
A VITAL AMBITION

DETERMINING THE COST OF ADDITIONAL
CO₂ EMISSION MITIGATION IN THE SOUTH
AFRICAN ELECTRICITY SYSTEM

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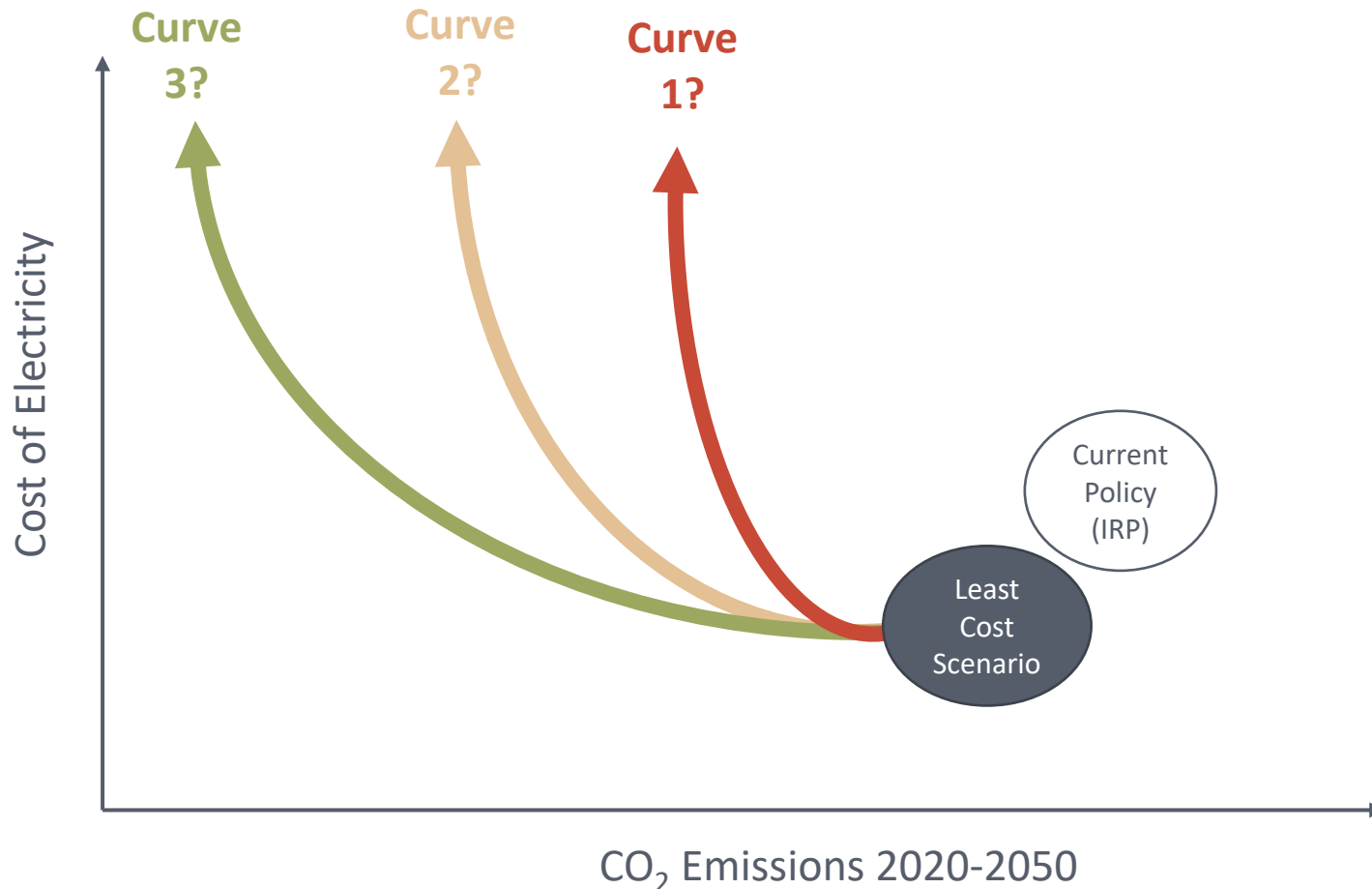
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THE QUESTIONS WE SET OUT TO ANSWER

- Can South Africa meet its power demand for the coming decades whilst drastically reducing CO₂ emissions from electricity generation?
- Do future versions of our power system with lower emissions result in higher electricity costs?
 - how much higher?
 - and for how much emission reduction?
- Is there an inflection point, in other words, a level of emission reduction beyond which the cost of cleaner power becomes unaffordable?
- **Why is this important?**
 - To inform rational policy decisions
 - To allow mitigation to be priced and any need for funds required to increase ambition to be quantified
 - To provide guidance regarding the size and cost of a possible climate transaction



HOW MUCH WILL ADDITIONAL MITIGATION COST?



If we move to scenarios with lower emissions than Least Cost, how much more will electricity system costs increase? More specifically, is the curve depicting optimised systems at lower emissions levels shallow or steep?

- For Curve 1, additional mitigation is expensive;
- For Curve 3, additional mitigation is less expensive

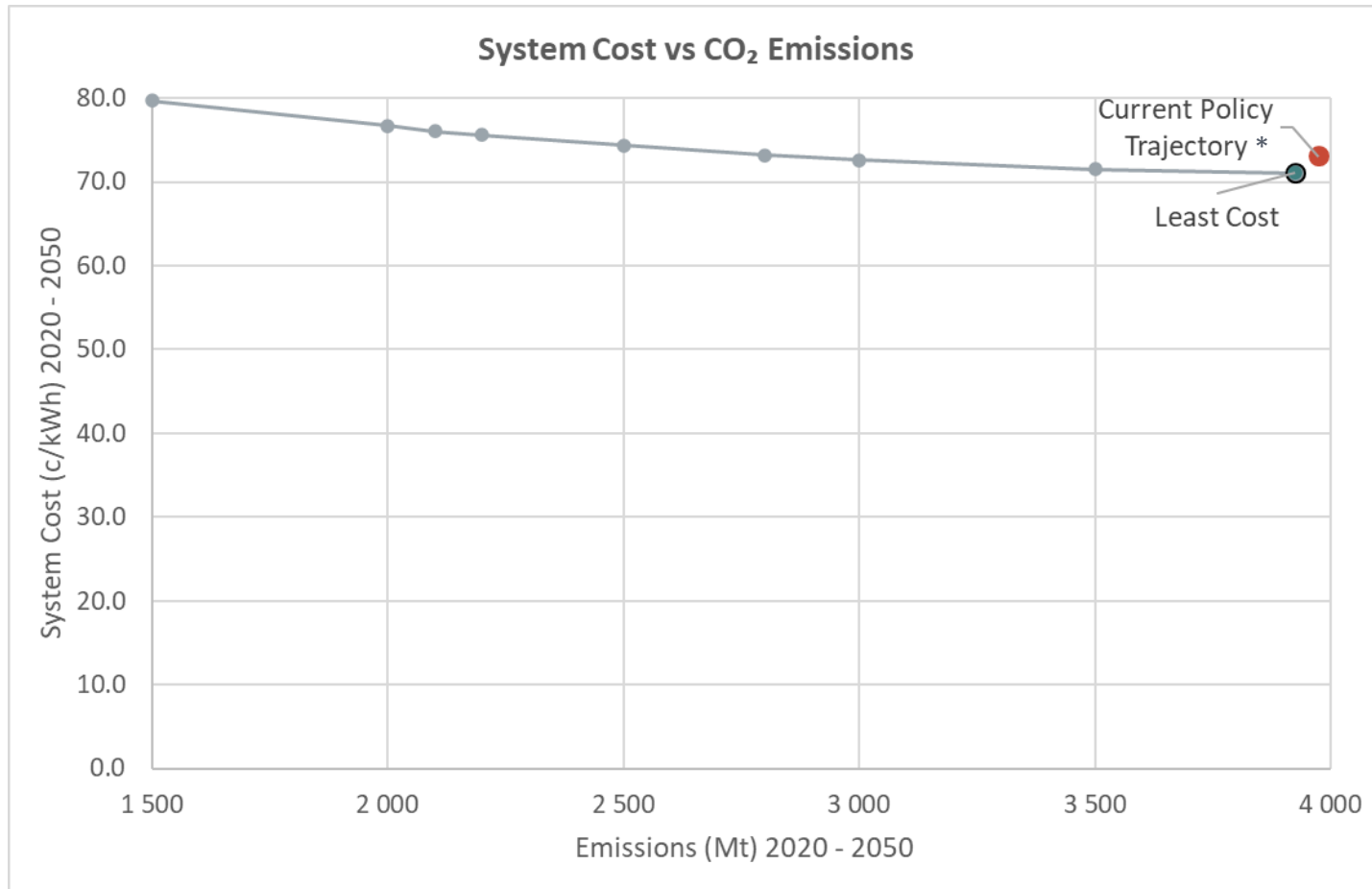
To properly assess this:

- All power system scenarios must be cost optimised
- All technologies must be considered
- The **only** constraint imposed is a CO₂ emissions one



ANSWER: LESS THAN WE THOUGHT

WE ARE ASKING THE WRONG QUESTION



**South Africa's Integrated Resource Plan (IRP) 2019 is used as a basis for constructing our 'Current Policy Trajectory' which extends to 2050.*

- The cost curve is almost flat at least until 2.5 Gt of CO₂ emissions. This means that the cost of lower emissions scenarios is not significantly different to that of the Least Cost scenario.
- The key driver for this is the plunge in renewable energy (RE) costs. New build RE is by far the lowest cost technology choice for future energy
- Displacing existing coal with new RE comes at a small cost (that decreases with time as RE costs continue to decline)
- Challenges remain to achieving emissions reductions along this curve, but cost is not one of them. These include: policy and regulatory factors, political will, the practicalities of renewable energy (RE) industrialisation ramp-up, grid constraints and system adjustments required for a greater proportion of variable generation. **None of these barriers is insurmountable.**



KEY MESSAGES

COST IS NO LONGER A BARRIER TO SIGNIFICANT MITIGATION IN THE RSA POWER SECTOR

1. **Significant climate mitigation does not increase the cost of power** – it potentially even reduces cost
2. **The RE cost revolution** resulted in a technological disruption in the power sector: **cost-optimal, reliable power supply is now best provided by RE, storage and peakers**. Coal, nuclear and hydro are no longer economically competitive new-build generation technologies in the SA power sector
3. **All cost optimal scenarios include a RE build equal to or greater than that envisaged in the current IRP**
4. **A more ambitious RE build will greatly benefit SA and must begin immediately**
 - It will deliver a large green stimulus plus value chain localisation opportunities
 - Important further benefits include: significant job creation, local air pollutant reduction, foreign and domestic investment, economic recovery for declining coal mining regions, reduction in the carbon intensity of exports, opportunities to export RE components into Africa, mitigating coal financing risk and enabling future growth areas such as electric vehicles and green hydrogen
 - It is a highly cost effectively strategy to deliver on our international climate mitigation commitments
5. **The modelling shows that an ambitious RE build scenario creates options in respect of RSA's energy future**
 - the decision to build expensive new gas infrastructure can be avoided for at least a decade and might not be necessary
 - should SA come under large pressure to close its coal plant in the longer term it will be able to do so cost effectively
6. **Implications for policymakers:**
 - The IRP should be reviewed urgently with updated RE cost assumptions, given their significant impact on modelling outcomes
 - The additional carbon savings could be used to negotiate a large climate finance transaction with climate funders and development finance institutions that can contribute to resolving Eskom's financing crisis and provide support for a Just Transition for affected communities



CONTEXTUALISING THE STUDY

THIS IS A SECTOR LEVEL STUDY TO ASSESS THE COST OF CLIMATE MITIGATION IN THE FUTURE RSA POWER SECTOR

- **What can the study tell us?**

- The power system cost curve associated with increasing carbon constraints on the RSA power system until 2050, with adequacy and reliability accounted for
- The cost implications of adopting power sector carbon budgets associated with RSA alignment with Paris climate change goals
- The impact of recent disruptive change in RE costs on cost optimal future RSA power system development paths
- A temporal perspective across three decades, and as such demonstrates potential for lock-ins and the creation of and foreclosing on options

- **What can the study comment on, but did not consider in detail?**

- Investment levels across different scenarios
- A comprehensive view of real world constraints to accelerated RE builds. This is partially dealt with [here](#).

- **What can the study not tell us?**

- It does not predict the future path of electricity prices, as this involves regulatory tariff-setting considerations
- How best to design an optimal RE build strategy for RSA, including aspects such as the optimal form of grid extension, who should finance and build the RE, contracting and procurement
- The macro-economic impact of various power sector scenarios, beyond using the cost of electricity as a (simplistic) proxy
- The impact on jobs associated with various scenarios
- The implications of disruptive demand profiles, including the effect of COVID in the near term



CONTENTS

- **Approach and methodology** – system modelling is required
- **Assumptions** – latest public domain information, common to all scenarios
- **Current policy reference scenario** – projecting the IRP policy intent to 2050
- **Least Cost** – the most economic scenario in a theoretical world
- **Understanding carbon emissions** – how low do we need to go in the power sector?
- **Optimised Mitigation Scenarios** - least cost theoretical power systems under emission constraints
- **Reality check** – do the results survive in the real world outside of a model?
- **Realistic Mitigation Scenarios** – assessment of realistic power sector infrastructure build programmes
- **Policy Implications**
- **Conclusion**
- **Appendix** - includes glossary of terms, reference list and additional technical information.

We acknowledge the support of Agora Energiewende and the Children's Investment Fund Foundation. This work was undertaken in collaboration with the Council of Scientific and Industrial Research (CSIR) Energy Centre.

This deck is accompanied by a detailed technical report: CSIR (2020) "[Systems analysis to support increasingly ambitious CO2 emissions scenarios in the South African electricity system](#)," Technical Report, July 2020.

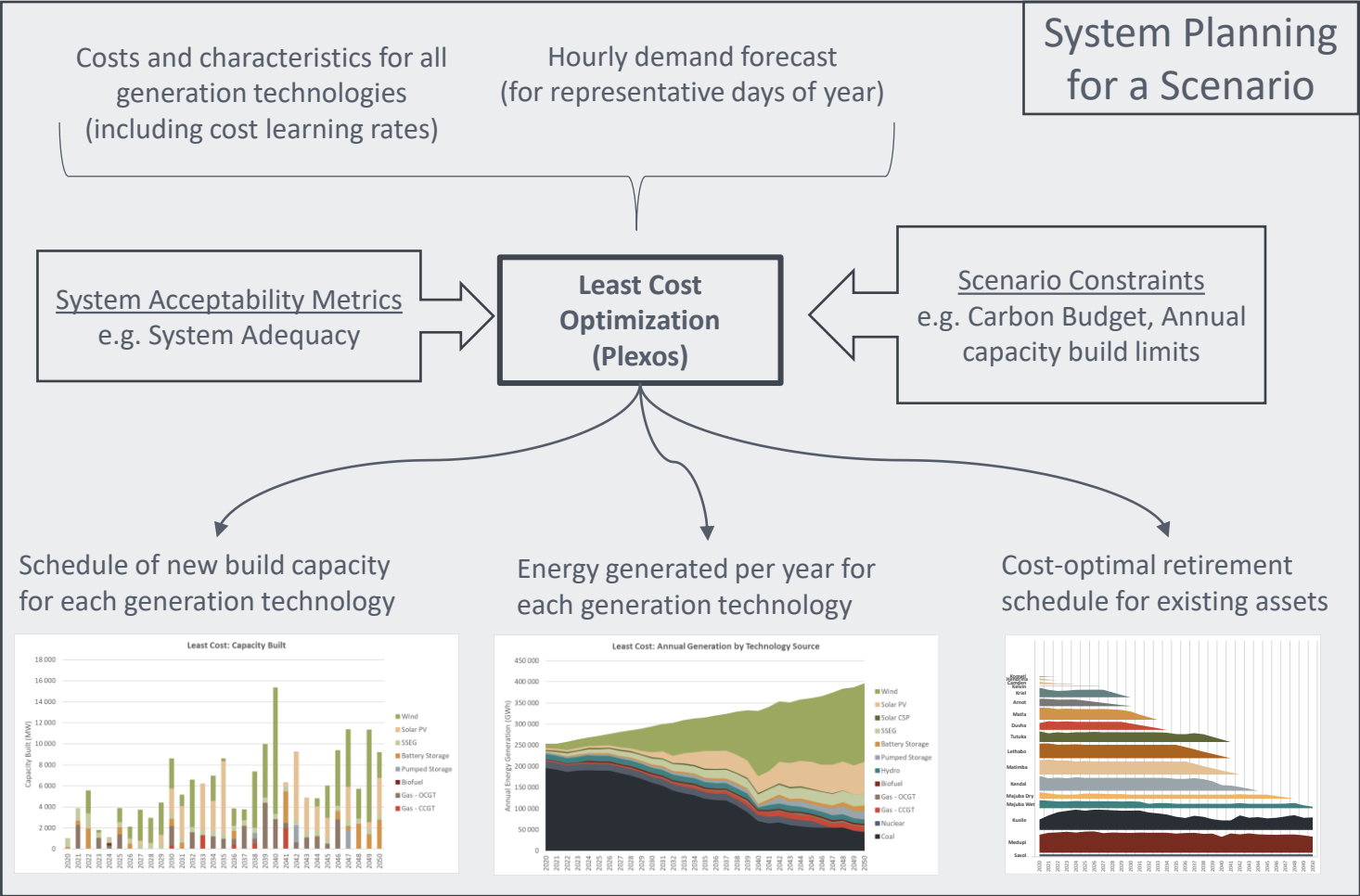
The detailed modeling output data is available on request.



THE INVESTIGATION REQUIRED SYSTEM PLANNING TOOLS

A LEAST COST OPTIMISATION MODEL ENSURES ELECTRICITY DEMAND IS MET RELIABLY AND COST EFFICIENTLY

- Different technologies have different capacity¹ and energy² profiles, and therefore direct cost comparisons are not always valuable.
 - Technologies are embedded in a system which has to deliver power reliably & optimally using characteristics of each generation source to meet demand most economically.
- We therefore needed to consider credible possible future evolutions (Scenarios) of the entire power system using powerful system planning software (Plexos³)
- The system planning model ensures that in all Scenarios, electricity demand is met on an hourly, daily, and seasonal basis - assessed by a ‘system adequacy’ test.
- All power systems reported are adequate (i.e. meet demand at all times with no load shedding)



¹**Capacity** refers to the maximum electrical power that can be generated from a source at different times of day.

²**Energy** refers to the cumulative amount of electricity that can be generated from a source over a period of hours, days or years.

³The same Plexos software is also used in the government process to develop the IRP



LEAST COST POWER SYSTEM DESIGN

OPTIMAL POWER SYSTEM IS BASED ON MINIMISING 'AVOIDABLE COSTS'

- **In economics, an 'avoidable cost' is a cost that can be eliminated by not engaging in or no longer performing an activity**
 - An avoidable cost is therefore any future cost over which we still have decision agency i.e. a cost that we choose to incur
 - In context of this study, these are all the yet-to-be-incurred costs of generating electricity from 2020 – 2050
 - We refer to the sum of these costs for each power system scenario as its 'system cost'
 - The model ensures the specified system constraints are met for each scenario at the lowest possible system cost
- **In attempting to minimise the system cost for a scenario the optimisation model performs the following:**
 - Selects most economic combination of new technologies and necessary capacity to install each year
 - Decides how hard to run existing resources to meet energy generation requirement for the year most economically
 - Including the cost-optimised dispatch of coal fired power
 - Optimally closes existing generators to avoid fixed costs from keeping them available
 - This is a critical element of the modelling we performed.
 - Retirement of existing capacity is based on an economic decision, not on a pre-defined retirement schedule



COSTS CONSIDERED IN OUR ANALYSIS

THE SCOPE OF COSTS INCLUDED AND THOSE COSTS WHICH FALL OUTSIDE THIS WORK

Included in the ambit of system costs modelled are:

- Energy generation costs which include
 - The capital cost of new capacity
 - Fixed and Variable Operation and Maintenance costs (FOM and VOM) of both existing and new capacity
 - Fuel cost
 - Start-up and Shutdown cost
- The cost of maintaining reserve capacity, which is required to maintain system adequacy
- The Cost of Unserved Energy (COUE) which refers to the opportunity cost to electricity consumers (and the economy) of electricity supply interruptions

Excluded costs:

Excluded due to unavailability of data

- Any necessary refurbishment capital costs required to sustain the coal fleet to current retirement date (Inclusion would further support our findings)
- Any retrofit costs required to run the coal fleet at low capacity factors (down to 35%)

Excluded as outside the scope of our modelling

- Costs associated with Distribution and Transmission (although the shallow connection cost is included in the cost of REIPPPP power)
- Short term reserve services (such as inertia)
- Metering, billing etc
- All **Unavoidable** costs (these costs are not incurred by future choices, but result from past choices – decision agency no longer exists over these costs)
 - Cost recovery to address legacy debt and returns on historic investments
 - Sunk capital costs – i.e. capital that has already been spent
 - Any capital costs committed but not yet spent (e.g. completion of Medupi and Kusile)
 - Actual cost of decommissioning plants

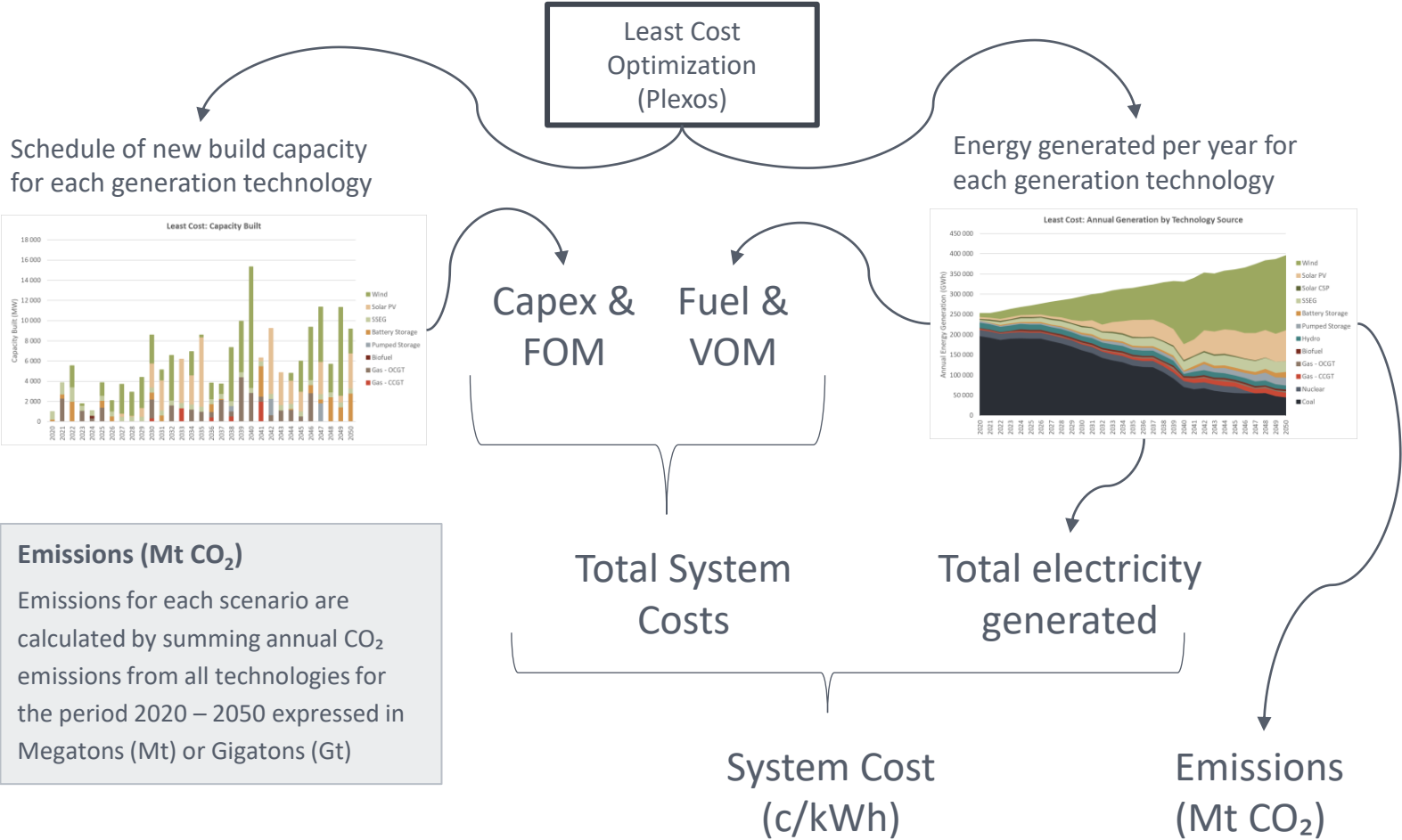


OUR PRIMARY METRICS: SYSTEM COST AND EMISSIONS

THE BASIS FOR COMPARISON OF DIFFERENT POWER SYSTEM PLANS

System Cost (c/kWh)

