic growth area as other economic sectors decline.

3.3.4 Next generation biofuels blending

Biofuels are typically classified into four generations (summarised in Figure 29)[100] – (i) biofuels based on edible feedstocks; (ii) biofuels produced from a range of feedstocks (non-edible lignocellulosic feedstocks and waste); (iii) algal biomass (also linked to utilising CO_2 as a feedstock); and (iv) genetically engineered high-yield feedstocks (including non-edible feedstocks and algae) combined with advanced process technologies. For the purposes of this research, advances in fourth generation biofuels are deemed 'next generation' biofuels (some second and third generation biofuels could also be considered).

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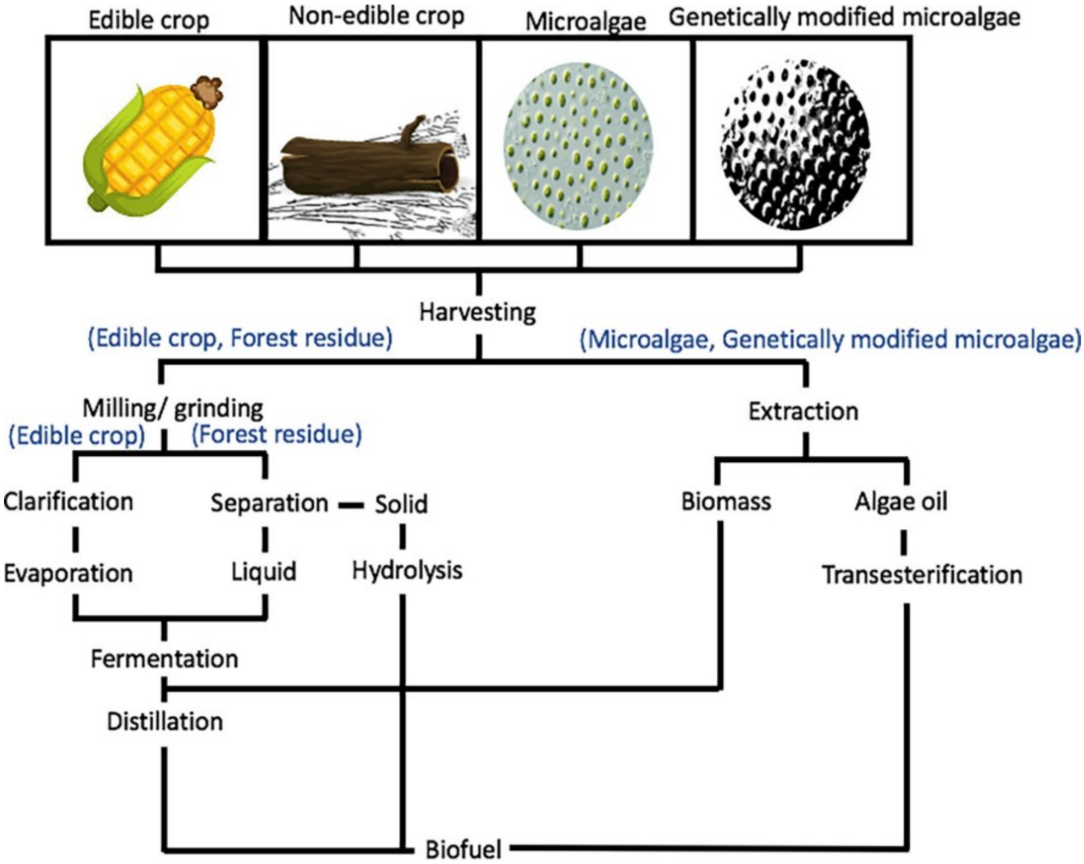
99 Ineratec, 'Launch of the world's largest power-to-liquid pilot plant', *webpage,* 2021. https://ineratec.de/en/launch-of-the-worlds-largest-power-to-liquid-pilot-plant/

100 R A Lee and J M Lavoie, 'From first- to third-generation biofuels: challenges of producing a commodity from a biomass of increasing complexity', *Animal Frontiers* 3(2), 2013, pp 6–11.
N S M Aron, K S Khoo, K W Chew, P L Show, W H Chen and T H P Nguyen, 'Sustainability of the four generations of biofuels: a review', *International Journal of Energy Research* 44(12), 2020, pp 9266–9282; H A Alalwan, A H Alminshid and H A Aljaafari, 'Promising evolution of biofuel generations. subject review', *Renewable Energy Focus*, 2019, 28(00), pp 127–139.