- It is useful to express the system cost per unit of electricity to allow comparison between different power system plans. This is achieved by ‘levelising’ the total system cost over the electricity consumed from 2020 – 2050
- System cost (c/kWh) is derived by dividing Present Value* of total System Costs by Present Value of Total electricity generated
- Levelised Cost of Electricity (LCOE) is often used to compare energy cost between technologies. The System cost (c/kWh) is the aggregate Levelised Cost of Electricity (LCOE) for the entire system
- Expressed in constant real 2019 c/kWh
- System cost (c/kWh) is NOT to be compared with the current or future tariff path:
 - The tariff must recover **all** costs, including those excluded from our analysis
 - The system cost is calculated to be constant in real terms. The actual tariff path is a function of the regulatory process.
 - System cost (c/kWh) can be seen as the portion of the future tariff that is necessary to cover the cost of future generation



OUTLINE OF OUR RESEARCH PROCESS

EXPLORING POSSIBLE FUTURES OF THE RSA POWER SYSTEM IN THE COST-EMISSIONS SPACE

1) Current Policy Reference Scenario

- The Integrated Resource Plan (2019) is South Africa’s electricity plan until 2030
- We construct a credible ‘Current Policy Trajectory’ reference scenario which is based on the IRP until 2030, and includes adjustments for policy intent until 2050
- System cost and CO₂ emissions is calculated for the extended IRP to locate it in the ‘cost vs emissions’ space

2) Least Cost Power System

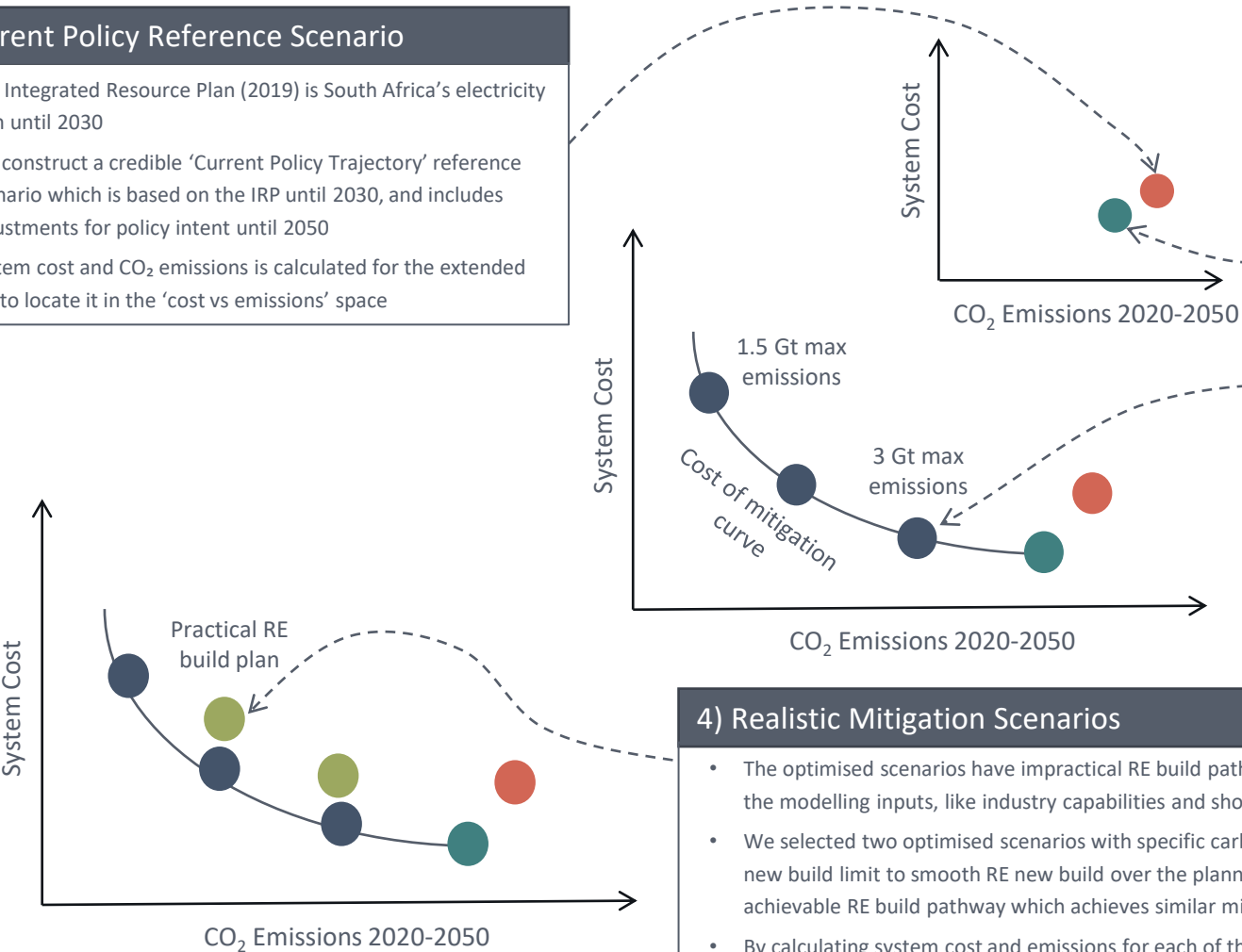
- With cost as the only consideration, we determined the optimal power system plan for 2020 to 2050 period
- System cost and CO₂ emissions are calculated for the Least Cost plan to locate it relative to the Current Policy Trajectory in the ‘cost vs emissions’ space

3) Optimised Mitigation Scenarios

- A carbon constraint (maximum total emissions for the power system) is introduced into the model
- This allowed us to determine a suite of optimal least cost power system scenarios for a range of carbon constraints
- System cost and carbon constraints are plotted for each scenario, which yields the curve representing the cost of mitigation

4) Realistic Mitigation Scenarios

- The optimised scenarios have impractical RE build paths due to the omission of real-world constraints from the modelling inputs, like industry capabilities and short-term regional grid capacity
- We selected two optimised scenarios with specific carbon constraints and included a minimum annual RE new build limit to smooth RE new build over the planning horizon, representing a more sustainable and achievable RE build pathway which achieves similar mitigation
- By calculating system cost and emissions for each of these scenarios, we could quantify any additional cost of mitigation due to real-world constraints



NEW-BUILD TECHNOLOGY ASSUMPTIONS

COMMON TO ALL POWER SYSTEM SCENARIOS INVESTIGATED

- Technology assumptions (cost and operating characteristics) **must be common to the analysis of all future power system scenarios** to allow like-for-like comparison
- Detailed technology assumptions can be found in the CSIR report¹ covering the Plexos systems analysis
- Assumptions from the 2019 IRP were replaced with latest best public domain information if available (replacements indicated by ***bold italics***)
- All costs are expressed in Jan 2019 Rands
- Summary of available technologies shown on this slide (for a full list of technologies made available to the optimiser see Appendix)

Technology	Overnight Capital Costs (OCC) [R/kW]	Fixed Operating Cost (FOM) [R/kW/year]	Variable Operating Cost (VOM) [R/MWh]	Capacity Factor (typical)	Build Period [years]	Economic Lifetime [years]	LCOE 2020 [c/kWh]	LCOE 2030 [c/kWh]	LCOE 2035 [c/kWh]
Wind	14 515	742	0	36%	4	20	70.6	62.1	60.0
Solar PV	10 140	328	0	20%	1	25	62.0	45.7	41.8
Solar CSP	110 576	1 236	1	60%	4	30	216.1	159.9	146.9
SSEG*	12 310	328	0	20%	1	25	100.0	72.0	66.0
Battery Storage	13 175	757	4	12%	1	10	235.4	175.3	168.8
Pumped Storage	24 680	222	0	33%	8	50	96.7	96.7	96.7
Hydro	50 156	484	0	67%	8	60	113.0	113.0	113.0
Biofuel	19 468	2 907	76	74%	1	30	79.6	79.6	79.6
Gas – OCGT/GE	10 015	196	3	8%	2	30	336.9	336.9	336.9
Gas – CCGT/GE	10 997	203	27	36%	3	30	153.1	153.1	153.1
Nuclear	75 728	1 187	45	90%	6	60	128.5	126.6	126.6
Coal (PF)	43 453	1 133	98	85%	9	30	116.7	116.7	116.7
Coal (FBC)	52 450	762	212	85%	4	30	120.2	120.2	120.2

*Small Scale Embedded Generation

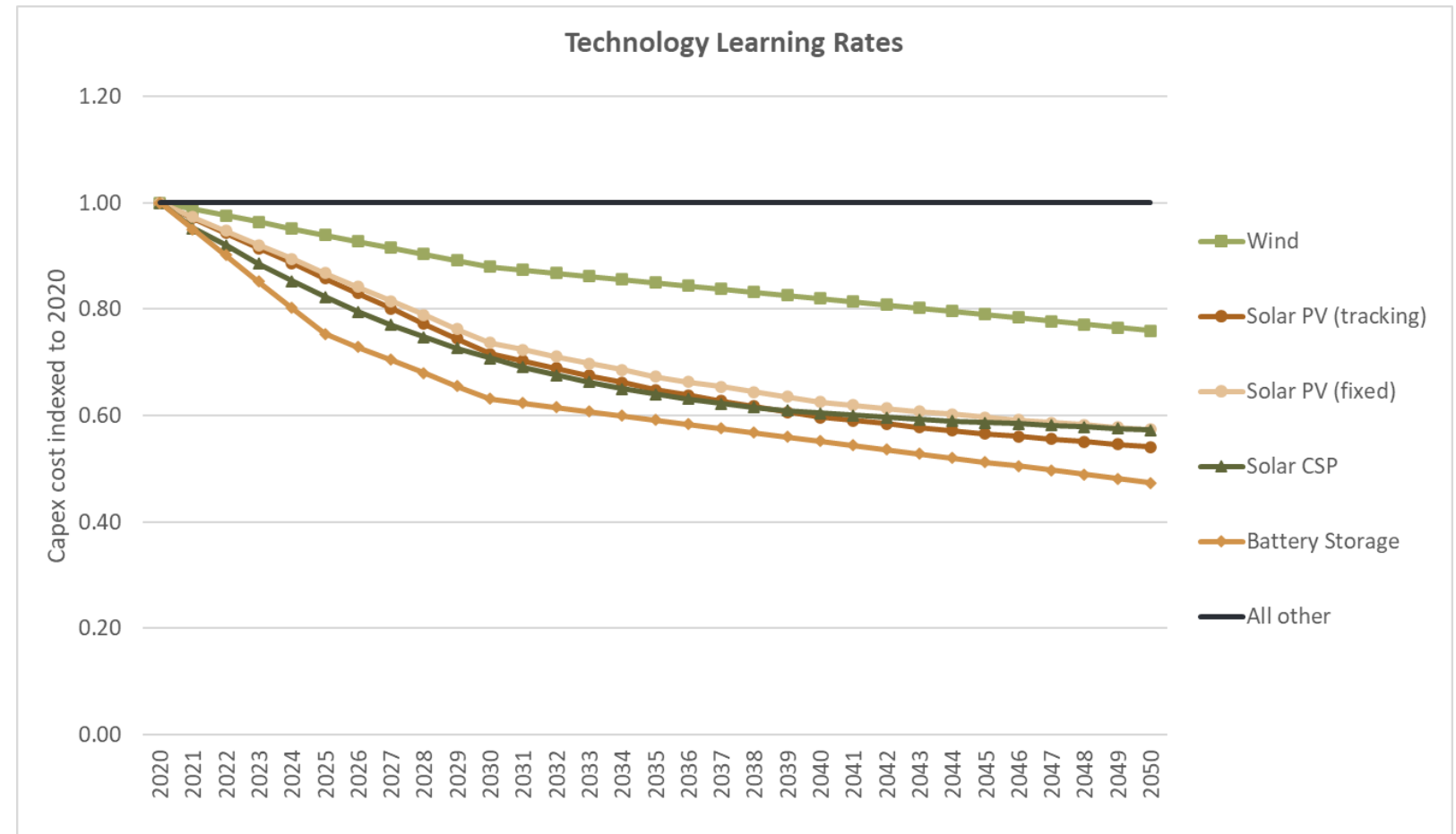
Sources: Integrated Resource Plan (2019); EPRI (2017); NREL Annual Technology Baseline (2019); ¹CSIR, 2020 "Systems analysis to support increasingly ambitious CO₂ emissions scenarios in the South African electricity system," Technical Report, July 2020.



ANTICIPATED TECHNOLOGY COST LEARNING RATES

DISRUPTIVE REDUCTION IN THE COST OF WIND AND SOLAR PV EXPECTED TO CONTINUE FOR NEXT TWO DECADES

- Renewable energy costs have seen dramatic declines in the past few years, now positioning them as the most cost-optimal energy generation source in many countries.
- These cost reductions are expected to continue for the foreseeable future.
- Nuclear and gas are 'mature technologies' hence cost declines are not anticipated.



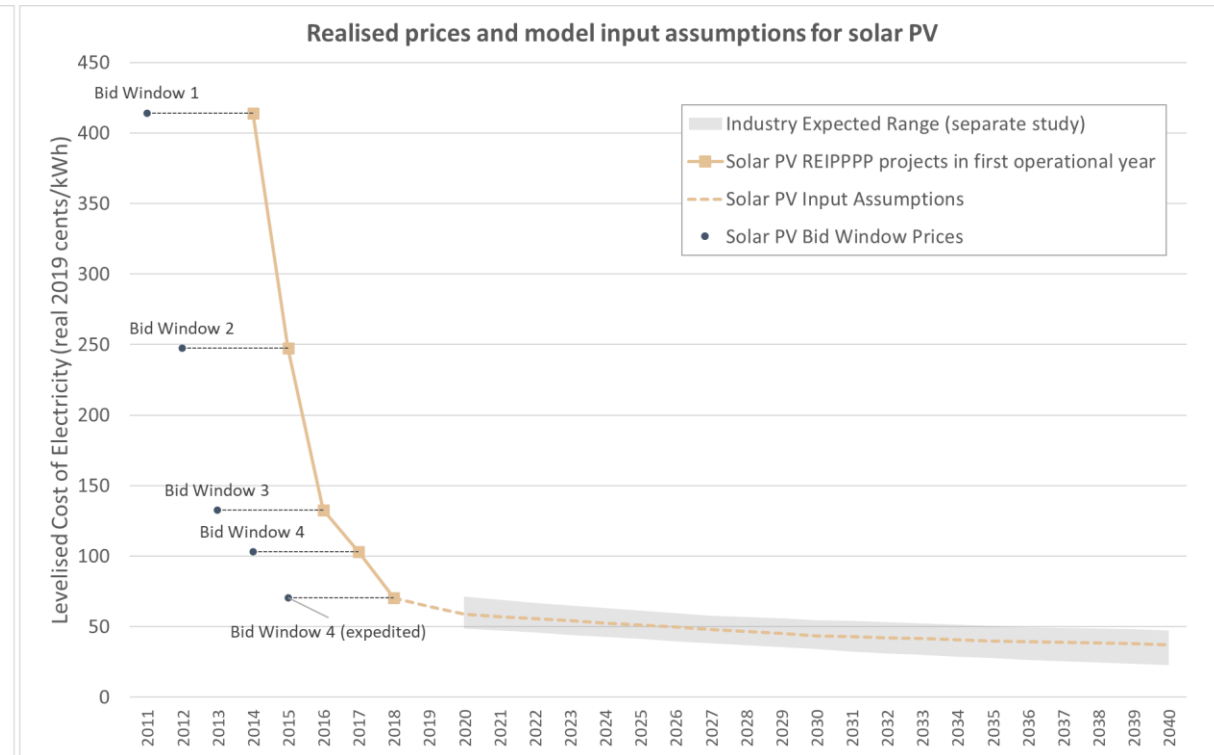
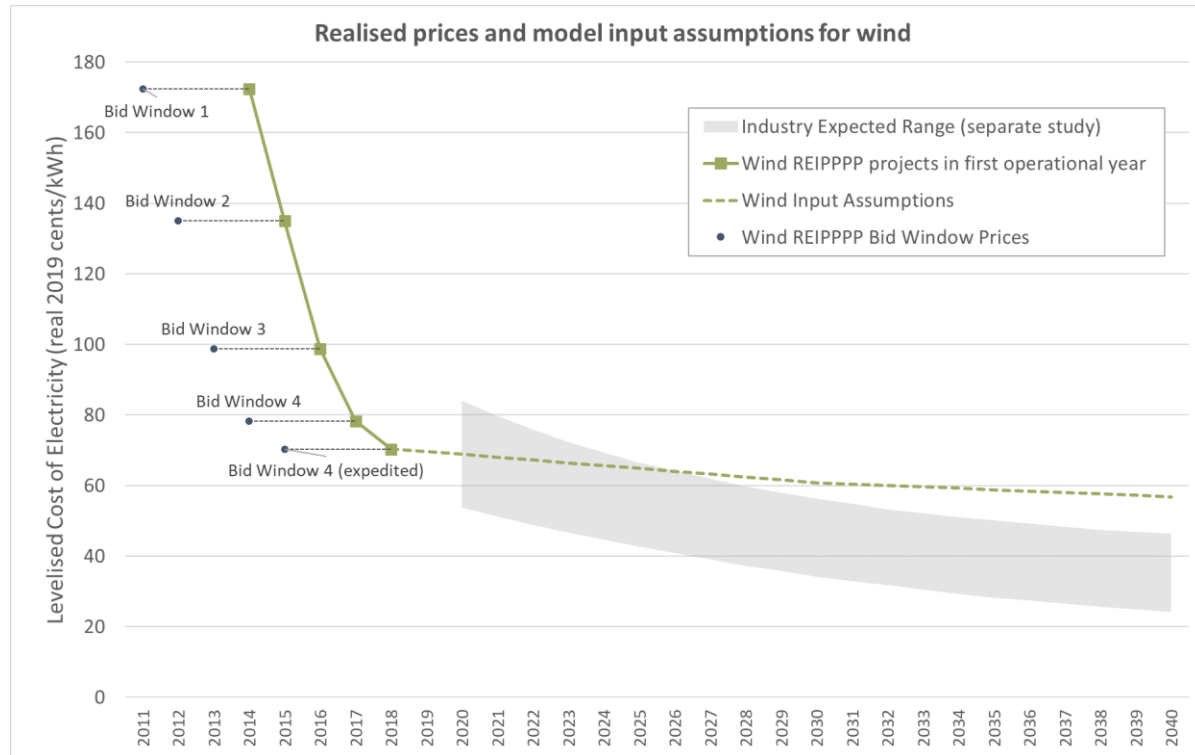
Sources: Integrated Resource Plan (2019); EPRI (2017); NREL Annual Technology Baseline (2019); for more information regarding these assumptions see CSIR (2020) technical report.



RE PROVIDES LOWEST COST ENERGY FOR NEW-BUILD

HISTORICAL AND FUTURE COST LEARNING IN RE CRITICAL TO POWER SYSTEMS OF THE FUTURE

South Africa has already witnessed rapid renewable energy price declines, as demonstrated through previous bid windows of the country's Renewable Energy Independent Power Producer Programme (REIPPPP). Based on interactions with South African industry experts in a separate study (Meridian Economics, 2020c), solar PV and wind energy cost declines are expected to continue – the assumptions used in this modelling work* lie above or within industry expectations as reported in that study.



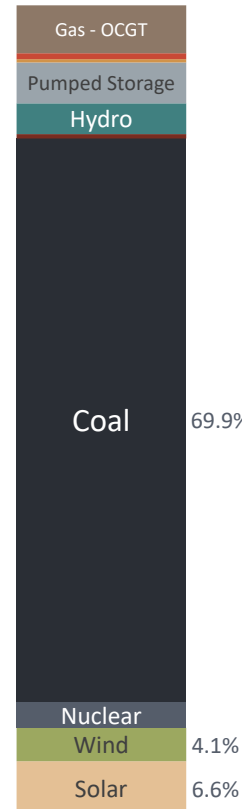
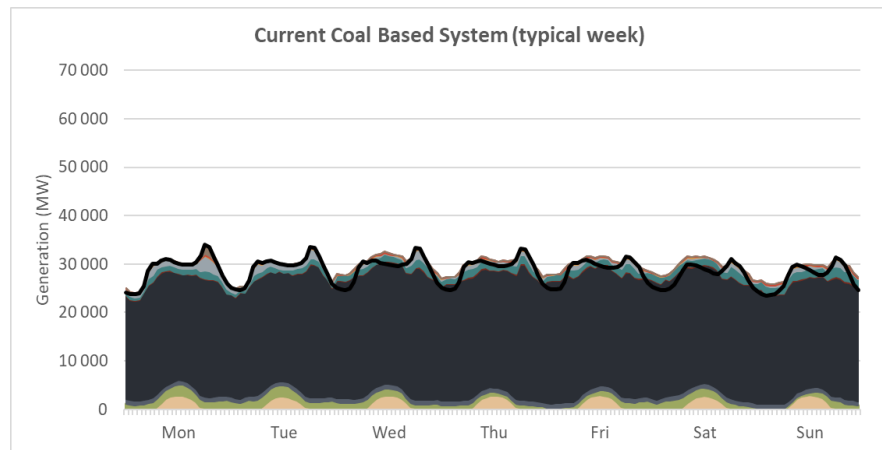
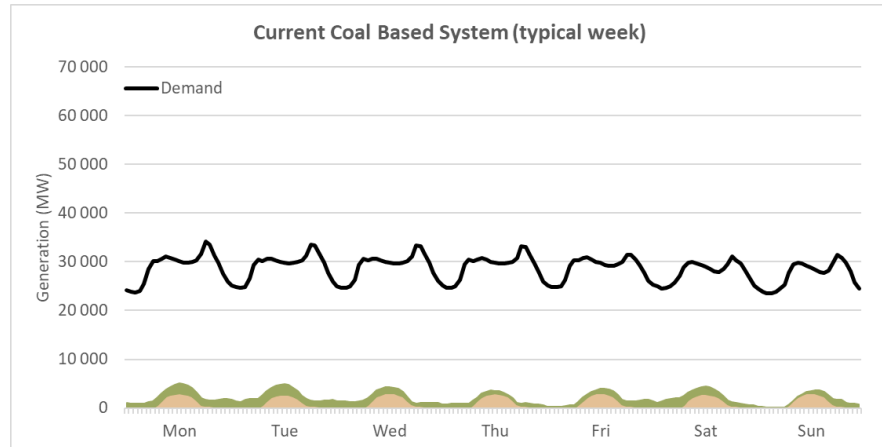
Sources: CSIR (2017); CSIR (2020); NREL (2019); StatsSA (2020); Meridian Economics (2020c)

*LCOE costs for new-build wind and solar PV were developed using the REIPPPP Bid Window (BW) 4 (Expedited) costs as a starting point (aligned with IRP 2019), with declining cost trajectories thereafter based on the NREL Annual Technology Baseline (2019) learning assumptions. Although capacity factor and fixed operations and maintenance costs are anticipated to reduce, only capital expenditure costs was reduced in this assumption. This is highly conservative (particularly for wind).