Figure 29: Four generations of biofuels and conversion processes[101]



Source: N S M Aron et al (2020)

The more likely applications in South Africa are to utilise biofuels in aviation and for blending into terrestrial liquid fuels (bioethanol and biodiesel).[102] However, despite biofuel blending of up to 2% having been part of South African energy policy for some time,[103] it has not yet scaled to expected levels (for a number of reasons beyond the scope of this research).[104]

With these specific challenges to available feedstocks and scale, the potential implications for increased adoption of PtX at scale (as discussed in section 3.3.3) may

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101 N S M Aron et al., 'Sustainability of the four generations of biofuels', *International Journal of Energy Research* 44(12), 2020.

102 World Wide Fund for Nature (WWF), 'Taking off: understanding the sustainable aviation biofuel potential in sub-Saharan Africa', 2019. Cape Town: WWF-SA. http://awsassets.wwf.org.za/downloads/sustainable_biofuel_potential_ssaf_summaryreport_finalized_v7_2_digital_pages.pdf

103 Department of Minerals and Energy, 'Biofuels industrial strategy of the Republic of South Africa', technical report, 2007. http://www.energy.gov.za/files/esources/renewables/biofuels_indus_strat.pdf(2).pdf

104 A Stone, G Henley and T Maseela, 'Modelling growth scenarios for biofuels in South Africa's transport sector', WIDER Working Paper 148/2015, 2015. https://www.wider.unu.edu/sites/default/files/wp2015-148.pdf

prove more likely considering existing natural resources, skills and experience in the fuels sector.

3.3.5 Shared mobility and autonomous vehicles

The increasing adoption of ride-sharing/e-hailing services (shared mobility) and autonomous vehicles in particular applications is also expected to reshape mobility (for goods and passengers).[105]

In the South African context, this will mean a notably augmented and relatively lower need for energy and transportation infrastructure despite a significant anticipated growth in mobility demand. With mobility electrification, this will impact electricity infrastructure needs, utility business models and institutional arrangements.[106] The exponential nature of these disruptive technologies will mean a relatively short diffusion period requiring careful and strategic consideration.

3.4 Agriculture and land use[107]

3.4.1 Soil and crop management

A range of interventions in soil and crop management could have significant impacts on domestic productivity and possible exports for South Africa, specifically in remote sensing and monitoring, increasingly resilient crops (to drought, extreme temperatures, disease and pests), precision farming, modern tillage practices, drip irrigation, crop diversity and the combination of inorganic/organic fertilisers and sustainably produced synthetic fertilisers.[108]

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105 R Iacobucci, B McLellan and T Tezuka, 'Modeling shared autonomous electric vehicles: potential for transport and power grid integration', *Energy* 158, 2018, pp 148–163.

106 J Weiss, R Hledik, R Lueken, T Lee and W Gorman, 'The electrification accelerator: understanding the implications of autonomous vehicles for electric utilities', *The Electricity Journal* 30(10), 2017, pp 50–57.

107 Other enabling technologies considered ancillary at this stage include adaptation technologies like integrated national climate change monitoring systems and improved remote sensing.

108 International Finance Corporation, 'CTRL-ALT-DEL: A green reboot for emerging markets', 2021; R Clements, J Haggar, A Quezada and J Torres, 'Technologies for climate change adaptation – agriculture sector', X. Zhu (ed). Roskilde: UNEP Risø Centre, 2011. F Shah and W Wu, 'Soil and crop management strategies to ensure higher crop productivity within sustainable environments', *Sustainability* 11(5), 2019, p 1485. S Visser, S Keesstra, G Maas, M de Cleen and C Molenaar, 'Soil as a basis to create enabling conditions for transitions towards sustainable land management as a key to achieve the SDGs by 2030', *Sustainability* 11(23), 2019, p 6792.

3.4.2 Livestock management and alternatives

As with soil and crop management, interventions in livestock management and alternatives have potentially significant impacts, including through selective breeding, alternative proteins and related plant-based substitutes for protein.[109]

3.4.3 Land cover and forest management

Increased investment is required in technologies that can drive biodiverse land-cover at scale for CO_2 sequestration (or at least to reverse deforestation) in combination with nature-based urban infrastructure (tree planting, roof greening, vertical agriculture).[110]

Examples of biodiverse forestation platform technologies include institutions like BioCarbon Partners and voluntary platforms like Natural Capital Exchange as a carbon marketplace (previously SylviaTerra). Recent academic efforts have increased transparency, leveraging blockchain (Tezos) as an underlying technology for the marketplace.[111] Such interventions must be carefully balanced with concerns about food security and long-term sequestration resiliency.

With near-global coverage (166 countries), a recent Organisation for Economic Co-operation and Development study attempted to better understand how forest sequestration could be most efficient.[112] Criteria included that carbon offsets should be real, permanent, quantifiable, verifiable, unique, transparent, conservative, account for leakage and be additional.[113] Although most of these criteria seem self-apparent,

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109 C Butler, A Denis-Ryan, P Graham, R Kelly, L Reedman, I Stewart and T Yankos, 'Decarbonisation futures', technical report, 2020. https://www.climateworksaustralia.org/wp-content/uploads/2020/04/CWA-DECARBONISATION-FUTURES-2020-TECH-REPORT.pdf

110 International Finance Corporation, 'CTRL-ALT-DEL: A green reboot for emerging markets', 2021; R Clements et al., 'Technologies for climate change adaptation – agriculture sector', 2011.

111 Cambridge University, 'Cambridge Centre for Carbon Credits (4C)', 2021. https://4c.cst.cam.ac.uk/

112 R Q Grafton, H L Chu, H Nelson and G Bonnis, 'A global analysis of the cost-efficiency of forest carbon sequestration', *OECD Environment Working Papers, No. 185*, Paris: OECD Publishing. https://doi.org/10.1787/e4d45973-en 2021

113 *Real:* Not generated from inaccurate accounting or modelling artefacts; *Permanent:* Include insurance/buffer to make up for potential loss; *Quantifiable:* Established methodology for baselines to determine stored carbon quantities; *Verifiable:* Third-party expert verification; *Unique:* Single registry (to avoid double-counting); *Transparent:* Methodology should be clear; *Conservative:* Estimates should not exaggerate capture; *Leakage:* Emissions shifted outside of a geographical area as a consequence of implementing offsets; *Additional:* Above the baseline that would not have happened without a payment incentive.

The analysis intentionally shifted towards a more integrated assessment of efficiency of sequestration by considering the opportunity costs of land use, forest productivity, agricultural GHG emissions, transaction costs (ease of doing business), labour costs and wildfire risk. South Africa featured well in the low opportunity cost of land use dimension but not as prominently in the other dimensions examined.

4. Evaluation of potential implications

4.1 Framework of assessment

The potential implications of the prioritised technologies and technological developments outlined in section 3 are evaluated in this section, and the expected impact of each technological development on relative transition risk for the South African economy and financial markets and institutions is described. By definition, the analysis is also limited to expected macroeconomic impacts (it is appreciated that microeconomic impacts will also occur simultaneously). This evaluation should be:

1. A qualitative starting point from which to consider the potential long-term implications of these technological developments (to inform a more rigorous quantitative analysis at a later stage); and
2. Periodically updated and reassessed considering the framework presented.

It is clear that transition risk increases as ambition to mitigate the effects of and adapt to climate change increases (see Figures 6 and 31). Hence, the focus of the evaluation is on the well-known Network of Central Banks and Supervisors for Greening the Financial System (NGFS) scenarios as a framework established via engagements with numerous central banks, supervisors and observers in partnership with a consortium of six academic institutions. These scenarios were developed to provide a common starting point for the analysis of climate risks to economies and financial systems. The NGFS scenarios were updated in 2021 to further align with net-zero commitments and expanded macroeconomic variables.