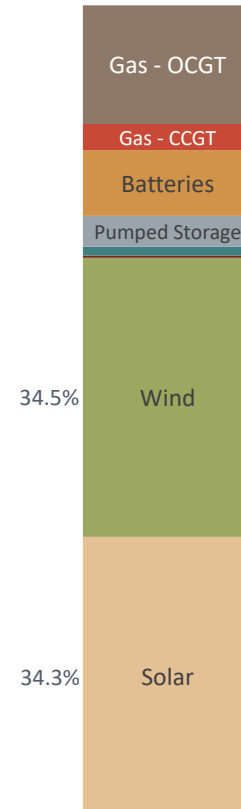


AFRAID OF THE DARK? SUFFERING FROM DUNKELFLAUTE?*

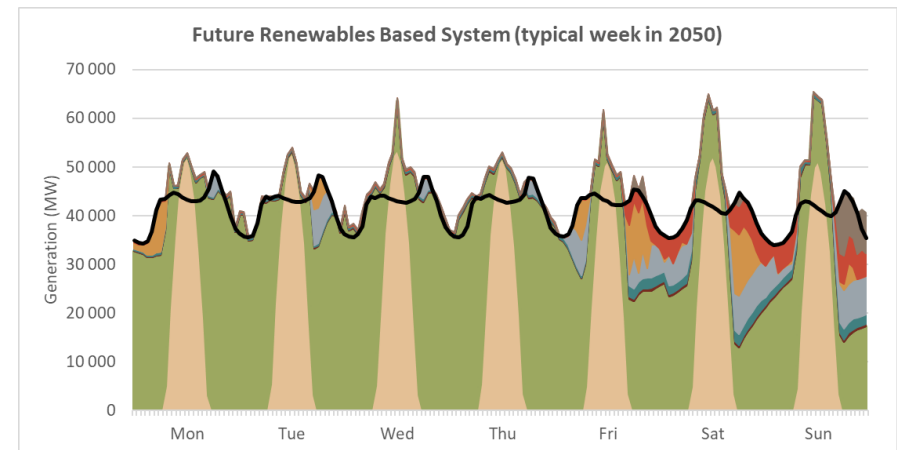
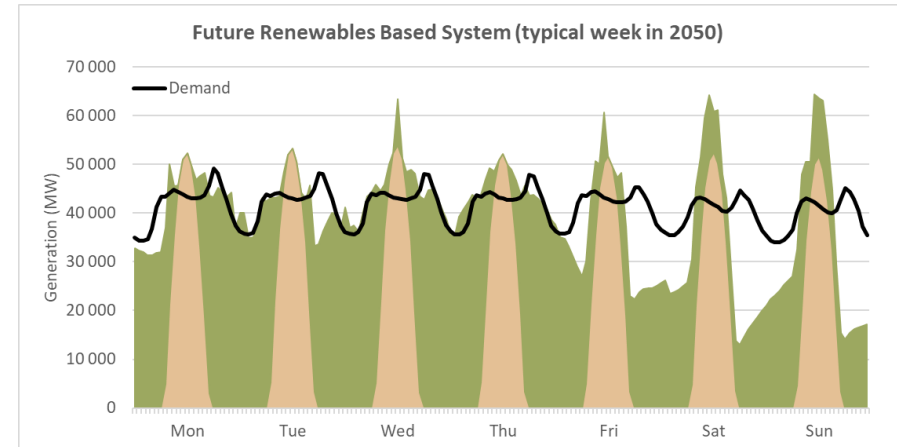
FILLING THE GAP BETWEEN DEMAND AND RENEWABLE ENERGY GENERATION IN A TYPICAL WEEK



2020
Coal-based
capacity mix



2050
RE-based
capacity mix

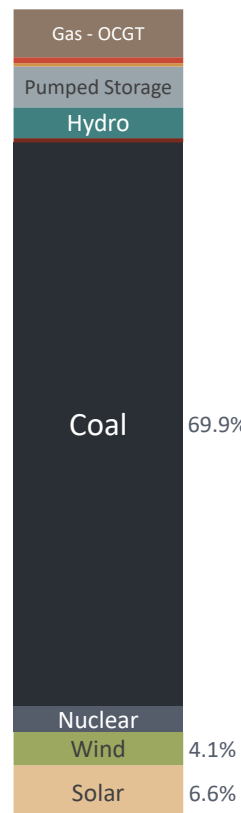
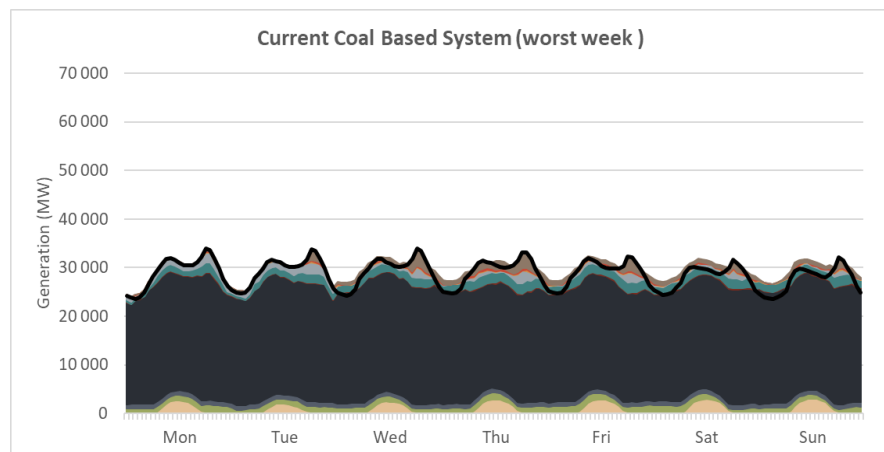
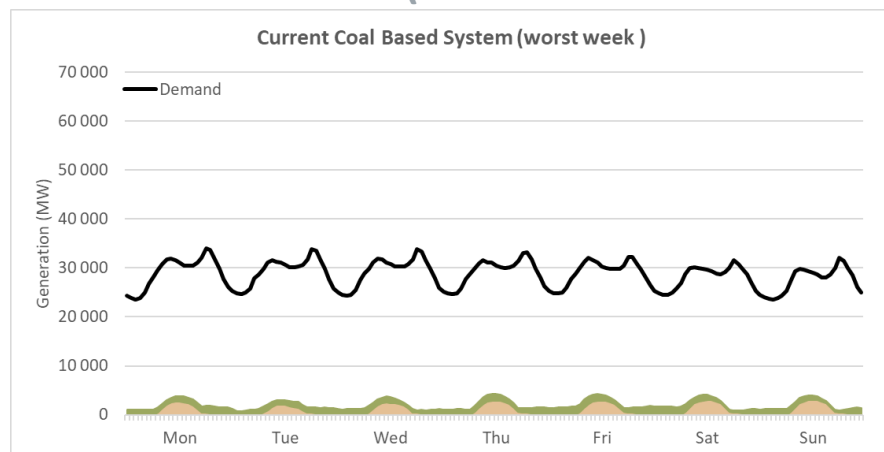


*In the German language, dunkelflaute is a word that refers to the fear of having inadequate sunshine or wind to maintain a viable supply of renewable energy.

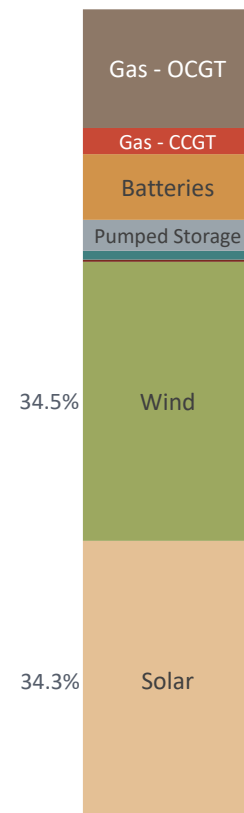


DON'T BE AFRAID

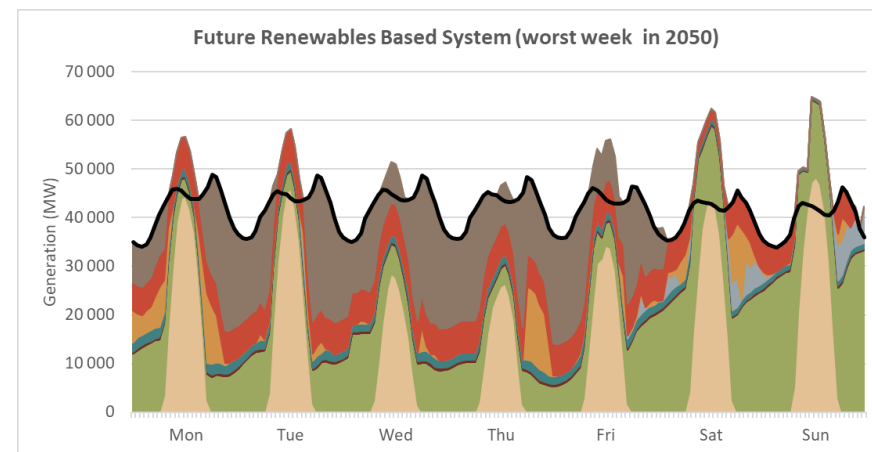
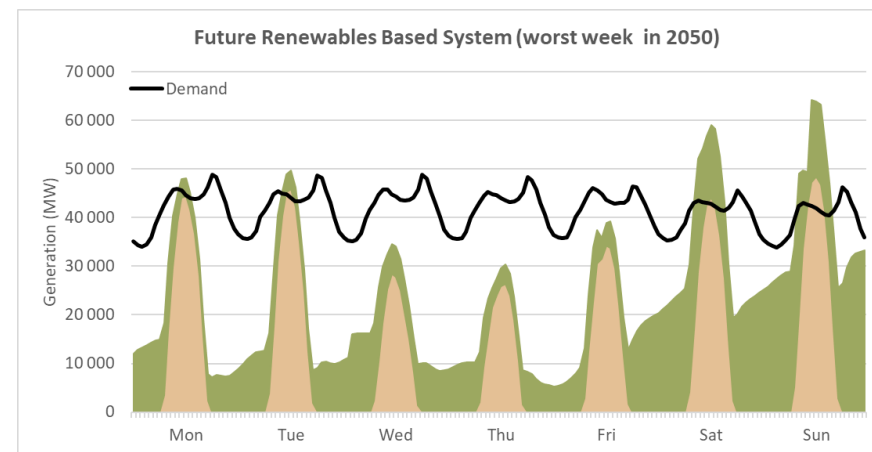
FLEXIBLE CAPACITY (DESIGNED TO STAND IDLE MOST OF THE TIME) FILLS THE GAP DURING ADVERSE WEATHER



2020
Coal-based
capacity mix



2050
RE-based
capacity mix



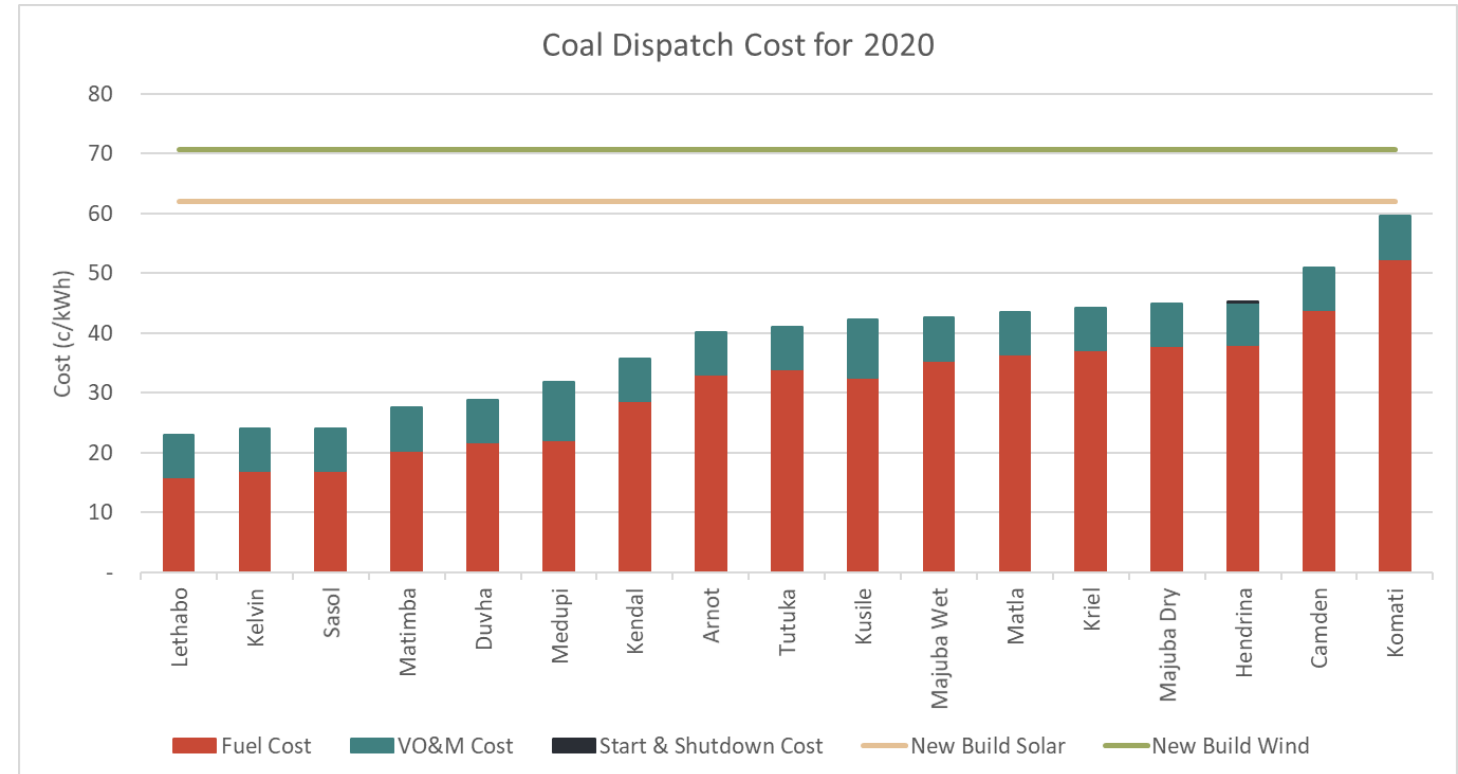
UNDERSTANDING THE COST OF COAL-FIRED POWER

DISPATCH COST OF COAL IS CURRENTLY LOWER THAN RENEWABLES – IS THIS A USEFUL COMPARISON?

- If early closure of coal power stations is not contemplated, then fixed costs and future capital expenditure (capex) for each station until retirement date is **unavoidable**
 - In this case, new sources of energy would **need to be lower than the dispatch cost** (coal fuel plus variable O&M) to economically replace coal power
- As of 2020, New Build Wind and Solar PV LCOE¹ is still higher than dispatch cost of all coal stations, as the chart shows
- BUT there is no rational reason not to close coal stations early if it is economically efficient to do so. **A more useful comparison is thus the cost of new build alternatives to the full cost of coal power including fixed costs and future capex.**

A note on coal fuel costs: The data available for analysis remains high-level, additional, more granular detail would allow:

- Understanding costs related to multiple supply sources per station, including more expensive short-term contracts
- Understanding the proportion of coal that is subject to Take-Or-Pay (TOP) contracts (some of this cost would remain unavoidable even if stations were closed)



Source: Eskom authored information in the public domain including Eskom (2019a), Dentons (2015), coal mining annual reports, interactions with coal supply and Eskom operations experts, EPRI.

¹ **LCOE** includes all Capital, Operations and Maintenance Costs, Socio-Economic Development (SED), Enterprise Development (ED), and grid connection cost (see Appendix for further information on SED and ED). In general comparing the LCOE of variable and dispatchable plant does not adequately account for the different capacity and ancillary benefits each bring to the system.



UNDERSTANDING THE COST OF COAL-FIRED POWER

FIXED OPERATIONS & MAINTENANCE (O&M) AND COST OF LOCAL AIR POLLUTION ABATEMENT

- **Fixed O&M**

- This cost component is based on EPRI (2017) information and is assumed to be the same R/kW for all units at all stations.
- We assume units can be closed one by one terminating the fixed cost per unit in the year of closure.

- **Local air pollution abatement: Compliance with Minimum Emission Standards (MES)**

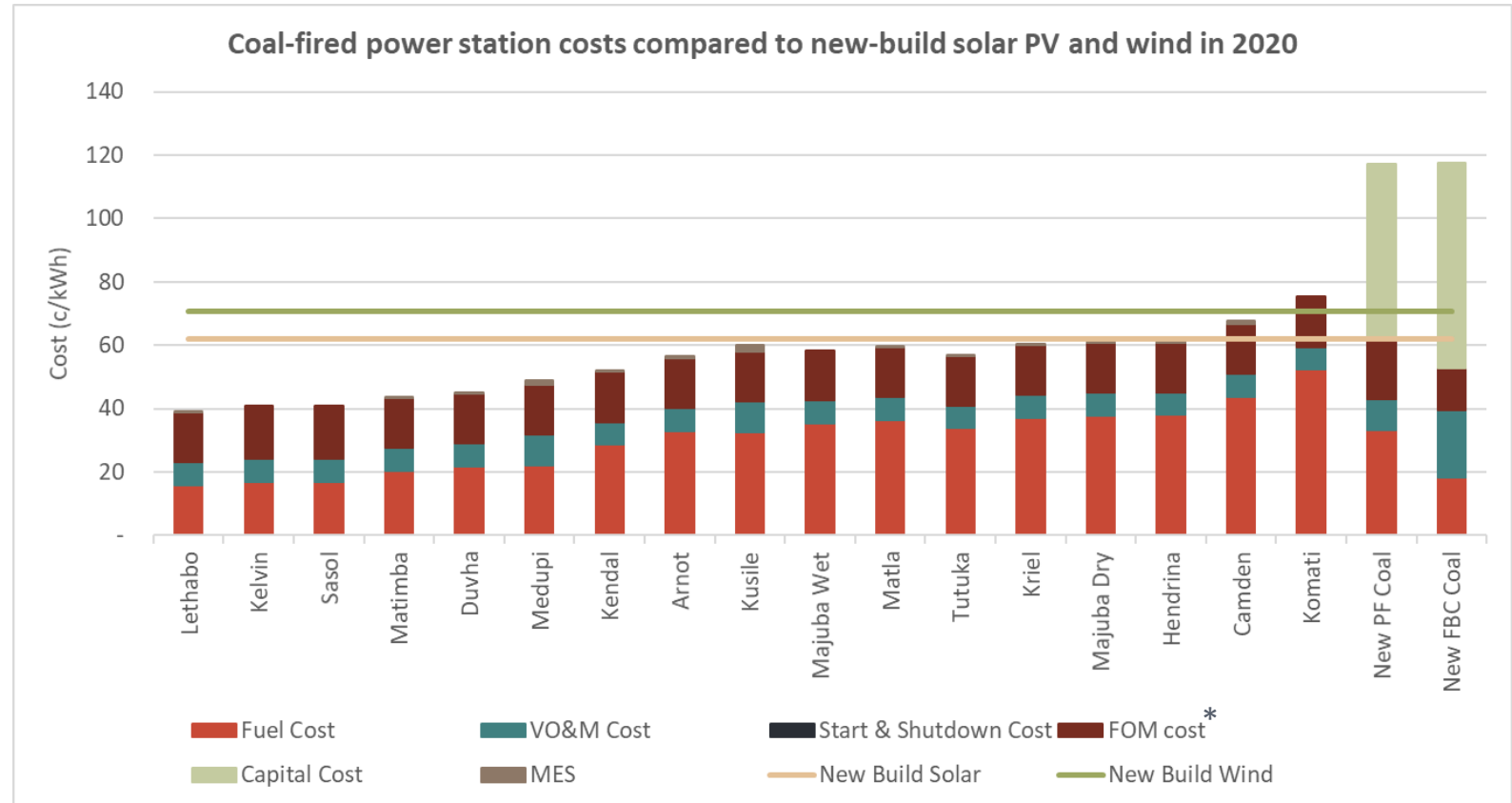
- Coal-fired power plants emit harmful local air pollutants, including Particulate Matter (PM), Nitrogen Dioxide (NO₂) and Sulphur Dioxide (SO₂) which are regulated under the Air Quality Act (2004).
- In order to be in compliance with Local Air Quality regulation, most of Eskom's coal fleet require retrofitting, which implies additional capital and fixed costs. Eskom has stated that these costs are prohibitive and has proposed a retrofitting schedule which leaves many of its plants out of compliance. How this issue will be resolved is uncertain at present.
- **This study requires assumptions to be made as to *what* technologies will be retrofitted at *which* stations *when*, and at *what* cost.** For this, we assume Eskom's retrofit schedule (Eskom, 2019b) and Eskom's associated costs (Naledzi, 2018) (critiqued as being inflated) for the following reasons:
 - Eskom's cost dataset is internally consistent, context-specific and publicly available. The alternative would be to use data from different sources and contexts for different technologies with differing degrees of credibility.
 - Eskom's schedule is consistent with that used in the IRP, promoting consistency and comparability.
 - The assumption of partial compliance is conservative, as it reduces the coal fleet costs relative to other technologies.
 - In our modelling both MES capital and MES operating expense (Opex) were treated as potentially avoidable costs.



COAL POWER IS CLOSED WHEN ECONOMIC TO DO SO

IN OUR MODELLING AND IN REALITY ALL FUTURE COAL-RELATED COSTS ARE POTENTIALLY AVOIDABLE

- Our modelling allows individual units to close when economic to do so, saving all future fuel and variable costs, fixed costs as well as future capital costs for that unit
 - In this study, individual coal station units are subject to an operability constraint - a minimum annual Capacity Factor of 35%.
- As of 2020 Solar power is cheaper than the full cost of power from only the more expensive coal stations.
 - Energy from new build coal plant costs nearly twice as much per kWh as new Solar



*A capacity factor of 65% is assumed for the calculation of FOM cost per kWh

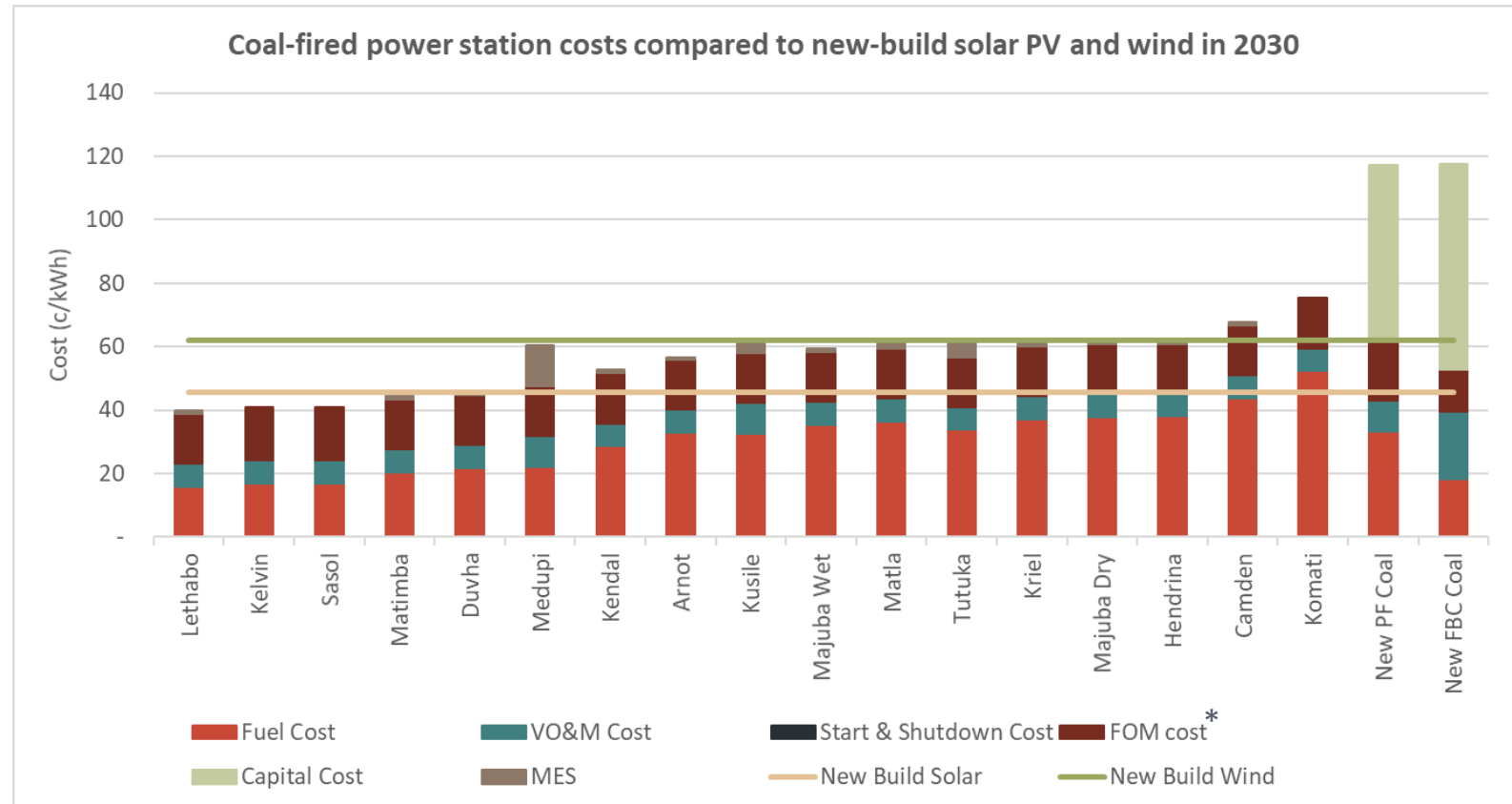


RE COSTS FALL, COAL COSTS, IF ANYTHING, RISE

BY 2030 SOLAR PV ENERGY IS CHEAPER THAN ALMOST ALL COAL

- Solar PV and Wind costs are expected to fall significantly over the next decade
- Assuming system adequacy and stability needs can be met, a substantial amount of coal-fired power should be able to be replaced by RE at a cost saving

- Any **capital costs** required to keep the existing coal fleet running (over and above typical FOM) are **unknown** and therefore not included
 - These are potentially substantial costs for Eskom's older and mid-life stations - avoidable through early closure of units/stations (Meridian Economics, 2017)
- Clearly, any required capital would increase the cost of running coal plant to pre-determined retirement dates as is the plan in the 2019 IRP
 - Plans that consider early retirement of coal can potentially avoid such capital costs



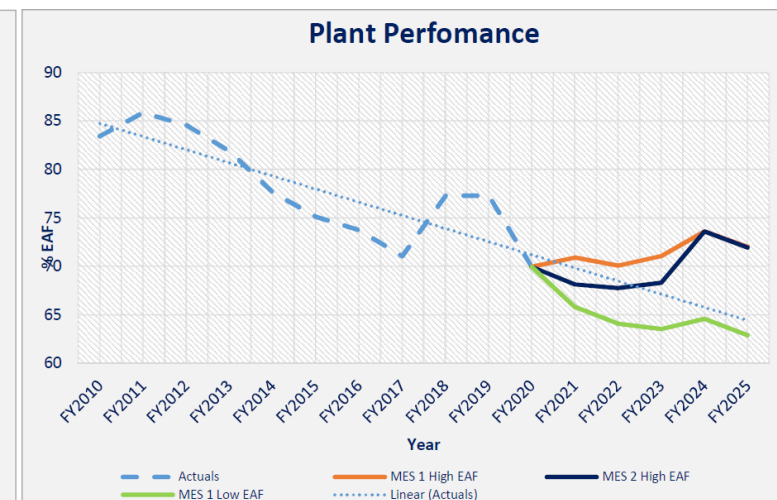
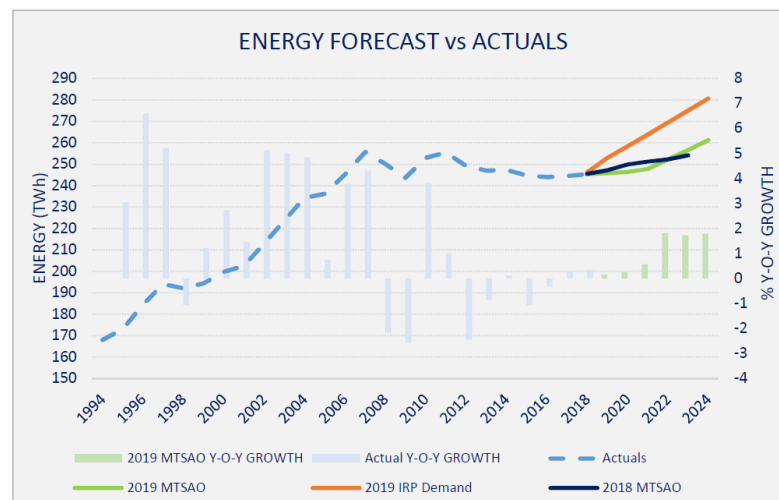
*A capacity factor of 65% is assumed for the calculation of FOM cost per kWh



ELECTRICITY DEMAND AND COAL FLEET PERFORMANCE

OUR ASSUMPTIONS CONSIDER LOWER DEMAND THAN IRP, BUT ALSO LOWER ENERGY AVAILABILITY FACTORS (EAF)

- SA's coal plants have been underperforming and electricity demand has been lower than expected.
- Demand and EAF assumptions for this study are in line with Eskom's Oct 2019 Medium Term System Adequacy Outlook [MTSAO] (green lines).
- The IRP 2019 and the MTSAO have highlighted a short-term energy supply gap of 2-3 GW between 2019 and 2022, but neither recommended specific actions to mitigate this gap.



Source: Fabricius et al (Eskom) (2019)

- In January 2020, the CSIR identified key interventions to mitigate the expected supply shortfall for this period, including emergency power procurement by the Department of Mineral Resources and Energy (DMRE), customer response through unlocking small-scale embedded generation (SSEG), and incorporating 200 MW of additional capacity from existing solar and wind projects (CSIR, 2020).
- In all scenarios, including the IRP, we assume that the CSIR's identified interventions will close the energy supply gap identified.
- SSEG for all scenarios we considered is thus assumed to provide installed capacity of 3.4 GW (built from 2020 – 2022) followed by an additional 500MW per year thereafter in line with the 2019 IRP assumptions

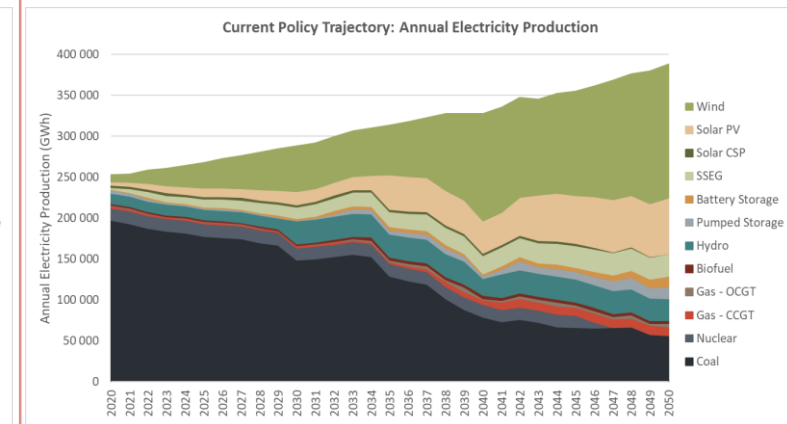
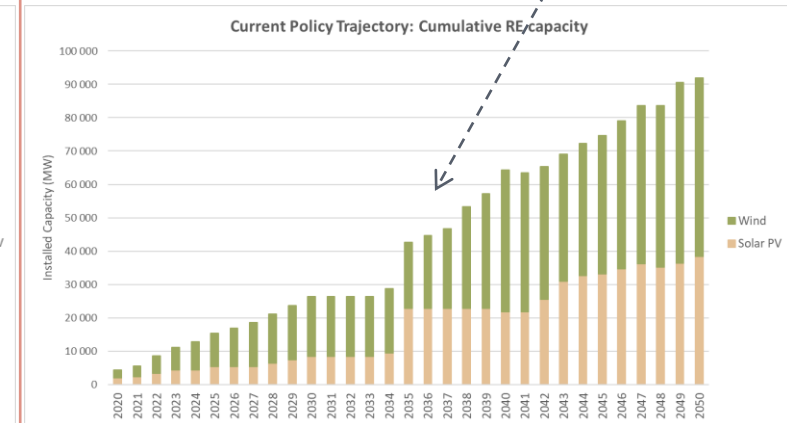
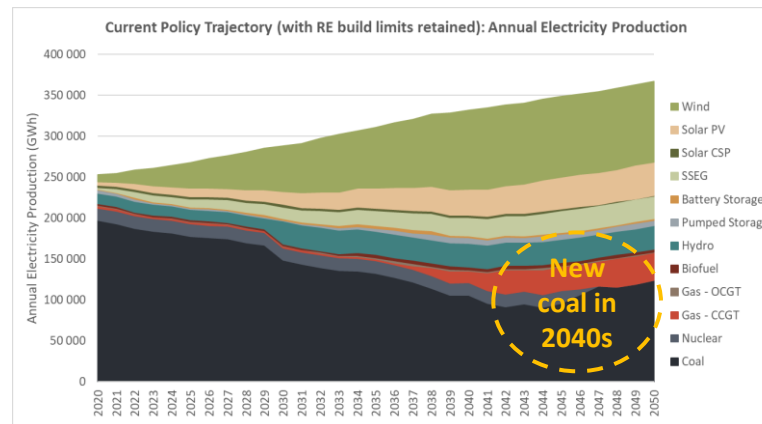
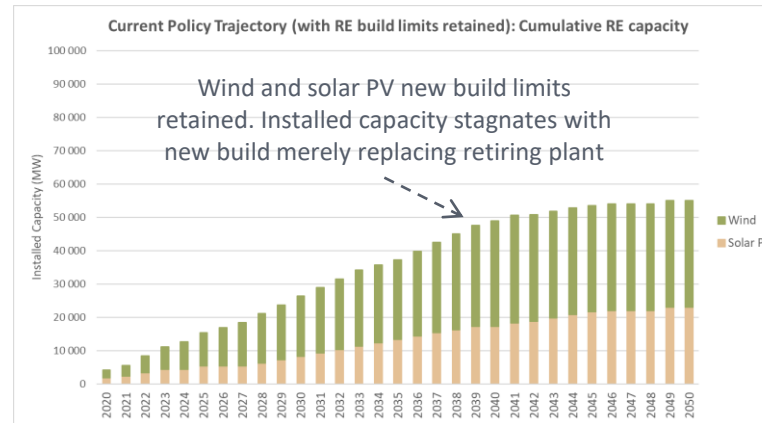
For more information regarding these assumptions see CSIR & Meridian, 2020. "Systems analysis to support increasingly ambitious CO2 emissions scenarios in the South African electricity system."



OUR CURRENT POLICY TRAJECTORY

CONSTRUCTING A CREDIBLE, POLICY REFERENCE SCENARIO BASED ON THE IRP 2019

- The Integrated Resource Plan (2019) contains the best existing expression of current government electricity policy. We therefore use this as the basis of our reference scenario – the plan against which mitigation scenarios can be compared.
- The IRP is constructed on a system modelling basis but
 - has ‘policy adjustment’ that forces in new coal, hydro and gas as well as creates annual new-build constraints on solar PV of 1 GW and wind of 1.6 GW
 - assumes coal stations will all run to their design life end dates, regardless of cost
 - only presents a plan as far as 2030
- We needed to extend the IRP policy intent from 2031 to 2050 for comparison with other scenarios
- Retaining the IRP RE build constraints beyond 2030 results in new-build coal in the late 2040s – an irrational policy outcome considering cost of new-build coal relative to RE* in future years (Merven et al (SA-TIED), 2018)
- Therefore our ‘current policy trajectory’ incorporates the same new build profile as the IRP for all technologies to 2030, but assumes that constraints on new build capacity for solar PV and wind are lifted from 2030 onwards, and that capacity expansion then proceeds on a least cost basis



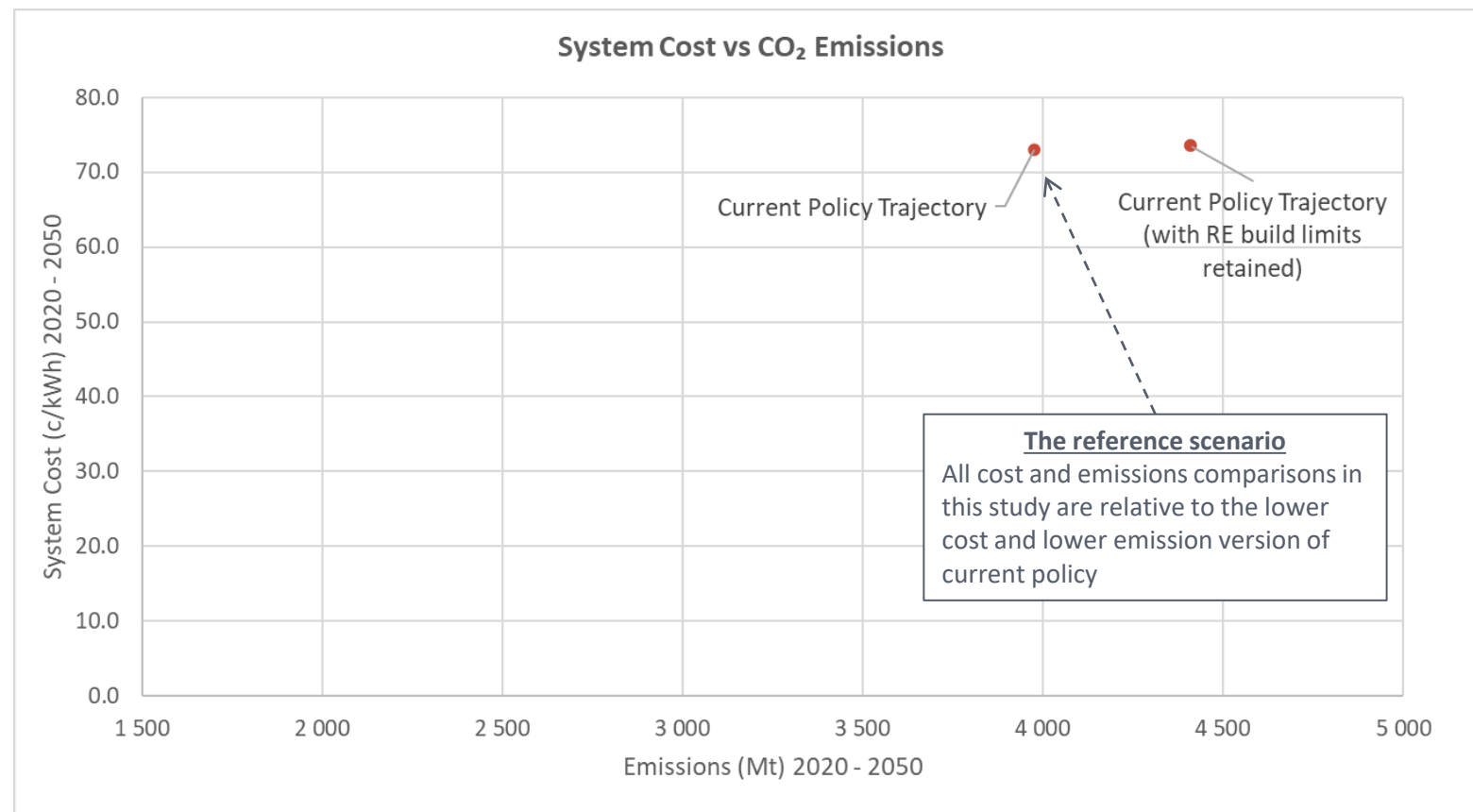
IRP 2019 is used as a basis for constructing our ‘current policy trajectory’

*Merven et al (2018) have explored the impact of retaining RE build limits from a macro-economic perspective and conclude the impact of constraining RE could be as high as ZAR 0.16/kWh by 2050, using conservative assumptions on RE and ZAR 0.18/kWh, using more optimistic RE costs.



LOCATING CURRENT POLICY IN THE COST–EMISSIONS SPACE

THE POLICY REFERENCE USED IN THIS STUDY IS CONSERVATIVE IN BOTH COST AND EMISSIONS

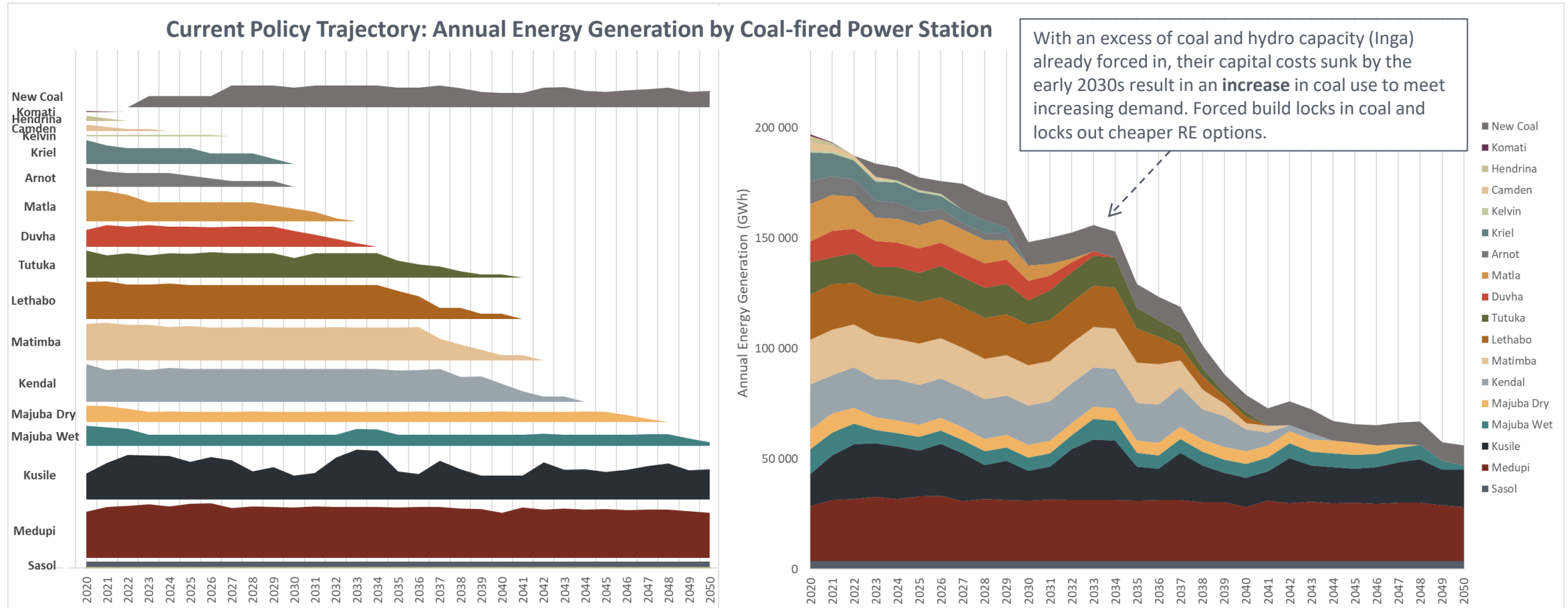


- The current policy trajectory (reference scenario) used in our study has cumulative emissions of 3.97GT and system cost of 73.0 c/kWh
- The impact of **retaining** the current annual RE new-build constraints after 2030 would be a **greater than 500 Mt increase in emissions, plus a small increase in system cost** compared to the reference scenario used
- The current policy trajectory used as the reference scenario is thus conservative in terms of both cost and emissions
- The reference scenario is further conservative in that it
 - assumes the post 2030 optimal build programme is feasible and can be built (any required smoothing of the build programme will increase cost)
 - assumes the post 2030 optimal build programme will be built (no policy adjustment)
- Relaxation of these conservative assumptions would serve to increase cost or emissions (or both) of the reference scenario – strengthening our findings



COAL-FIRED GENERATION AS PER CURRENT POLICY

ALL UNITS RUN TO SCHEDULED RETIREMENT. FORCED-IN NEW COAL CREATES PATH-DEPENDENCE

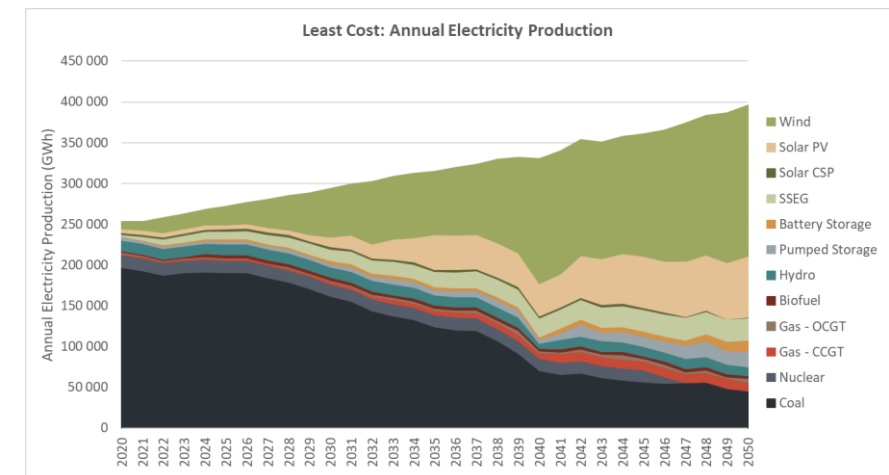
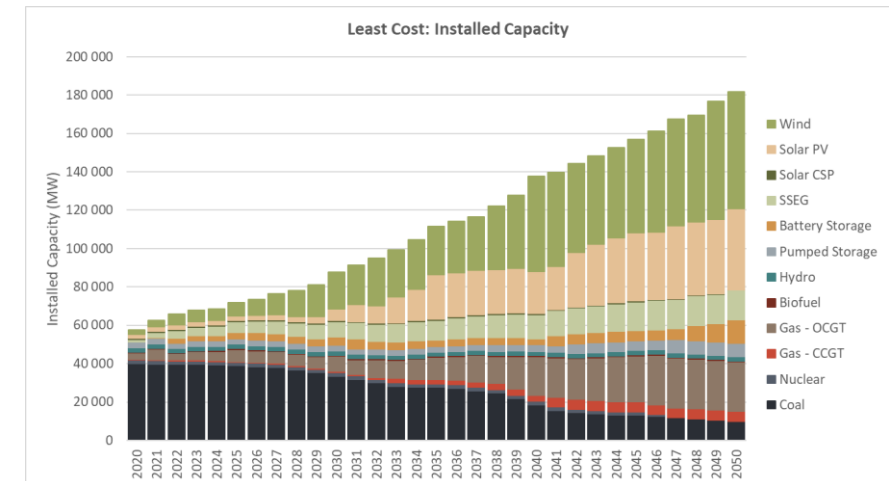