In the NGFS scenarios, ‘moderate’ to ‘fast’ technology change occurs (see Figure 30), and the scenarios provide for transitions in an ‘orderly’ or ‘disorderly’ manner (Figure 31). Hence, two NGFS scenarios are considered as part of this analysis:

- **The NGFS Net-Zero 2050 (1.5°C)** scenario limits warming to 1.5°C via stringent climate policies and innovation, reaching global net-zero CO_2 emissions by

2050 (some developed economies to reach net-zero for all GHGs).

- **The NGFS Delayed Transition (<2°C)** scenario assumes that annual emissions will not decrease until 2030 and that strong climate policies and innovation will limit warming to below 2°C; CO_2 removal is limited but regional response variation is high.

Figure 30: Characteristics of NGFS Climate Scenarios (note specific 'moderate' to 'fast' technology change scenarios and regional policy variation)[114]

		Physical risk	Transition risk			
Category	**Scenario**	**Policy ambition**	**Policy reaction**	**Technology change**	**Carbon dioxide removal**	**Regional policy variation⁺**
Orderly	Net Zero 2050	1.5°C	Immediate and smooth	Fast change	Medium use	Medium variation
	Below 2°C	1.7°C	Immediate and smooth	Moderate change	Medium use	Low variation
Disorderly	Divergent Net Zero	1.5°C	Immediate but divergent	Fast change	Low use	Medium variation
	Delayed transition	1.8°C	Delayed	Slow/Fast change	Low use	High variation
Hot House World	Nationally Determined Contributions (NDCs)	~2.5°C	NDCs	Slow change	Low use	Low variation
	Current Policies	3°C+	None – current policies	Slow change	Low use	Low variation

Colour coding indicates whether the characteristic makes the scenario more or less severe from a macro-financial risk perspective^

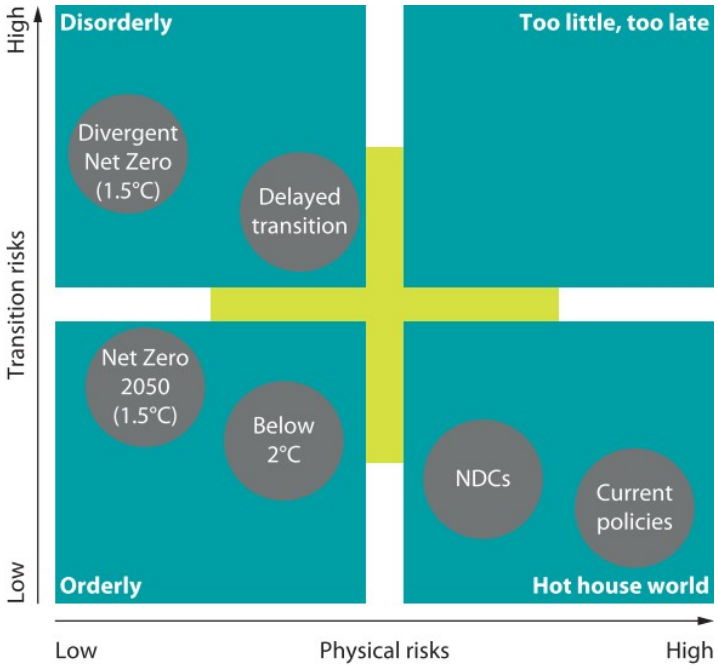
Lower risk

Moderate risk

Higher risk

Source: NGFS (2021)

Figure 31: NGFS climate scenarios framed in the context of physical risk and transition risk[115]



Positioning of scenarios is approximate, based on an assessment of physical and transition risks out to 2100.

Source: NGFS (2021)

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114 NGFS, 'NGFS climate scenarios for central banks and supervisors', Technical report, 2021. https://www.ngfs.net/en/ngfs-climate-scenarios-central-banks-and-supervisors

115 Ibid.

4.2 Potential transition risks for the economy and financial systems

The main transition risks outlined below are utilised to qualitatively assess the potential implications of the priority technological developments presented and assessed in section 3.[116] Sectors expected to play a key role in each of the transition risks are highlighted and related impacts are described (and are followed by a description of the sectors most likely to be impacted).

A first-pass summary of whether the highlighted risks are relevant and material is presented in the assessment of potential implications in Tables 1 to 4. The qualitative assessment utilises measures of high (H), medium (M) and low (L) to understand impacts in either an NGFS Net-Zero 2050 (1.5°C) scenario (NZ) or an NGFS Delayed Transition (<2°C) scenario (DT) (as described in section 4.1).