LEAST COST POWER SYSTEM

THIS IS A THEORETICAL COST-OPTIMAL POWER SYSTEM PLAN WITHOUT CONSTRAINTS

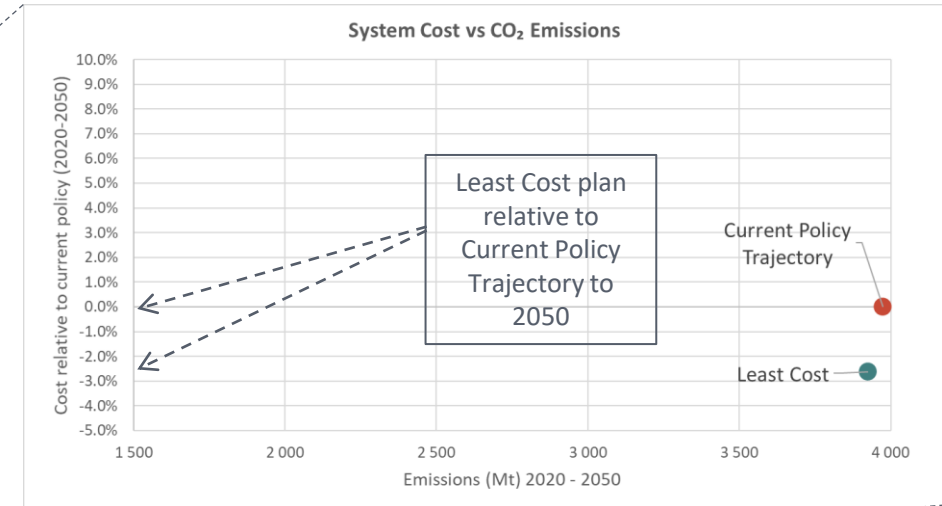
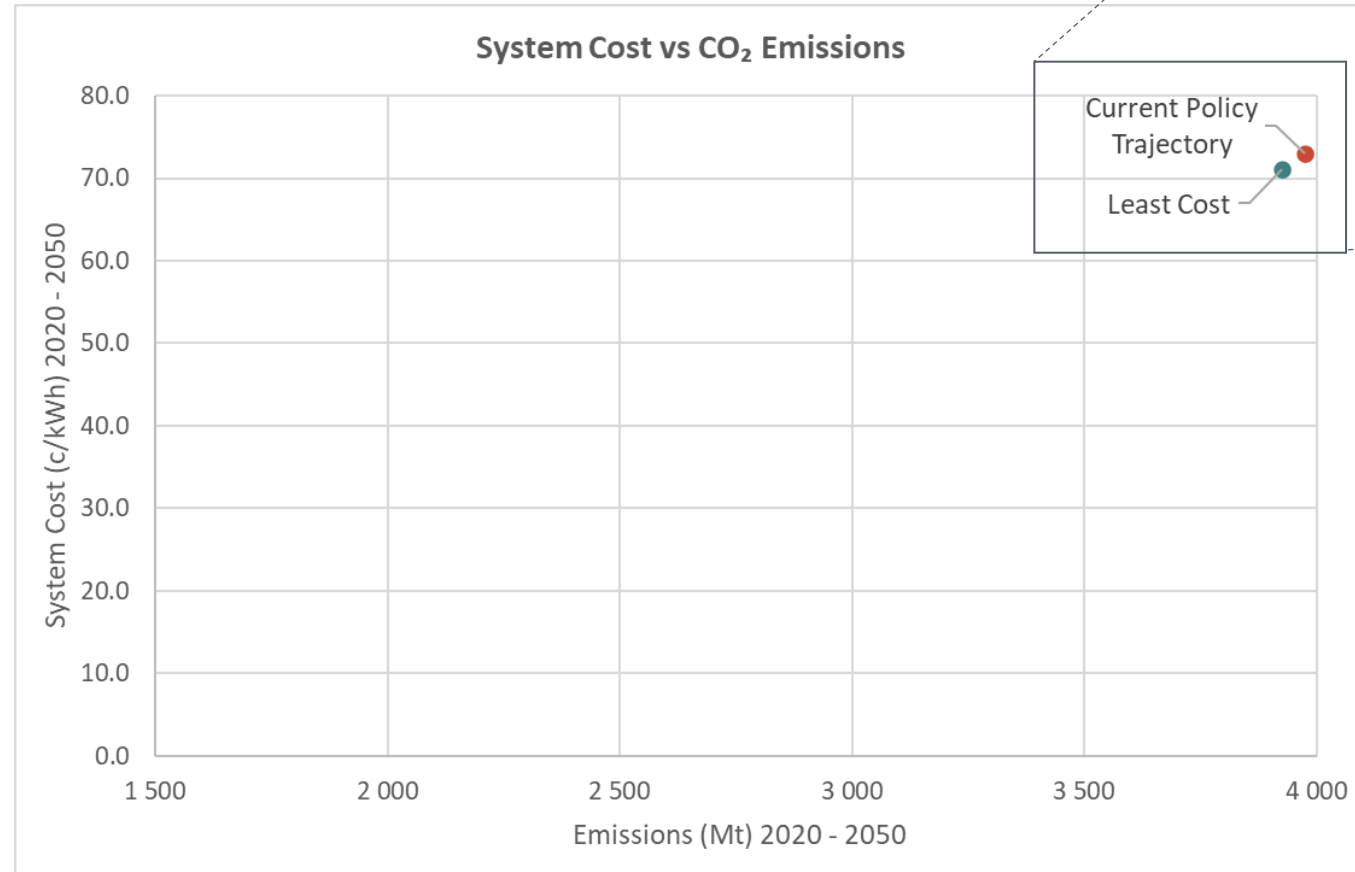
- No limits are placed on any technology
 - new capacity is built and old capacity is retired purely on the basis of minimising cost
- No new coal, nuclear or hydro is chosen by the optimiser
 - these technologies are **more costly** than the portfolio of alternatives
- Most new build capacity is wind and solar PV, with gas and storage to provide flexibility and reserve capacity as coal retires (reserve capacity is required when the primary generation sources are not available)

Technology	Total new capacity built in the least cost scenario from 2020-2050 (GW)
Wind	76.8
Solar PV	42.3
Solar CSP	-
SSEG	17.4
Battery Storage	16.9
Pumped Storage	3.9
Hydro	-
Biofuel	0.3
Gas – OCGT/GE	28.2
Gas – CCGT/GE	4.7
Nuclear	-
Coal	-



LOCATING THE LEAST COST POWER SYSTEM IN THE COST EMISSIONS SPACE

LOWER COST THAN CURRENT POLICY, WITH LOWER EMISSIONS



- A 'least cost' power system plan is 2.5% cheaper than current policy and has lower emissions
- Emissions from new coal in the current policy trajectory are offset by new hydro (Inga)
 - Inga is not chosen in the least cost optimisation due to its expense
 - There are serious questions around the reality / viability of the Inga project, bringing its emissions mitigation effect into question.
- Including coal refurbishment capital costs (unavailable to us) into the assumptions underpinning all scenarios would
 - increase cost of current policy trajectory relative to least cost scenario and
 - decrease the cost of RE compared to coal, causing the least cost scenario to build more RE, further decreasing emissions



UNDERSTANDING THE GLOBAL CARBON EMISSIONS SPACE

HOW DO WE TRANSLATE THIS INTO A CARBON BUDGET?

- The Paris Agreement of the United Nations Framework Convention on Climate Change (UNFCCC) includes the goal of keeping global temperatures ‘**well below 2 degrees**’.
- Achieving this goal requires significant constraints on global carbon emissions. As a signatory to the Paris Agreement, South Africa is required to align with these global efforts. **How is such alignment assessed, at a global, South African and SA power sector level?**
- **There is no definitive way of ascertaining this.** Apart from complexities in the climate science, factors that need to be considered include equity of effort, capabilities, existing fossil fuel intensities, and domestic policy objectives. **The task is as much ethical and political as it is scientific.**
- Carbon budgets represent a rigorous yet flexible metric for *considering* effort over time. **A carbon budget is a number representing cumulative emissions over a timeframe** (here, 2020 to 2050), i.e. the area below an emissions trajectory. By defining the trajectory, the budget is implied.
- For example, hypothetical global carbon budgets representing 1.5 and 2 degrees of warming are presented in Figure 1. A carbon budget can be considered against the cost of achieving this, as shown in Figure 2.

Figure 1. Hypothetical Global Emissions Reduction Trajectories

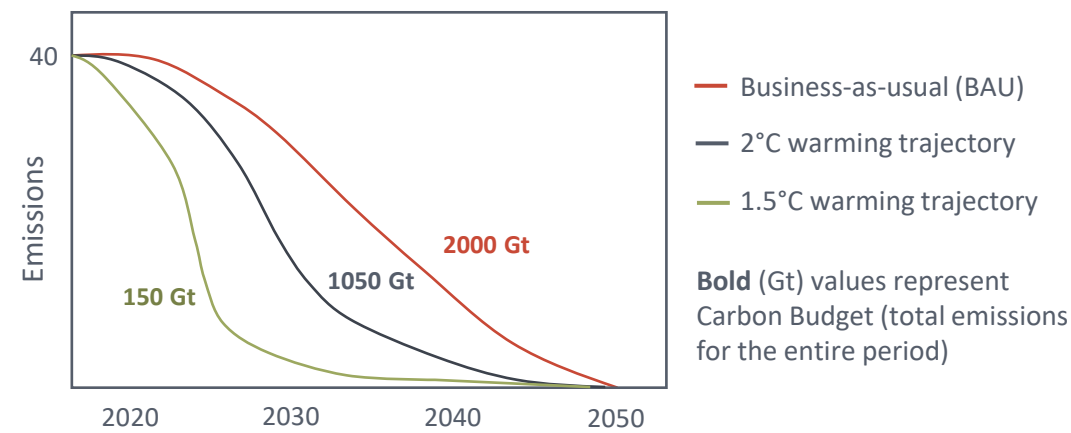
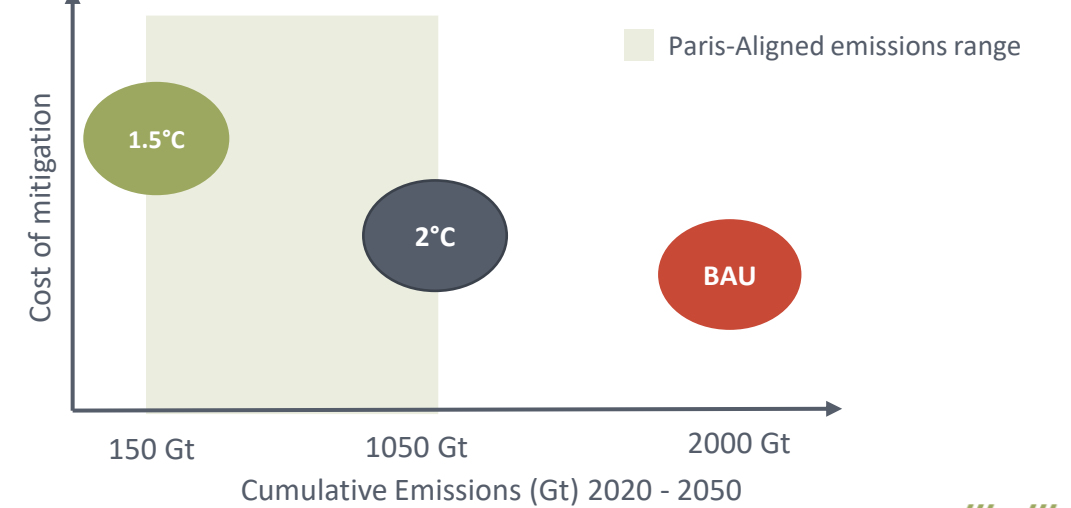


Figure 2. Costing Hypothetical Global Emissions Budgets

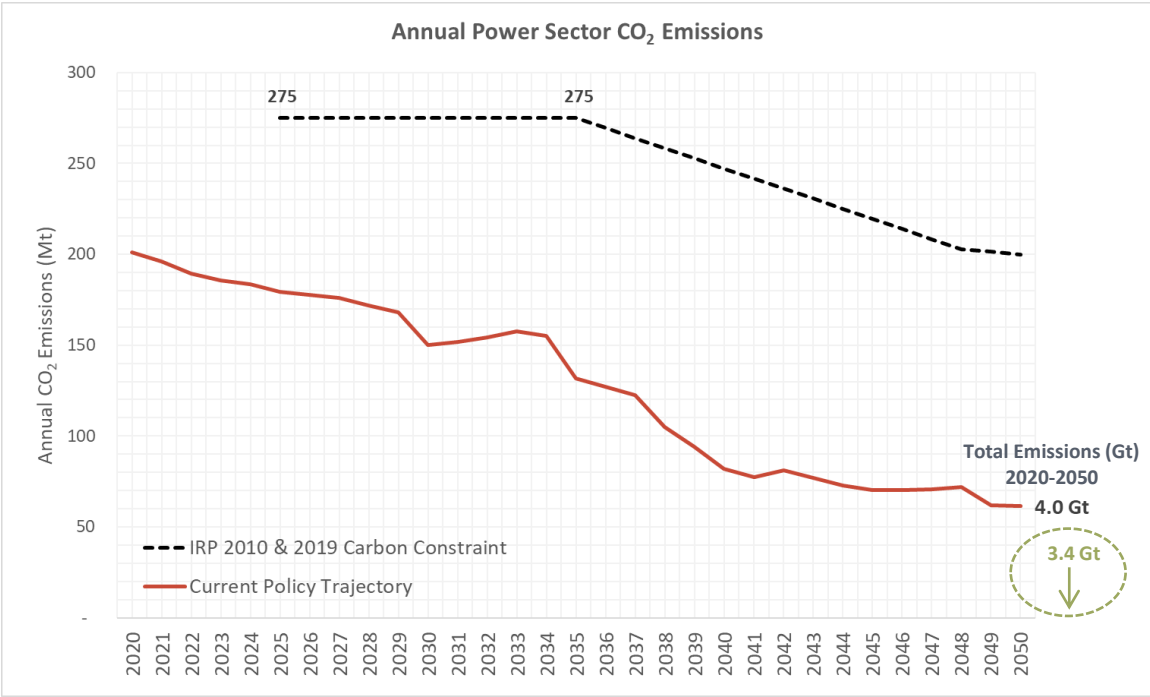


MAPPING THE TERRAIN OF EXISTING RSA CARBON BUDGETS

- The analysis presented here draws on the literature considering the allocation of global budgets to nations, and then on the role of the power sector in achieving South Africa's contribution to this global effort. The intention is to identify a range of budgets for the power sector which are likely to support an emissions trajectory for RSA that is Paris-aligned.
- The National Benchmark Carbon Trajectory Range** is South Africa’s current international and domestic climate policy position, which has an Upper Trajectory carbon budget of 17.5Gt and a Lower Trajectory carbon budget of 10.8Gt for **economy-wide emissions**. The Lower Trajectory has been assessed as being aligned to 66% probability levels of the global 2°C target being achieved, which is generally associated with ‘well below 2°C’ (Peters, 2017). A Paris-aligned budget at the national, economy-wide level could therefore be said to be 10,8Gt and below.

Suggesting a Paris-aligned carbon budget range for the RSA power sector

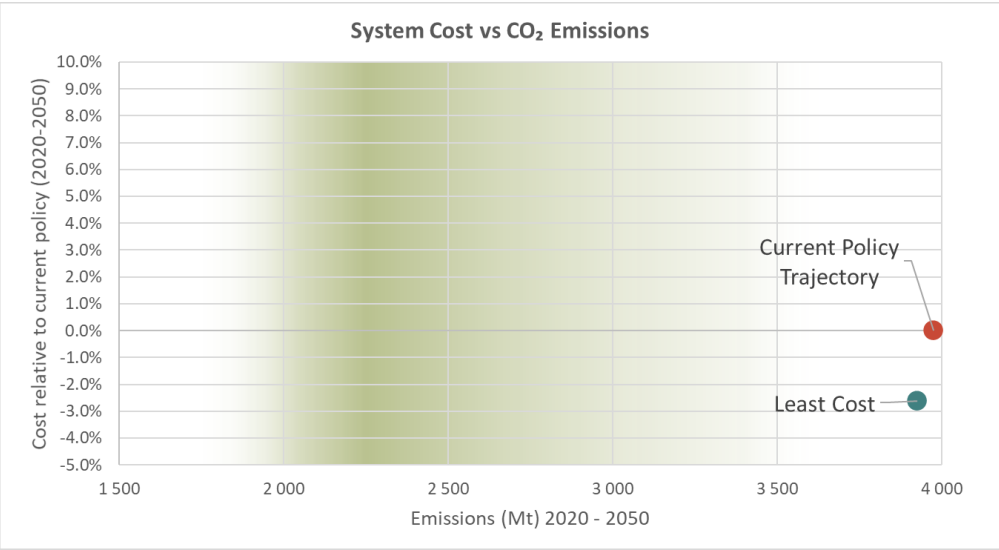
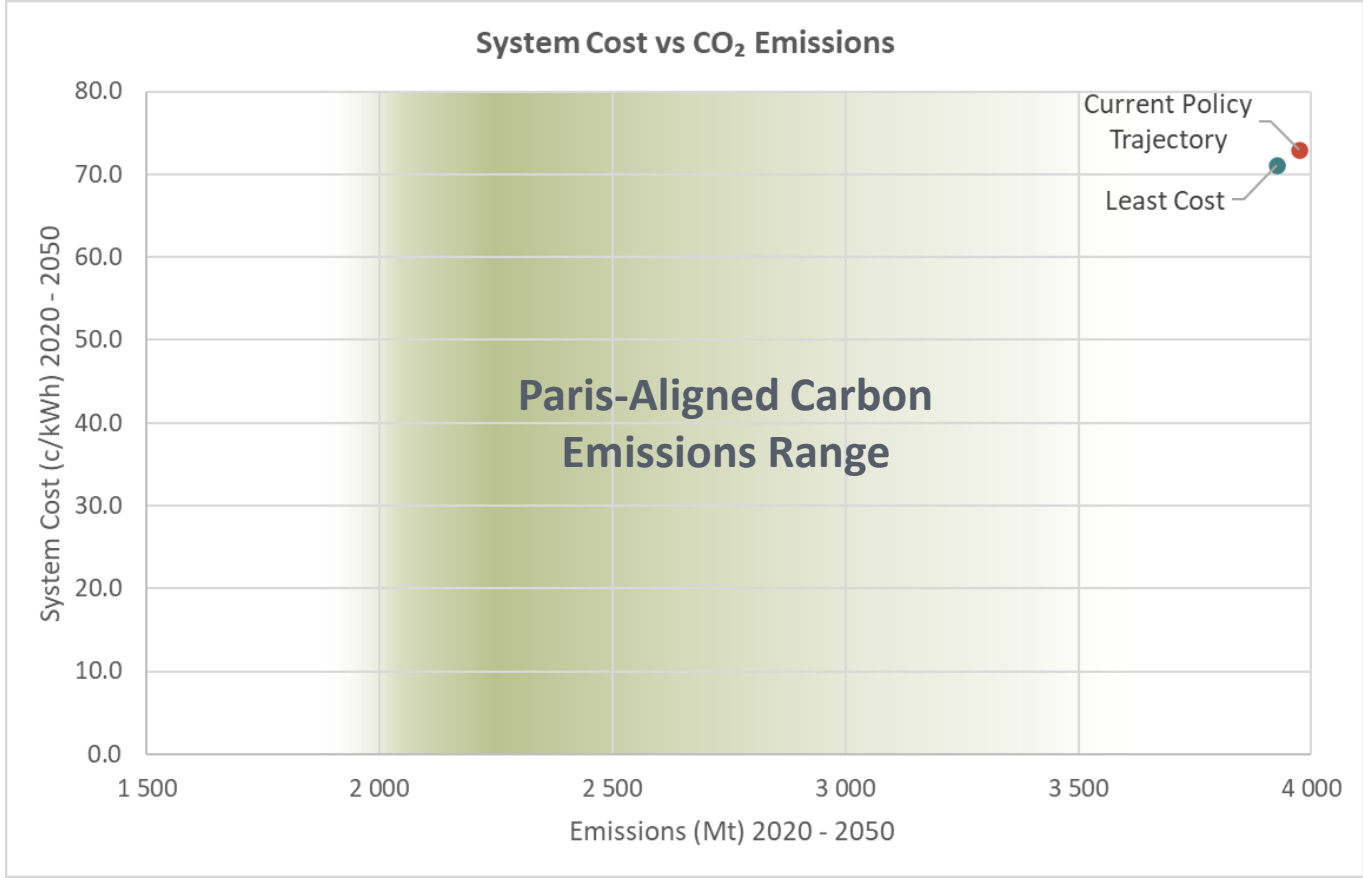
- The IRP 2010 & IRP 2019 Carbon constraint:** A carbon constraint was included in the 2010 IRP based on the power sector continuing to contribute its historical **45% of SA emissions**. This constraint, extended in the 2019 IRP to 2050 is related to the Upper Trajectory and **is therefore both outdated and unlikely to be aligned to the Paris goals**.
- Emissions associated with the Current Policy Trajectory scenario:** Consistently below the IRP carbon constraint, this represents a 3.97 Gt budget. But is it Paris-aligned? The literature suggests that to enable RSA to achieve 2 degree alignment, a power sector budget between 2.9 Gt to 3.4 Gt (Burton et al, 2018) would be appropriate, and for ‘well below 2 degrees’, 2.3 Gt. (McCall et al, 2019).
- Noting the uncertainty around these budgets, the broad articulation of the Paris goals, and the precautionary principle of the UNFCCC, **we decided to explore the range of 2.0 Gt – 3.4 Gt, with an emphasis on 2.3 Gt.**



**Noting that the allocation of the global carbon budget to nations has not been achievable in the UNFCCC process to date. In this study we are referring to the use of carbon budgets to assess Paris goal alignment. Further elaboration of this analysis is provided in ME, 2020b.*



A LIKELY PARIS-ALIGNED CARBON BUDGET RANGE FOR THE RSA POWER SECTOR



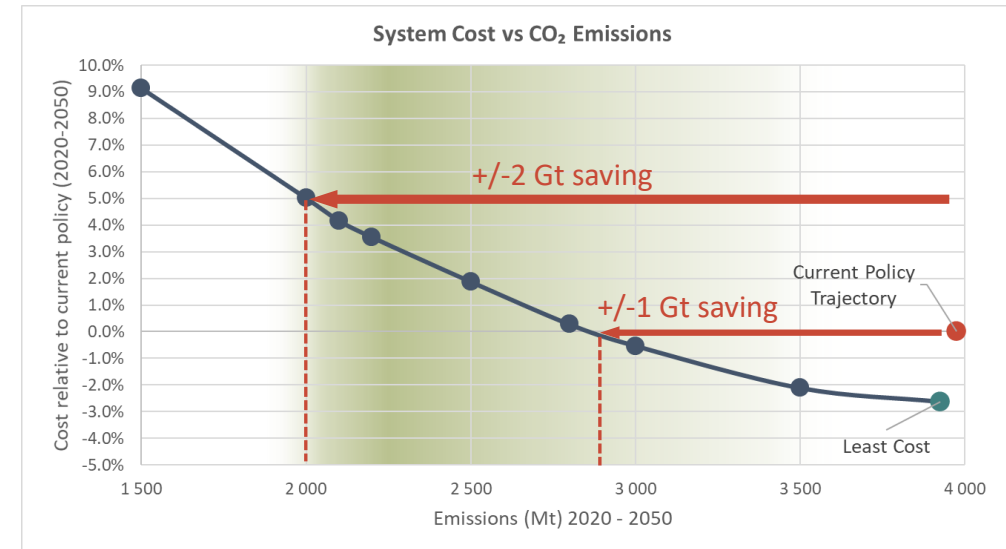
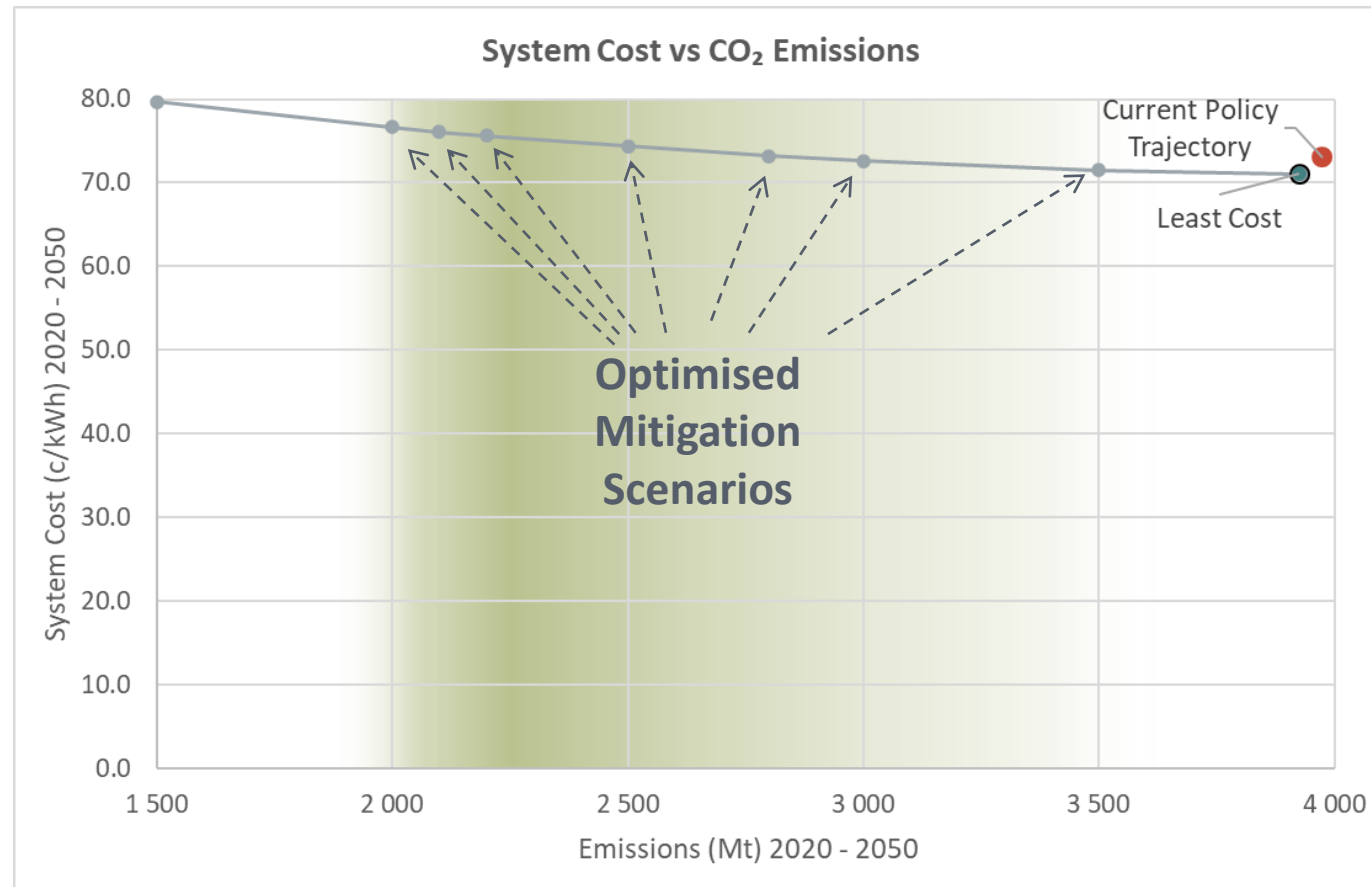
- If a likely Paris-aligned emissions range is 2.0 Gt - 3.4 Gt...
- Current Policy Trajectory and Least Cost scenarios result in emissions far above Paris-aligned levels
- **We must explore scenarios that achieve emissions in the likely Paris-aligned carbon budget range**
- The optimal way of exploring lower emission options is to re-run the Least Cost scenario with successively lower emissions budget constraints
- Another metric for considering alignment with Paris specific to the power sector is the date when no more coal is burnt for thermal power. This has been suggested as 2040 in global analyses (ME, 2020b). We return to this later.



RESULTS OF OUR ANALYSIS



A SERIES OF COST-OPTIMISED SCENARIOS WERE DEVELOPED WITH DECREASING CARBON BUDGETS



- Power sector scenarios that emit far less than the current policy trajectory are also cheaper
- **The Cost vs Emissions curve is almost flat for the likely Paris-aligned emissions range**
- **Substantial mitigation** (+/- 1 Gt saving relative to the current policy trajectory) can be achieved with **no increase in cost** relative to the Current Policy Trajectory
- Even deeper mitigation comes at a fractional increase in cost
 - Emissions can almost be halved (+/- 2 Gt saving relative to the current policy trajectory) for a 5% increase in electricity cost relative to the Current Policy Trajectory
- Given the 30-year future timeframe over which any cost difference will manifest, and inherent difficulty in forecasting over such a period, cost difference of this magnitude is likely in the error noise
 - Relaxing any of our already conservative assumptions would only serve to reduce any mitigation cost further



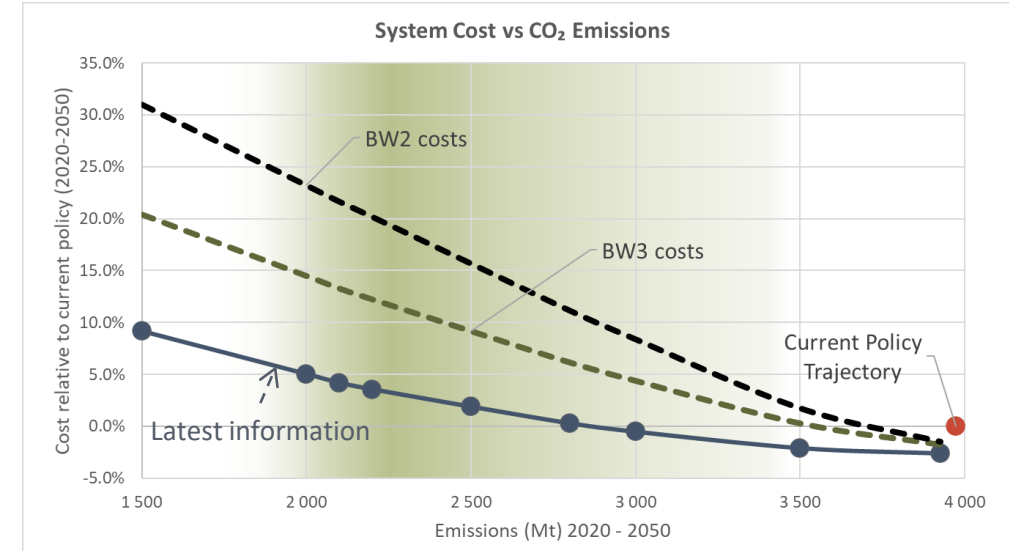
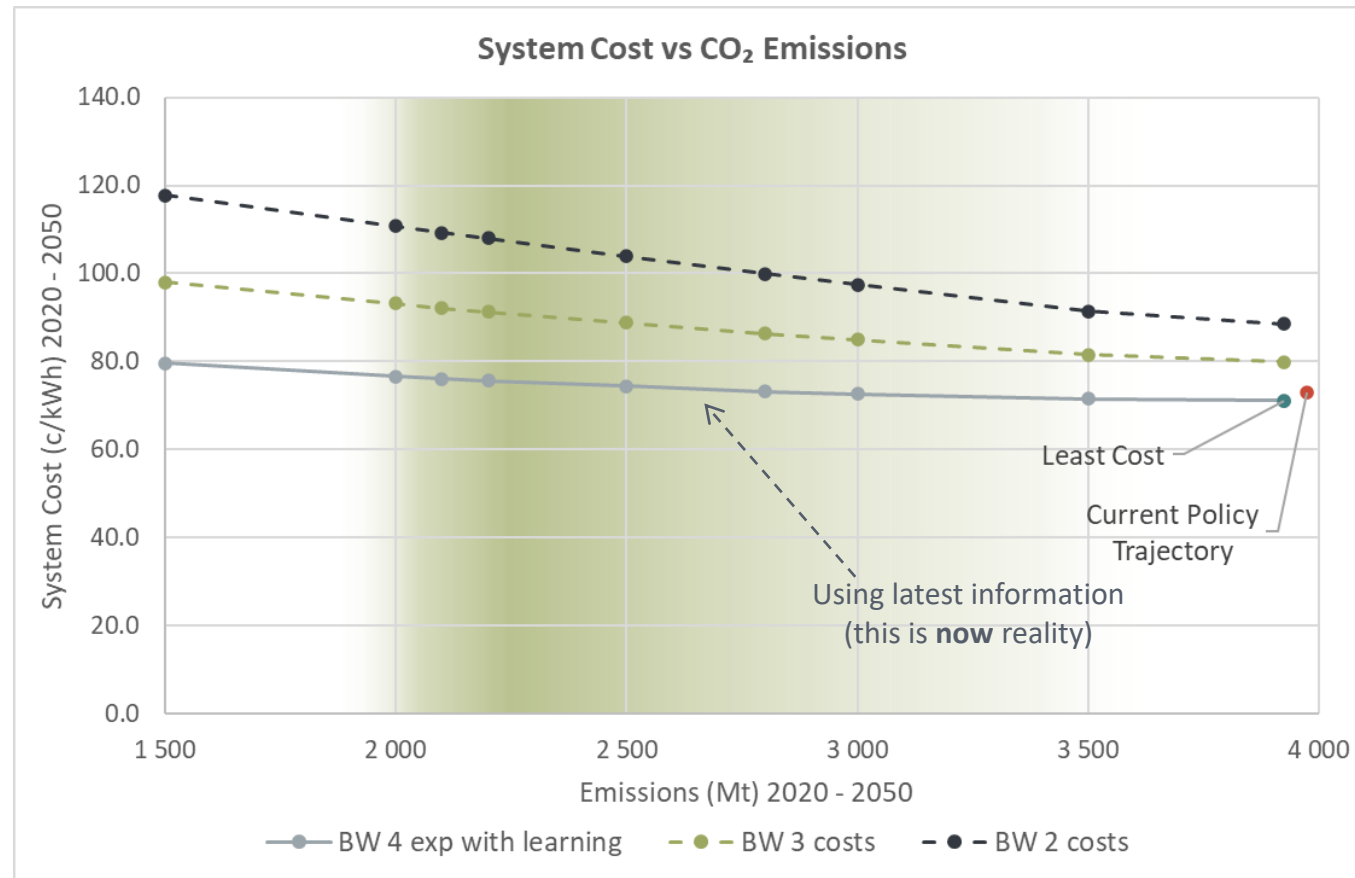
POWER SYSTEM PLANS WITH LOWER CARBON EMISSIONS DO NOT COST SIGNIFICANTLY MORE THAN THE LEAST COST SCENARIO

WHAT DRIVES THIS FINDING?

- **RE is currently the lowest cost new build power generation technology available**, ensuring that there are no significant emissions associated with new capacity in *any* cost optimised scenario.
- **The emissions represented in each scenario therefore come predominantly from the coal fleet** (emissions from gas are not material in any optimised mitigation scenario due to its low usage)
- As a result, what drives the reduction in emissions is the accelerated reduction of coal burnt in the existing coal fleet (i.e. **increasingly less energy generated from coal**)
- Lowering the carbon budget requires the reduction of coal burn to happen ever sooner.
 - This can only happen if RE is built “too early” i.e. earlier than the date determined as optimal from the perspective of technology learning curves. Hence the (slight) increase in cost as more emissions are mitigated.
 - At historic RE costs the penalty of building “too early” was indeed high. With the precipitous drop in RE costs this is no longer the case
 - The following slide elaborates this point



DISRUPTIVE RE COST DECLINES DRIVE CHEAP MITIGATION ACROSS ALL SCENARIOS



- Is it surprising mitigation is so cheap? Why? Has our intuition around the cost of RE kept pace with reality?
- If RE costs had remained the same as earlier REIPPP bid rounds, **any** mitigation would come with a cost increase
 - 1GT mitigation would increase cost 5%-10%
 - 2GT mitigation would increase cost 15%-25%
 - **This is no longer the reality**
- RE costs have fallen and will continue to fall into the future as technology cost learning manifests

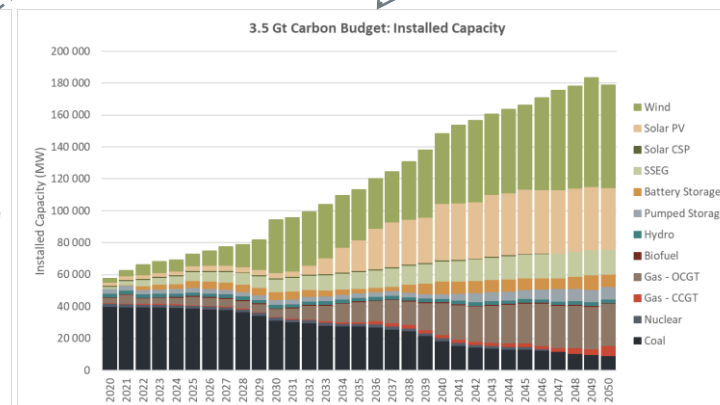
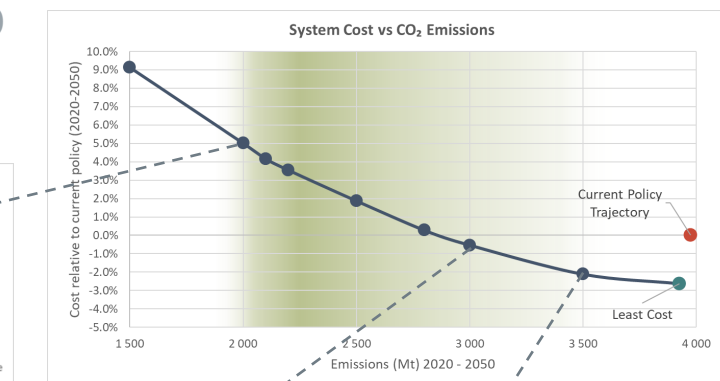
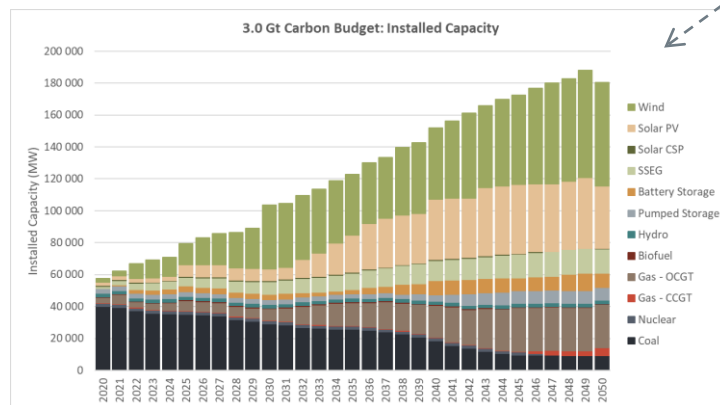
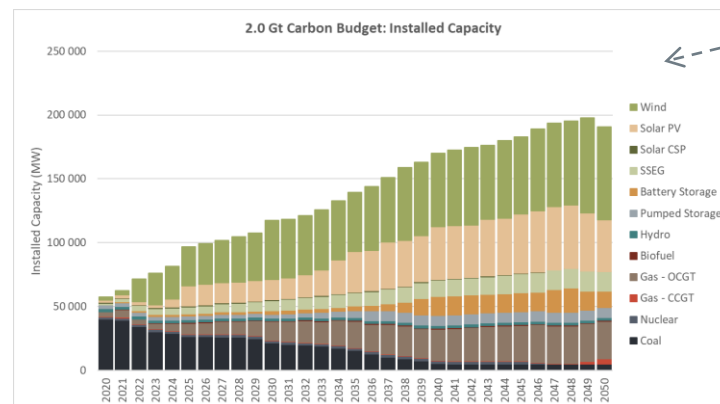


NEW GENERATION CAPACITY: RE IS THE OPTIMAL CHOICE

NO NEW COAL, NUCLEAR OR HYDRO IS BUILT UNDER ANY COST-OPTIMAL SCENARIO

In all cost-optimal scenarios, the majority of new build capacity is wind and solar PV, with gas and storage providing flexibility and reserve capacity as coal retires.

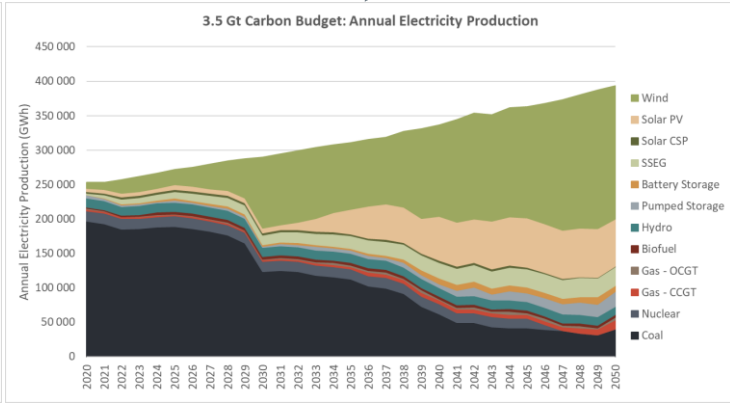
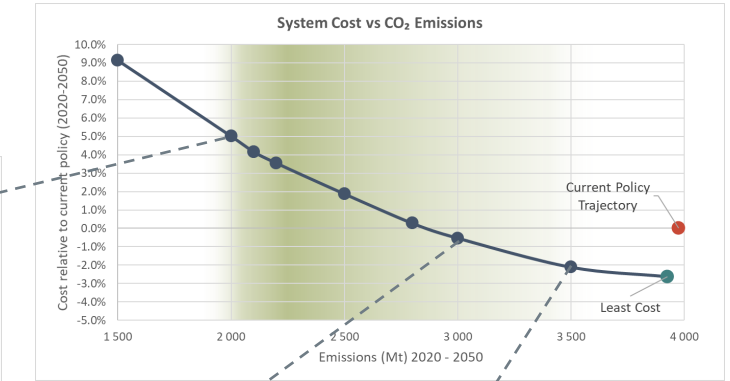
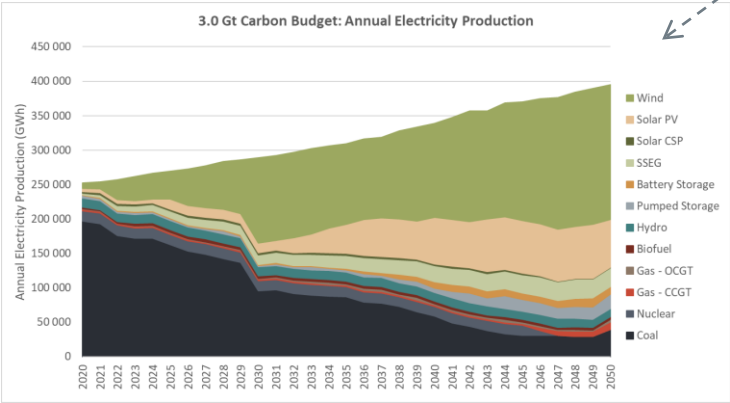
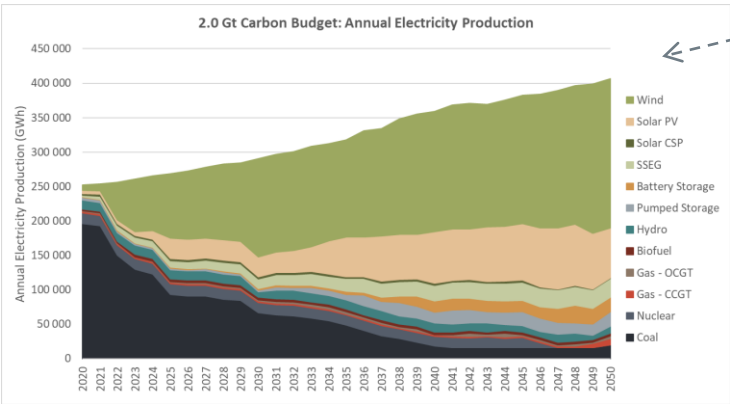
Total new capacity built (GW) in each cost-optimal scenario from 2020 - 2050			
Technology	2.0 Gt Carbon Budget	3.0 Gt Carbon Budget	3.5 Gt Carbon Budget
Wind	115.4	101.4	94.1
Solar PV	54.3	44.3	39.6
Solar CSP	-	-	-
SSEG	17.4	17.4	17.4
Battery Storage	27.5	18.5	17.5
Pumped Storage	5.0	5.0	5.0
Hydro	-	-	-
Biofuel	0.3	0.3	0.3
Gas – OCGT/GE	32.1	29.4	28.8
Gas – CCGT/GE	3.6	4.5	5.7
Nuclear	-	-	-
Coal	-	-	-



OPTIMAL LOW EMISSIONS ENERGY GENERATION

THE FUTURE IS RENEWABLES WITH AN INCREASED ROLE FOR STORAGE

- Wind and Solar PV generate by far most of the energy into the future in all mitigation scenarios
- Although significant gas peaking *capacity* is built, its primary role is to provide flexible reserve capacity not energy. Gas makes a very small contribution to the energy mix – between 1.5% and 2.0% in the optimised mitigation scenarios
- Storage cost reductions into the future result in increased battery usage in the latter part of the period in scenarios with higher emission budgets. Gas provides flexibility in the first 15 – 20 years.
- Paris-compliant scenarios exchange coal and gas energy for increased RE and storage capacity at little if any cost above the current policy scenario



WHAT HAPPENS TO THE COAL FLEET EMISSIONS?