- Moderate economic impacts: Increased GDP from transition investments (even if delayed) is offset by expected, seemingly unavoidable physical risks (temperature extremes, precipitation). *[energy, industrial, mobility, financial, agricultural]*
- Adjusted multi-factor productivity: Potentially increased by deployment of technologies and technological developments ameliorated by reduced labour and land productivity (as some physical risks seem unavoidable, e.g. temperature extremes). *[energy, industrial, mobility, financial, agricultural]*
- Relative pricing changes: Supply-demand misalignment resulting in supply shocks and demand shocks due to structural effects as systems transition.

[116] Ibid; P Grippa et al., 'Climate change and financial risk', Finance and Development, Dec 2019; NGFS, 'NGFS climate scenarios for central banks and supervisors', Technical report, 2021. NGFS, 'Progress report on the guide for supervisors', technical document, 2021. https://www.ngfs.net/sites/default/files/progress_report_on_the_guide_for_supervisors_0.pdf; U Volz, J Beirne, N A Preudhomme, A Fenton, E Mazzacurati, N Renzhi and J Stampe, *'Climate change and sovereign risk'*, London: SOAS Centre for Sustainable Finance, 2020. Bank for International Settlements, Basel Committee on Banking Supervision, 'Climate-related risk drivers and their transmission channels', analytical report, 2021. https://www.bis.org/bcbs/publ/d517.pdf E Campiglio, Y Dafermos, P Monnin, J Ryan-Collins, G Schotten and M Tanaka, 'Climate change challenges for central banks and financial regulators', *Nature Climate Change* 2018, 8, pp 462–468. D Faccia, M Parker and L Stracca, 'What we know about climate change and drought', VoxEU CEPR, 2021. https://voxeu.org/article/what-we-know-about-climate-change-and-inflation D Faccia, M Parker and L Stracca, 'Feeling the heat: extreme temperatures and price stability', *European Central Bank Working Paper No 2626*, 2021. https://www.ecb.europa.eu/pub/pdf/scpwps/ecb.wp2626~e86e2be2b4.en.pdf

[energy, mobility, agricultural]

- Economic input costs: Domestic and corporate energy price increases as carbon is explicitly priced across more sectors, abating as the economy decarbonises and switches to cleaner energy solutions. *[energy, mobility]*
- Labour market frictions: As economic systems transition (stranded labour and reduced labour productivity). *[energy, industrial, agricultural]*
- Carbon border adjustments: In a delayed transition, existing South African carbon-intensive exports may be penalised by trading partners imposing border tax adjustments, for example carbon border adjustment mechanisms under consideration in the EU. *[energy, industrial, mobility, financial]*
- International trade growth: Increased export of new products, commodities and possibly technologies with potential for strengthened long-term exchange rates as new export opportunities grow. *[energy, industrial]*
- Socio-economic changes: Changing consumption patterns driven by population growth and upward mobility. *[energy, mobility, agricultural]*
- Accelerated capital depreciation: Potential for stranded assets for debt-holders and equity investors in existing infrastructure*. [energy, industrial, mobility, financial]*
- Fiscal space: Potential increase in revenues from carbon pricing, assuming carbon tax as a proxy but appreciating that most transition policies will not result in direct revenue to government. This would also be balanced by lower income tax revenue (lower labour productivity) and a reduction in taxes and royalties from incumbent fossil fuel industries (e.g. fuel levies). The extent of impact will depend on the extent to which revenues are recycled back into the economy, that is the share between investment and debt payments.[117]
- Relative decrease in public health costs: Fewer localised pollutants as a co-benefit of reduced GHG emissions from fossil fuel sources. *[energy, industrial, mobility, financial, agricultural]*
- Improved energy security: Lower relative levels of energy imports and a consequent trade balance improvement (energy imports reduced even with

117 M C Paoli, R van der Ploeg, 'Recycling revenue to improve political feasibility of carbon pricing in the UK', CEPR Policy Portal, 2021; R van der Ploeg, A Rezai, M T November, D Furceri, M Ganslmeier, J D Ostry, D Klenert and C Hepburn, 'Carbon tax recycling and popular support in Germany', CEPR Policy Portal, 2021.