COAL-FIRED UNITS ARE CLOSED EARLY OR OPERATED TO GENERATE LESS ENERGY OVER THEIR REMAINING LIFE

- **Coal fired capacity is retired when it is economically efficient to do so** given each scenario's carbon constraint
 - There is no requirement to continue running coal stations even if their design life has not been reached
- Although coal capacity closure is a favoured measure of mitigation success, our findings indicate **emission mitigation may be more optimally achieved by retaining coal capacity at minimum burn levels**
 - Keeping coal capacity on the system but running at much lower capacity factors (minimum 35%) provides system stability/capacity while the RE is being built
 - Determination of a reliably optimal station-level unit closure schedule is beyond the scope of our modelling due to lack of granular information regarding the condition of units, the exact Capex and Opex requirements and individual coal contract details
 - Premature closure of coal plant in the South African context could result in a need for more gas fired power and associated gas infrastructure resulting in a costly and high-emission future locked into long term gas commitments.
- **With each progressively tighter carbon constraint, energy generated from coal reduces.**



THE TIGHTER THE CARBON CONSTRAINT, THE EARLIER COAL GENERATION MUST BE REDUCED

THIS REQUIRES BUILDING SOLAR PV AND WIND BEFORE IT IS COST-OPTIMAL TO DO SO

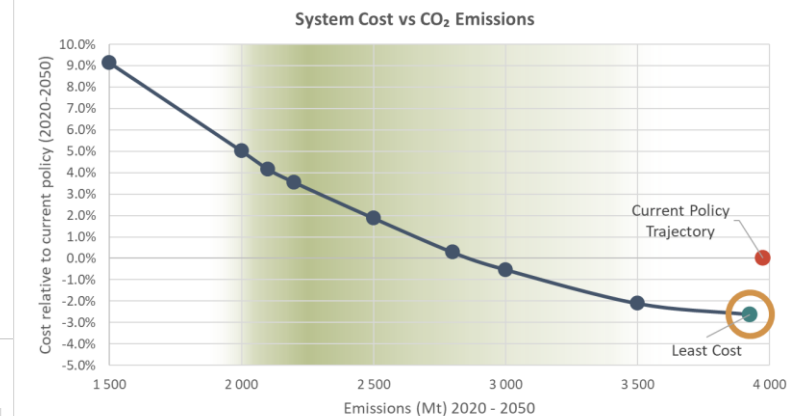
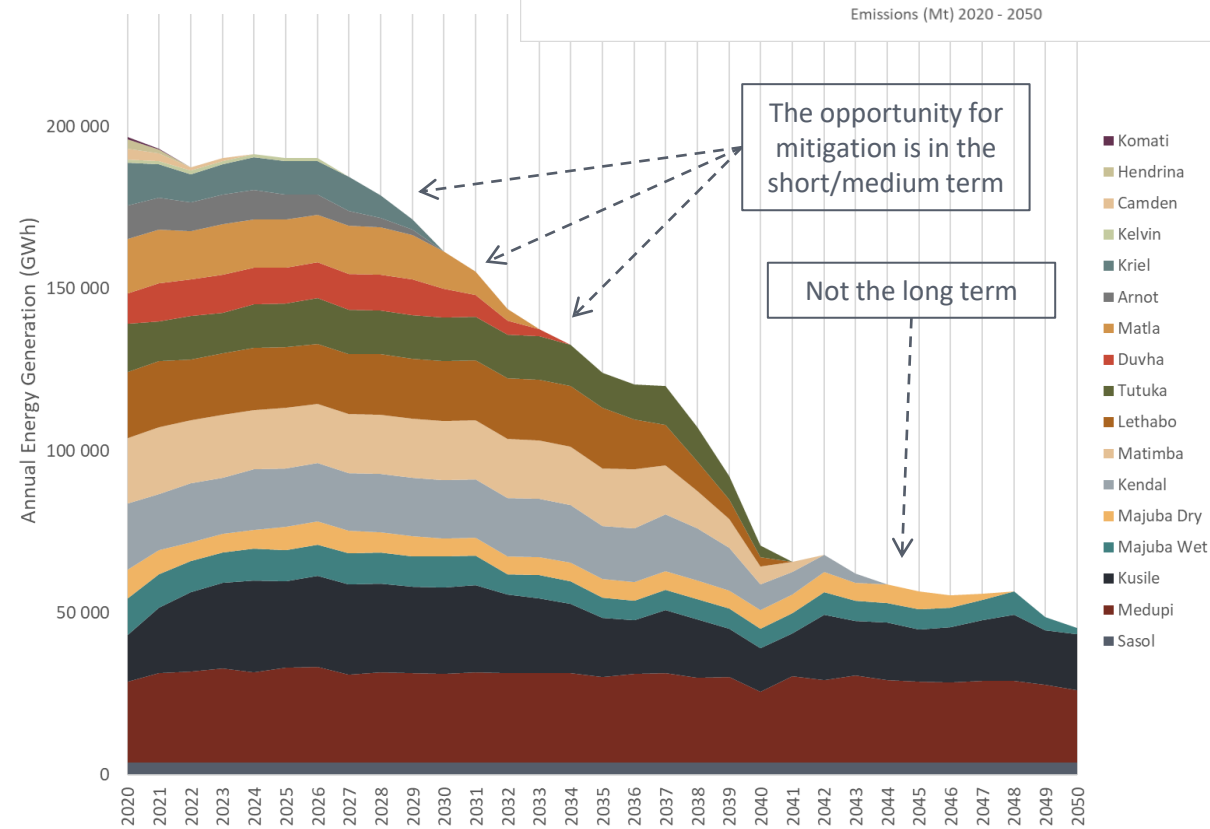
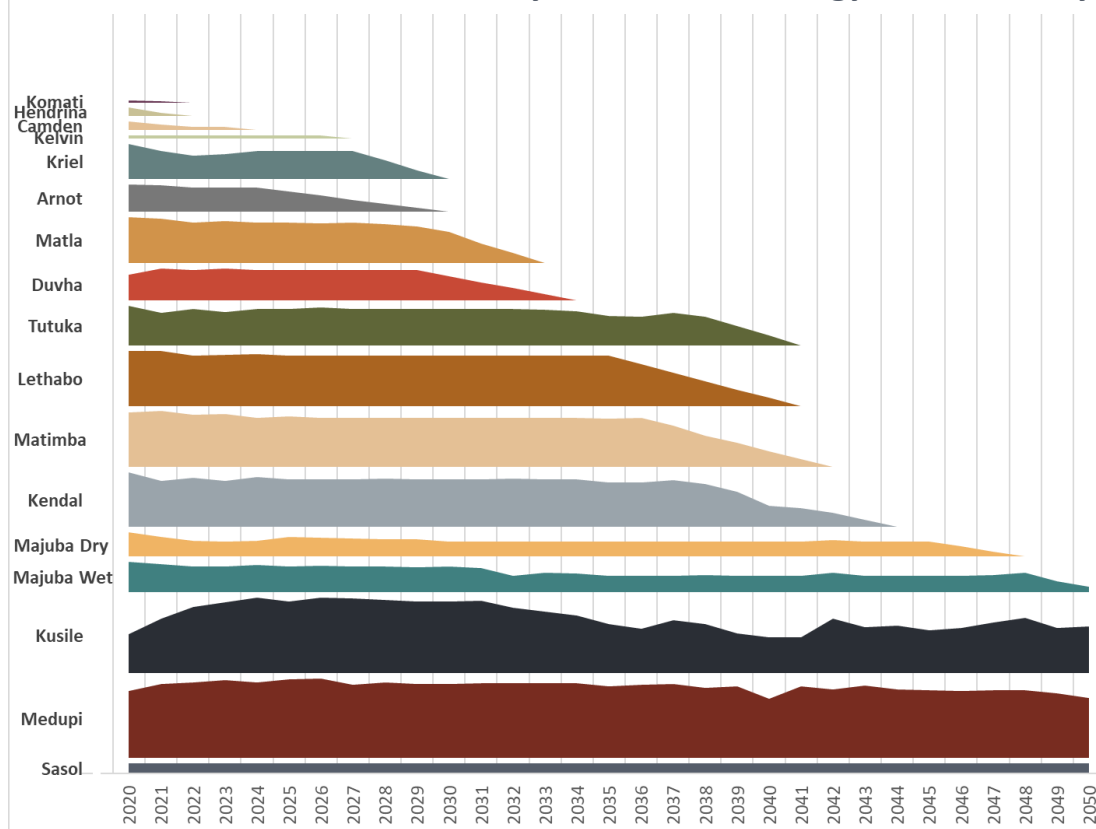
- In the Least Cost Scenario there is a natural decline in energy generated from coal as the coal fleet ages and retires
- This means the bulk of energy generated from coal – and hence emissions - occurs in the first two decades of the timeframe explored (i.e. 2020s and 2030s).
- Therefore, **the opportunity for increasing carbon mitigation is in the short and medium term**, when coal is a substantial fraction of the mix, not later when it has already reduced.
- **This implies rapid early RE build** to replace coal generation in the short and medium term
- There are also realistic constraints on how much RE can be built in one year (considered in the next section)
- The following sequence of slides details the theoretically cost-optimal reduction of coal-generated power for the least cost and increasingly ambitious mitigation scenarios.



COAL GENERATION IN LEAST COST SCENARIO

COAL FIRED POWER GENERATION IS SHOWN PER POWER PLANT

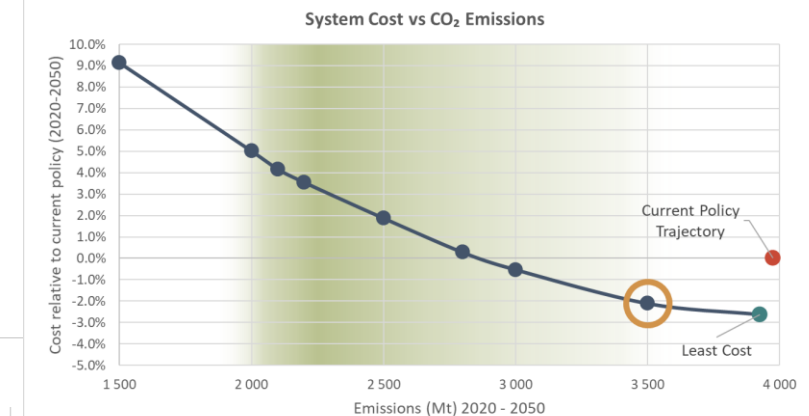
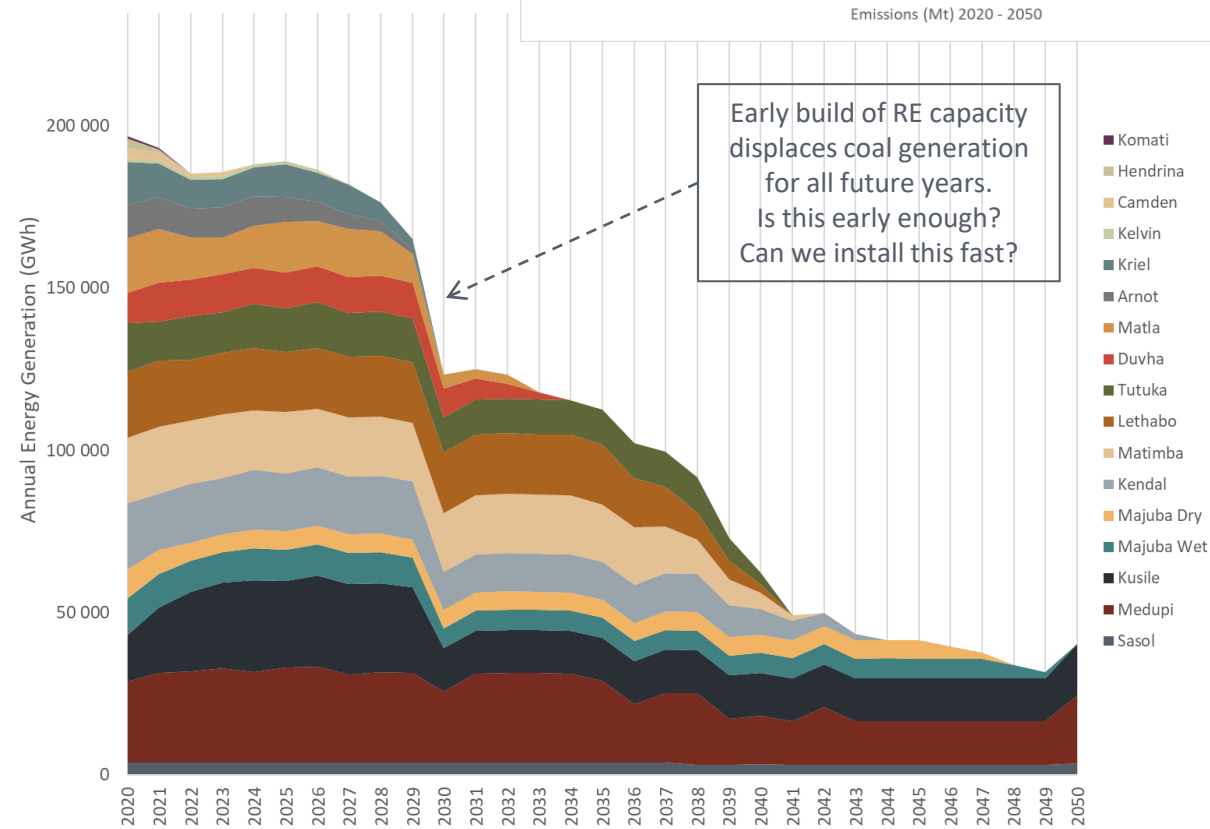
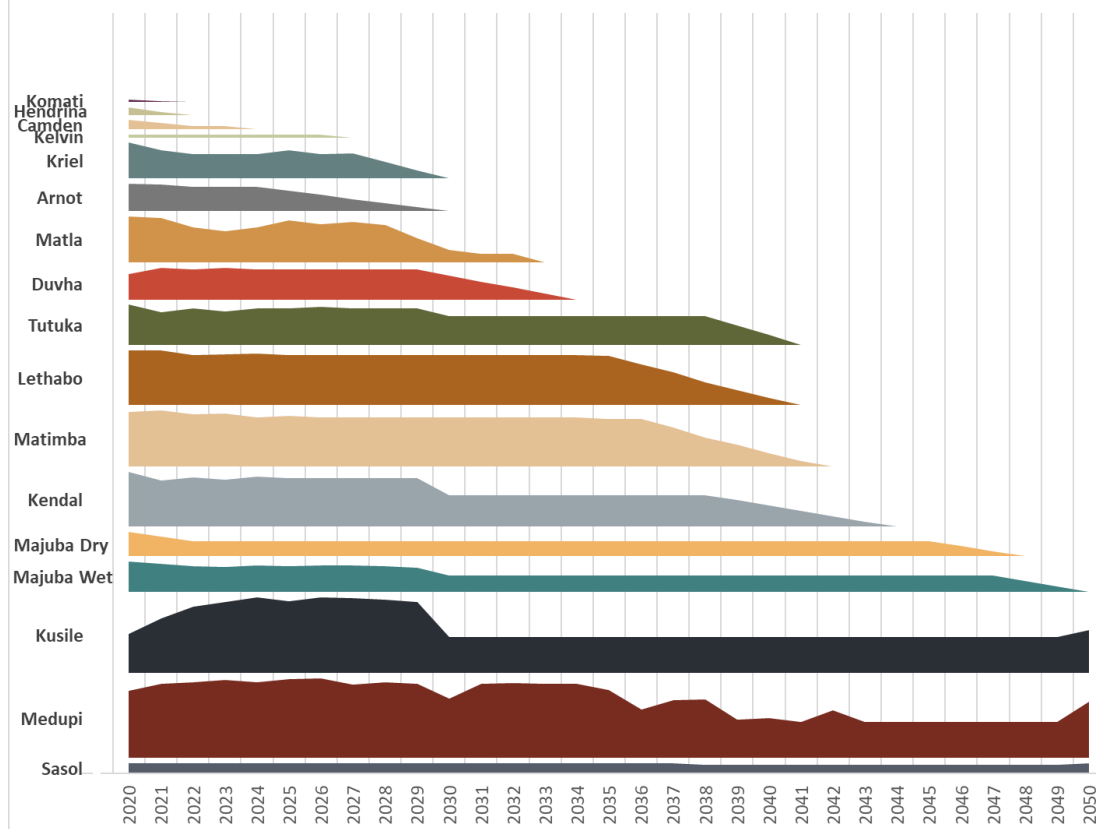
Least Cost Power System: Annual Energy Generation by Coal-fired Power Station



3.5 GT SCENARIO

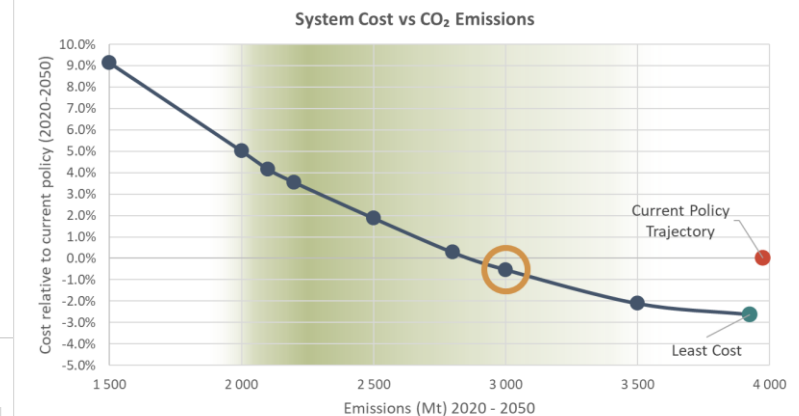
SIGNIFICANT COAL OFF CIRCA 2030

3.5 Gt Carbon Budget: Annual Energy Generation by Coal-fired Power Station

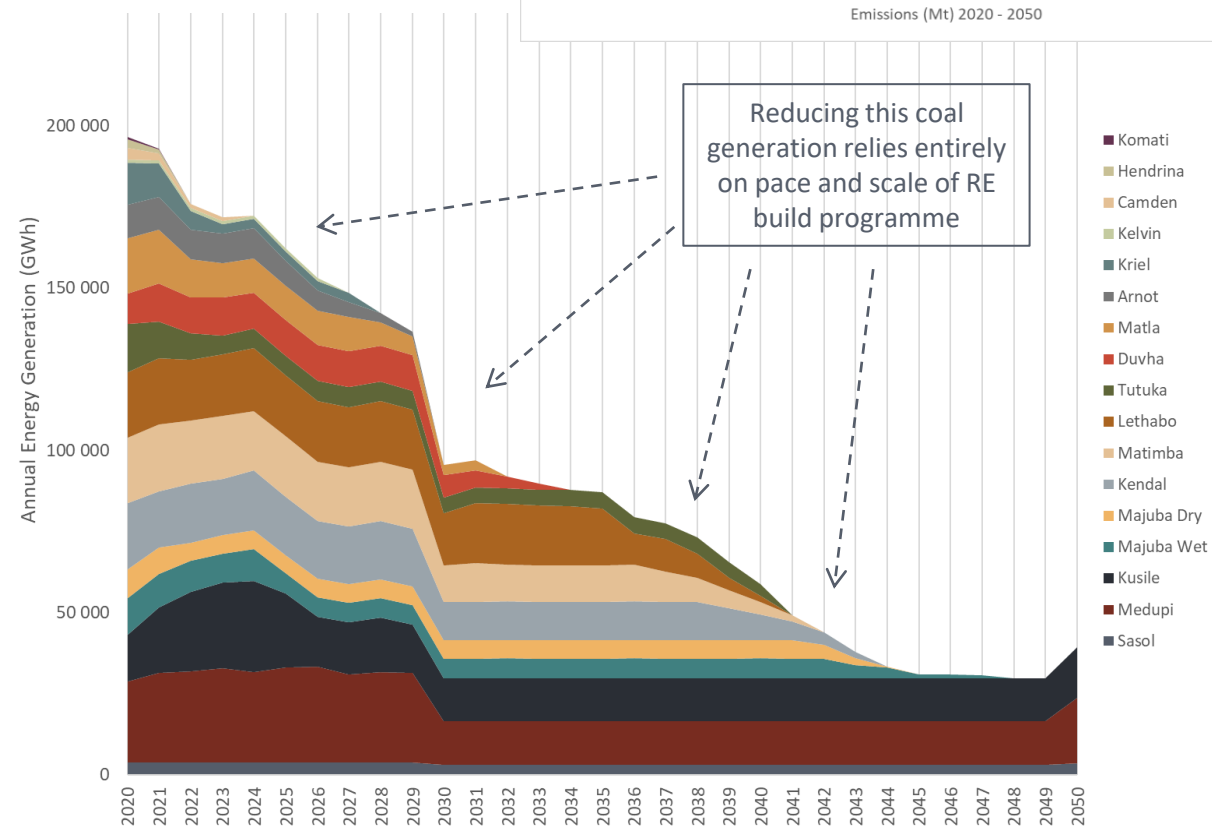
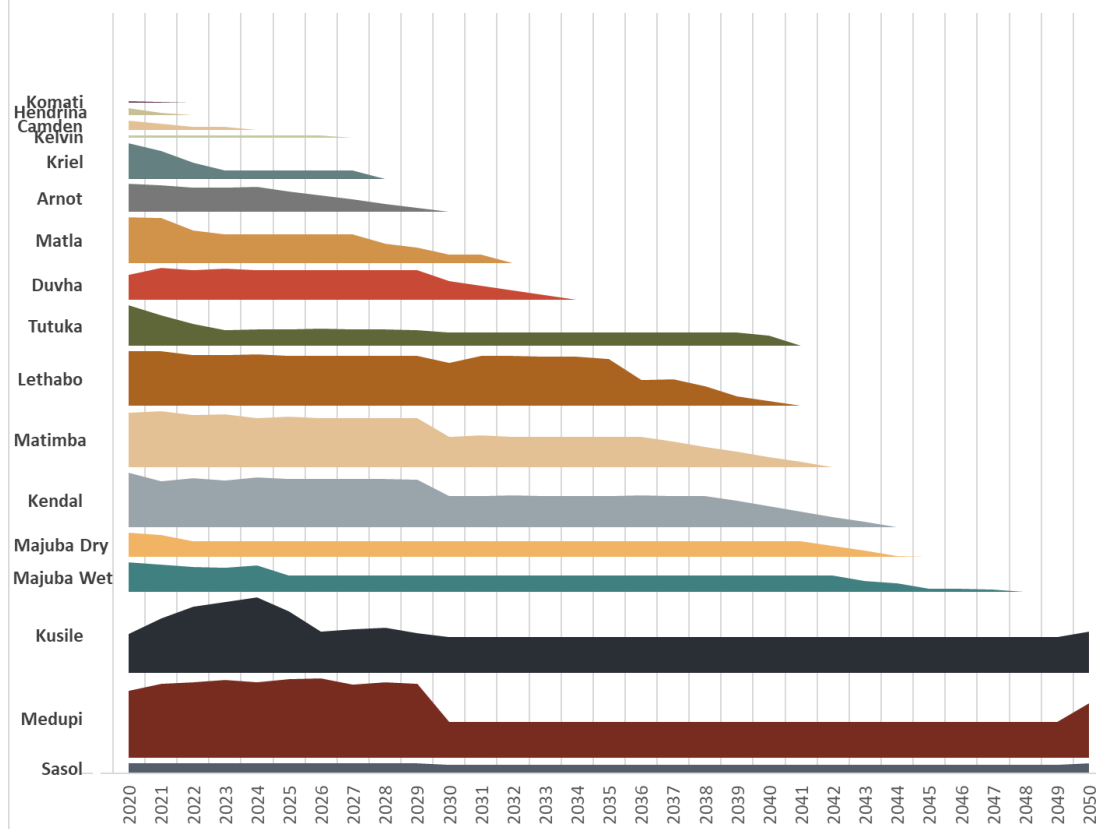