expected reduction in coal exports if international trade partners transition simultaneously). *[energy, mobility]*

- Increased relative food security: When prioritised, sustainable agricultural and food production methods can improve food security. *[Financial, agricultural]*
- Sectoral disruption: Likely to occur in incumbent sectors as technological developments push transitions (new economic growth sectors). *[energy, industrial, mobility, financial, agricultural]*
- Reduced incumbent business profitability: Lower market growth or absolute market declines and carbon pricing impacting profitability. Depending on business strategy, relatively cheaper clean energy supply should ameliorate this impact. *[energy, industrial, mobility, financial]*
- Operational risks for firms: If forced facility closures are imposed, competitors may gain market share. In addition, increased liability risk exists for firms as a result of historical environmental conduct. *[energy, industrial, financial]*
- Increased corporate and government litigation: Mostly from incumbents, but also possible as a result of an increased focus on climate change attribution in delayed transitions. *[energy, industrial, financial]*
- Market losses: Likely in equities (repricing carbon-intensive assets), bonds and selected commodities (coal and fossil fuel-based synthetic liquid fuel production) if either or both the domestic economy and international trade partners transition. *[energy, mobility, financial]*
- Household wealth: Increase in carbon pricing and insurance premiums potentially offset by least-cost pathways in the energy sector. *[Energy, financial]*
- Moderately reduced underwriting risk: Transitions resulting in fewer climate-related claims. *[financial]*
- Long-term interest rates would rise as a result of inflationary pressure created by increased levels of carbon pricing and increased investment demand in less carbon-intensive technologies. Potential for higher risk aversion resulting in increased funding costs impacting on firms (potentially offset by lenders able to justify higher interest rates). *[energy, industrial, mobility, financial]*

Table 1: Summarised evaluation of technological developments (energy sector)

Technological development	Speed of technology change		Transition risk and impact on RSA economy, financial markets and institutions	
	NZ	*DT*	*NZ*	*DT*
Scaled-up VRE technologies	Fast	Fast	H	M
Electrical energy storage	Fast	Fast	M	M
CCS technologies for electricity production	Fast	Slow	M	L
Electrolytic hydrogen	Fast	Slow	H	M
Nuclear fission (SMRs)	Fast	Slow	H	M
Digitalisation	Fast	Fast	H	H

NZ - NGFS Net-Zero 2050 (1.5°C) scenario; DT - NGFS Delayed transition (<2°C) scenario; H - High; M - Moderate; L - Low

Source: Author

Table 2: Summarised evaluation of technological developments (industrial sector)

Technological development	Speed of technology change		Transition risk and impact on RSA economy, financial markets and institutions	
	NZ	*DT*	*NZ*	*DT*
Blue hydrogen	Fast	Slow	M	L
Direct air carbon capture and storage (DACCS)	Fast	Slow	M	L
Electrolytic hydrogen (export focus)	Fast	Slow	H	M

NZ - NGFS Net-Zero 2050 (1.5°C) scenario; DT - NGFS Delayed transition (<2°C) scenario; H - High; M - Moderate; L - Low

Source: Author

Table 3: Summarised evaluation of technological developments (mobility sector)

Technological development	Speed of technology change		Transition risk and impact on RSA economy, financial markets and institutions	
	NZ	*DT*	*NZ*	*DT*
Electrification of mobility	Fast	Slow	H	M
Hydrogen mobility	Fast	Slow	H	M
Powerfuels - Power-to-X (PtX)	Fast	Slow	H	L
Next generation biofuels blending	Fast	Slow	M	M
Ride-sharing and autonomous vehicles	Fast	Slow	H	L

NZ - NGFS Net-Zero 2050 (1.5˚C) scenario; DT - NGFS Delayed transition (<2˚C) scenario; H - High; M - Moderate; L - Low

Source: Author

Table 4: Summarised evaluation of technological developments (agriculture and land-use sector)

Technological development	Speed of technology change		Transition risk and impact on RSA economy, financial markets and institutions	
	NZ	*DT*	*NZ*	*DT*
Soil and crop management	Fast	Fast	M	H
Livestock management and alternatives	Fast	Slow	M	L
Land-cover and forest management	Fast	Slow	H	H

NZ - NGFS Net-Zero 2050 (1.5˚C) scenario; DT - NGFS Delayed transition (<2˚C) scenario; H - High; M - Moderate; L - Low

Source: Author

5. Summary

Technologies and technological developments relevant to South Africa in the next decade (into 2030–2035) to mitigate and adapt to climate change were presented. A preliminary evaluation of these technologies was undertaken to assess their potential transition risks and impacts on the South African economy and on financial institutions and markets.

Technologies and technological developments were categorised into four sectors: (i) energy; (ii) industry; (iii) mobility; and (iv) agriculture and land use. A total of 17 technologies and technological developments were highlighted across these sectors, with six identified in the energy sector, three in the industrial sector, five in mobility and three in the agricultural and land-use sector. Technologies like scaled-up VRE technologies (energy), the export of electrolytic hydrogen and hydrogen-based derivatives (industrial), electrification (mobility) and soil and crop management (agricultural) provide an indication of the technologies and technological developments that are part of the analysis.

A descriptive presentation of the expected transition risks and impact of each technological development intentionally focussed on a macroeconomic level. As a framework for this analysis, two scenarios from the well-known NGFS Climate Scenarios were utilised to consider variations in domestic and global transition risk (‘moderate’ to ‘fast’ technology change). These were the Net-Zero 2050 (1.5°C) and NGFS Delayed Transition (<2°C) scenarios. A range of transition risks and possible implications of considered technologies were presented on the basis of these two scenarios, resulting in both positive impacts (opportunities) and negative impacts (risks). Policy interventions to minimise risks or maximise potential opportunities are not within the scope of this research but would be a logical next step for consideration.

For the economy, key risks include well-known moderate GDP impacts, including an increase in multi-factor productivity ameliorated by a possible reduction in labour productivity and stranded labour as a result of seemingly unavoidable physical risks (temperature extremes). Relative pricing changes and related transitory supply and demand shocks should also be expected, while increased relative domestic and corporate energy prices are anticipated but would abate as the economy decarbonised. With this, accelerated capital depreciation on existing infrastructure (stranded assets) would be a substantive risk.

Technologies that could be implemented rapidly should exhibit notable cost reductions or be expected to do so in future, should already have been scaled and should have been deployed in a number of jurisdictions. For South Africa, these would include variable renewable energy (VRE) technologies like utility-scale onshore wind and utility-scale and distributed solar PV. Although still nascent, this would also include electrical energy storage, which is being driven by global electric vehicle deployments and is becoming sufficiently cost competitive to be deployed either standalone or in hybrid configurations in power systems. Clean hydrogen production via electrolysis or potentially more traditional methods (with CCS) could be implemented quickly for export markets, followed by some niche domestic applications. Rapid deployment of these technologies would require existing policy positioning and regulatory constraints to be addressed, including policy coherence, national procurement mechanisms, environmental approvals and regulatory processes. There also needs to be increased granularity and certainty as to the long-term trajectory of GHG emissions in South Africa. Hence, it is essential that there is an intentional focus on selected technological developments to inform and address energy, industrial, mobility and agricultural emissions.

Opportunities presented are likely to include a relative decrease in public health costs and increased relative food security (more efficient food production methods), and improved national energy security (fewer energy imports) should also be expected. More fiscal space as a result of increased revenues from carbon pricing would be balanced by lower income tax revenue (lower labour productivity) and less taxes and royalties from incumbent fossil fuel industries. Population growth and upward mobility will drive socio-economic changes implicit in the transitioning economy.

The implications of these technological developments for financial markets and institutions are anticipated to be imminent sectoral disruption in incumbent sectors resulting in reduced profitability, increased liability risk and potential forced closures. There should also be an expected level of corporate and government litigation from incumbents or conversely from other stakeholders considering increasing focus on climate change attribution. Specific lender and investor financial risks in existing infrastructure will present themselves (potential for stranded assets), while market losses in equities (repricing carbon-intensive assets) and initially lower household wealth (increased carbon pricing, increased insurance premiums) with higher risk aversion may lead to increased funding costs. Opportunities will include new business creation and moderately reduced underwriting risk.