3.0 GT SCENARIO

REQUIRES MORE COAL OFF IN THE 2020s

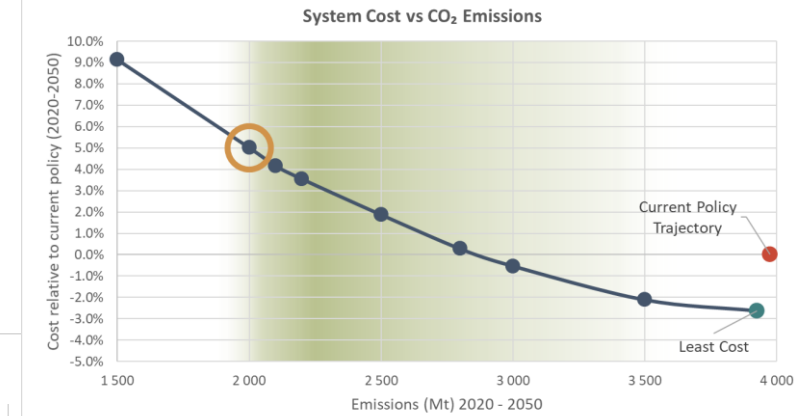


3.0 Gt Carbon Budget: Annual Energy Generation by Coal-fired Power Station

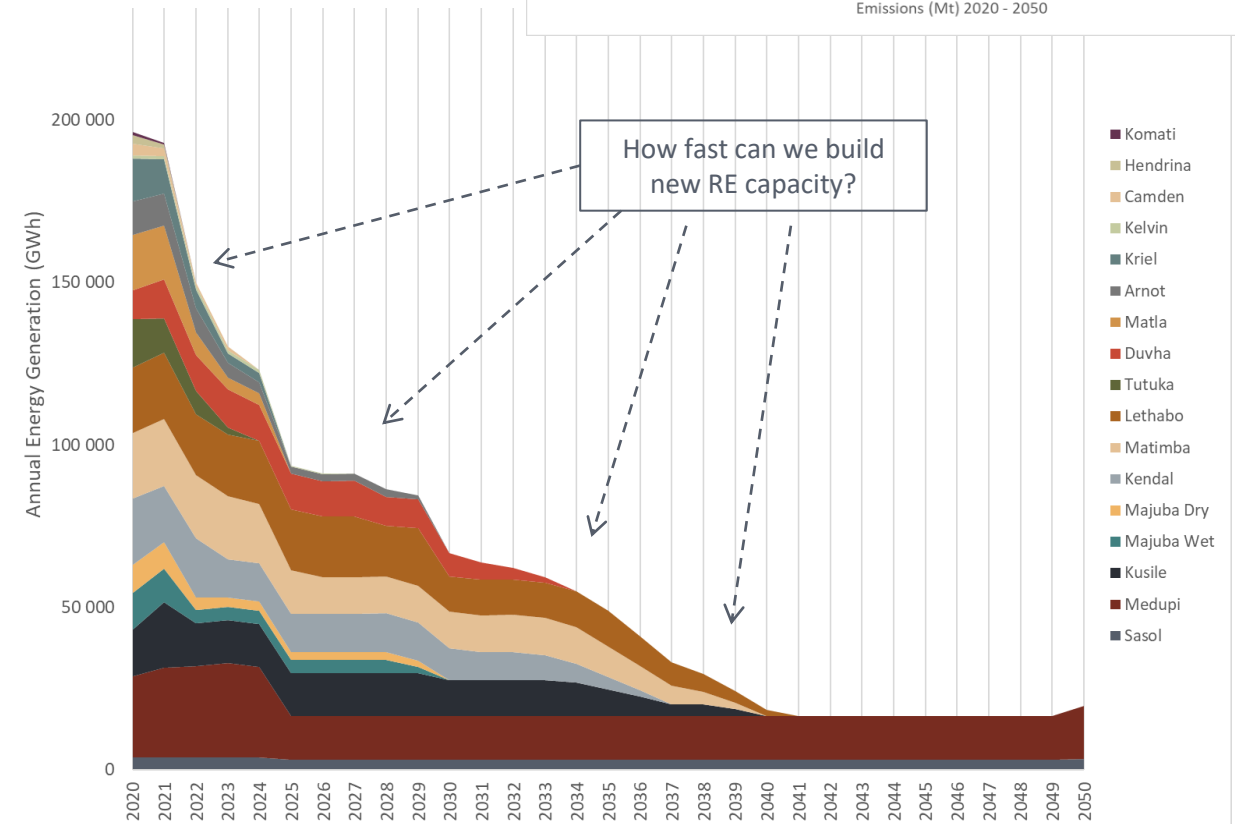
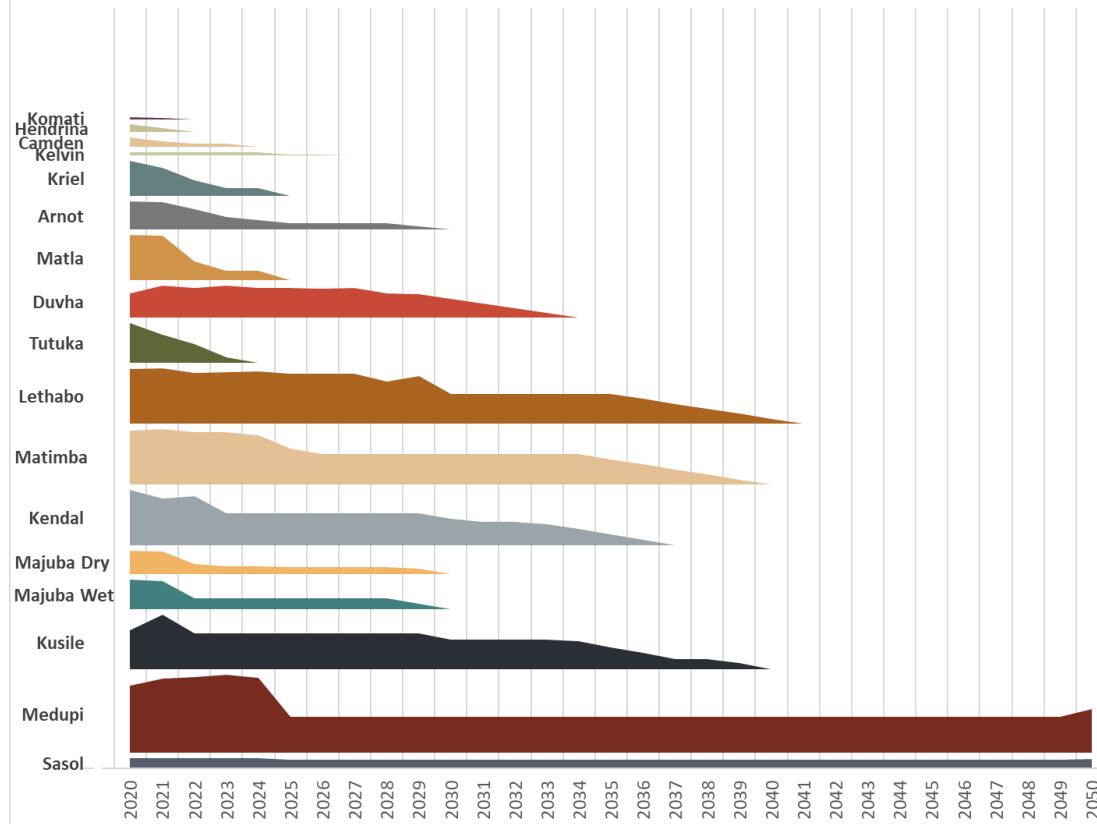


2.0 GT SCENARIO

COAL GENERATION MUST DECLINE PRECIPITOUSLY IMMEDIATELY



2.0 Gt Carbon Budget: Annual Energy Generation by Coal-fired Power Station



REAL WORLD VS “MODEL-VILLE”

SHORTCOMINGS OF THE OPTIMISATION AND HOW TO ACCOUNT FOR THEM

- Theoretically optimal scenarios are important as they allow us to understand the relative differences in cost and trends in the choice of new build technologies
- These scenarios have shown that a huge opportunity for cost-effective mitigation exists in the world of optimised modelling. Do these scenarios exist in reality?
- **We need to stress-test whether our findings are sustained when moving from optimal modelling to real world-type scenarios**
- To do this we consider two aspects of the real world not accounted for in the optimised modelling world:
 - The need for transmission (Tx) and distribution (Dx) grid infrastructure expansion to accommodate RE
 - Practically achievable RE industry build levels over time
- The following slides describe these aspects and their likely impact on the RE build pathways in the Optimised Mitigation Scenarios



TRANSMISSION GRID CONSTRAINTS

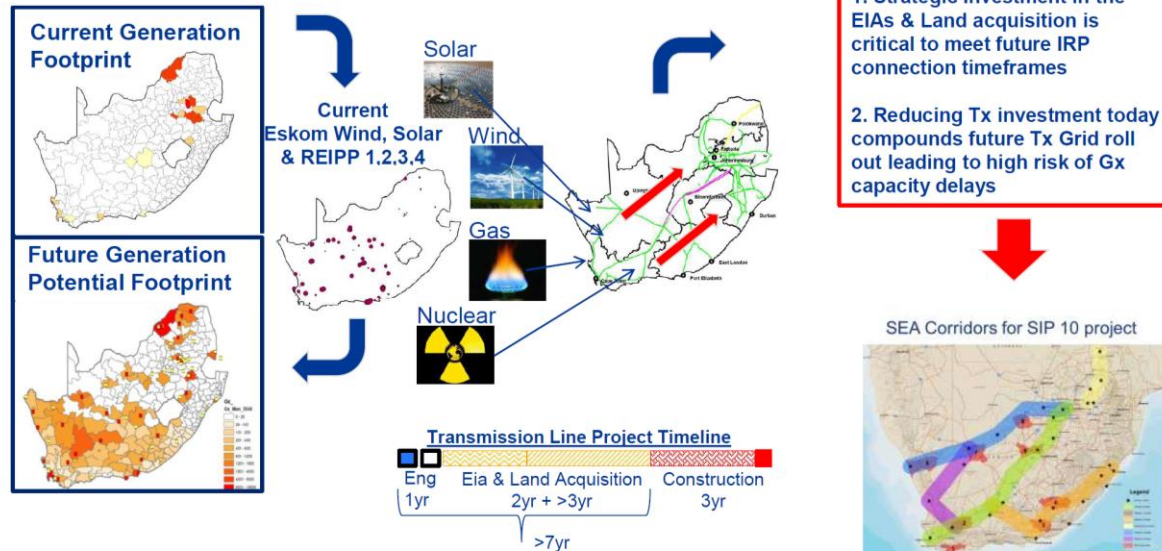
GRID EXPANSION LEAD TIMES MAY LIMIT CHOICE OF OPTIMAL RE LOCATION IN THE SHORT TERM

Tx Strategy to increase Grid Access to meet future needs of the IRP and customers



Change in generation diversity has major impact on future Tx Grid

- Grid Access – Increased connection capacity needed in new areas (delivery time > 8yr)
- On Time Connection – Smaller IPP generation plant can be constructed faster (delivery time < 5yr)
- Unknown locations - Multiple unspecified IPP sites require market access for best price



Source: Eskom Transmission Entity (2019d)

- The transmission (Tx) network needs to be strengthened to accommodate the change in net flow of power (from North-South to South-North) resulting from a more geographically distributed network of generation sources.
- Whilst CSIR (2016) shows excellent wind and solar resources across most of RSA, project interest remains highest in regions with less access to Tx infrastructure.
- Availability of grid infrastructure is a key consideration for integrating renewable energy projects
- Eskom Transmission has expressed that currently, transmission network development has longer lead times than project development from an EIA and servitude perspective
 - Transmission network development takes 7-10 years
 - Project development < 5 years (roughly 1-4)
- **Tx network expansion lead times are therefore a real-world bottleneck which may constrain the RE build initially**
- However, the optimised modelling analysis revealed the importance of ramping up RE capacity significantly in the early years in order to achieve ambitious mitigation.



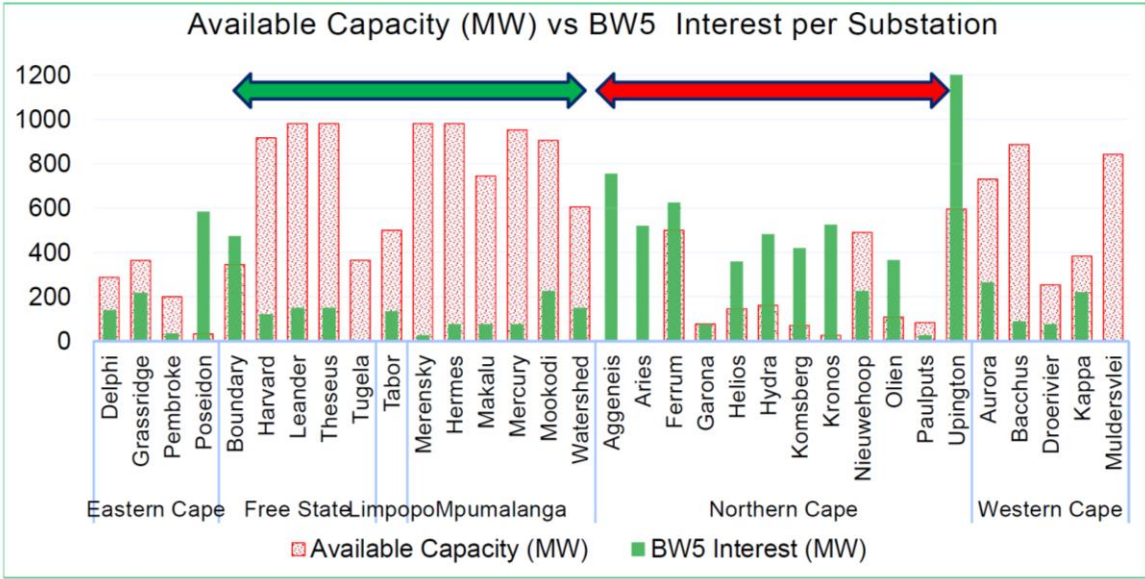
THE IMPLICATIONS OF USING EXISTING EXCESS GRID CAPACITY

EXCESS CAPACITY EXISTS IN DECLINING MINING REGIONS

Available Capacity vs BW5 Interest



- Interest in RE generation is inverse to network availability
- Capacity will have to be increased in deficit areas or generation must follow capacity



Source: Eskom Transmission Entity (2019c)

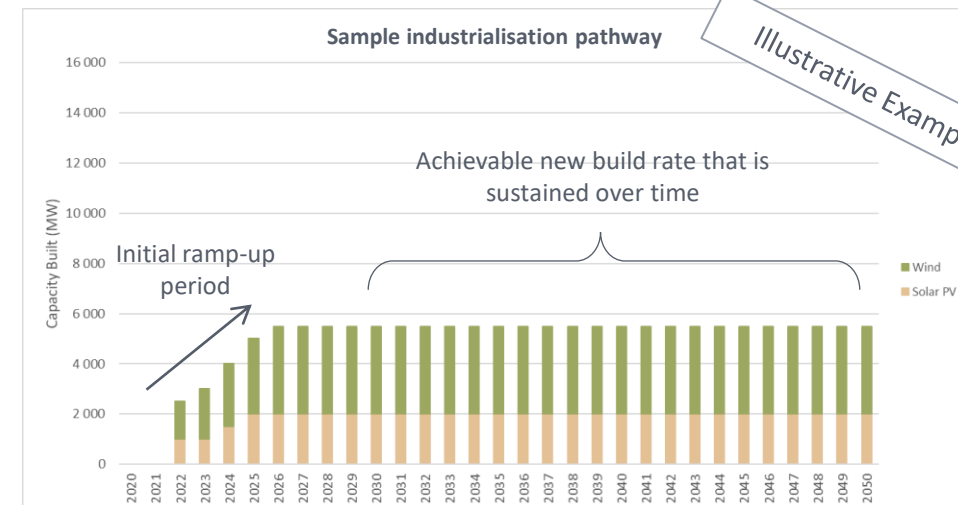
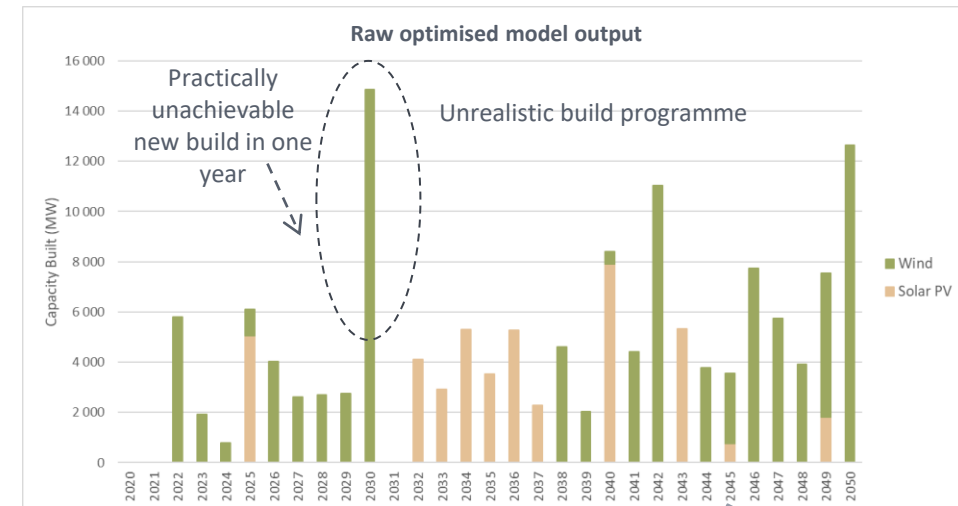
- Eskom Transmission Grid Connection Capacity Assessment indicates that previous rounds of the REIPPPP have saturated grid capacity in the optimal wind and solar resource profile areas (e.g. Northern Cape)
- However, there is significant available capacity in Mpumalanga and Northern Free-Sate (declining coal and gold mining regions with well-developed Tx infrastructure). As the coal fleet is phased down this capacity will increase.
- Whilst the RE resources here are not optimal, they are still feasible (CSIR, 2016) and aligned with efforts by DEFF to secure expedited licensing approvals for RE development in these areas, and 'Just Transition' imperatives (SAREM, 2020)
- In addition, with solar resource potential less site-specific than wind, solar may provide greater opportunity at locations chosen purely on the basis of available grid capacity.
- This would suggest a solar heavy mix may be required in any initial RE build if grid capacity is not resolved in the short term.**
- Utilising both non-optimal RE resources and specifying a RE build mix unaligned to that of the optimised modelling is likely to result in system cost penalties.
- Only the latter is considered here (conservative RE assumptions already account for the former)



THE RE BUILD NEEDS TO BE PRACTICALLY ACHIEVABLE

WITH IMPLICATIONS FOR MAXIMUM TECHNOLOGY BUILD IN ANY ONE YEAR

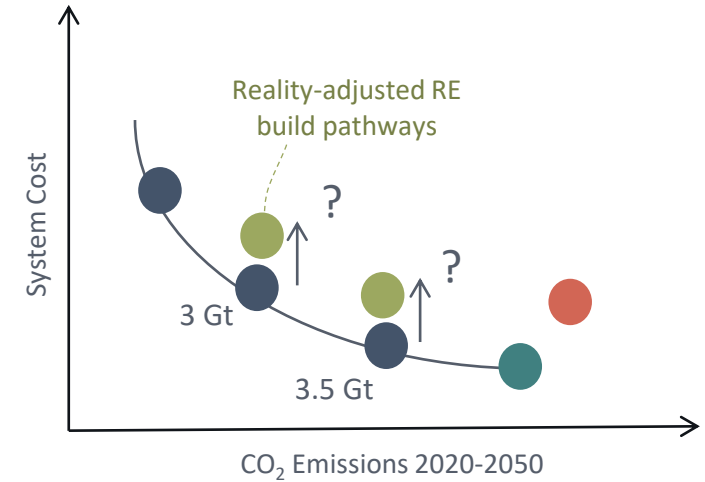
- Another important real-world consideration is: **what sustained build rate can the South African renewable energy industry achieve?**
- A reasonable industrialisation pathway would include sufficient time for the industry to establish itself (an initial ramp-up period) and a consistent, achievable build rate over time which would signal certainty to the industry.
- Interactions with experts suggest that the South African renewable energy industry may require a 2-3 year 'ramp-up' period, after which it could achieve a sustainable RE build rate of 5-10 GW per year (Meridian Economics, 2020a).



MODELLING REAL-WORLD RE PATHWAYS

TO ASSESS THE COST IMPLICATIONS OF INCORPORATING REAL-WORLD CONSTRAINTS

- We need to understand whether the findings of our Optimised Mitigation Scenarios are sustained when we adjust for real world constraints such as RE build mix and realistic annual build. i.e. **How much additional cost will this impose over the full period?**
- To do this, we adjusted the RE build pathways determined by the model for two Optimised Mitigation Scenarios (3.0 Gt carbon budget and 3.5 Gt carbon budget) to:
 - incorporate a solar heavy RE mix until 2030, and
 - ensure a minimum annual capacity build which would be sufficient to signal industry certainty (no stop-starts in planning horizon of 20+ years)
- **Two credible, accelerated and reality-adjusted RE build pathways for RSA were the result: Modest and Ambitious**
- These build pathways were checked against international RE build experience and interaction with local industry participants and deemed ambitious but achievable (Meridian, 2020a)
- Cost and Emissions for the **Modest and Ambitious RE pathways** were calculated by re-running the least cost optimisation whilst imposing the respective minimum annual build specified
- Finally, we added a '**coal-off-by-2040**' constraint to the Ambitious scenario in order to test this additional version of mitigation target emanating from the international climate mitigation discussion, yielding a third Realistic Mitigation Scenario with even lower carbon emissions.
- This process and the findings are expanded in the following slides.



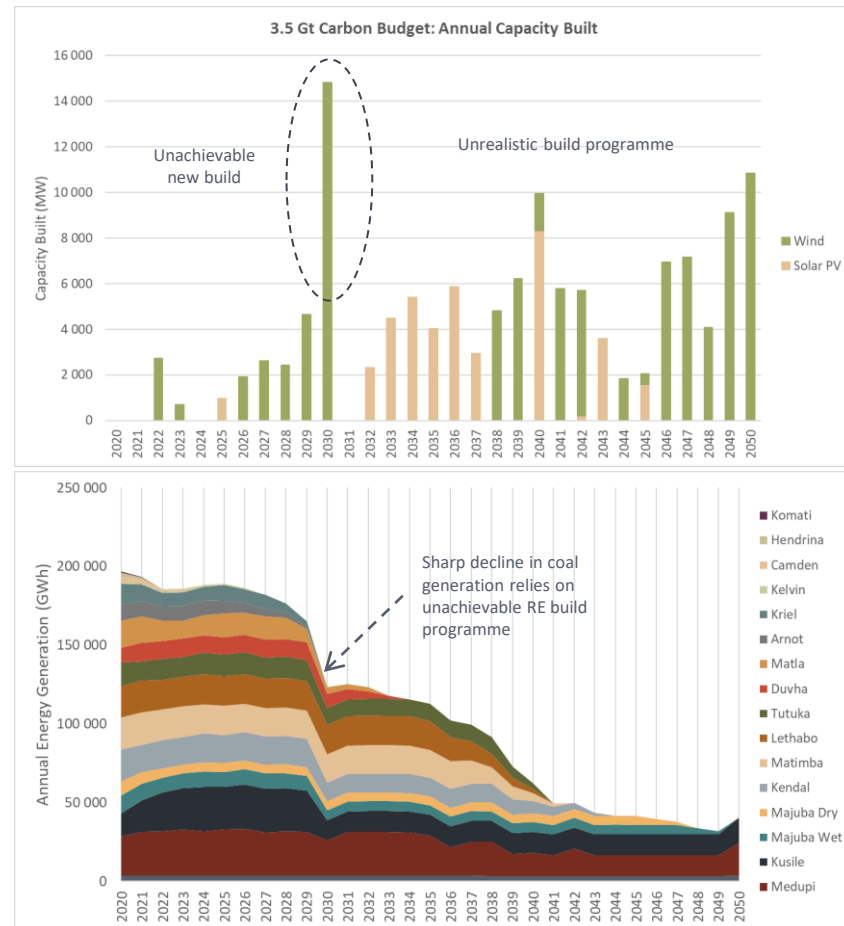
- **Importantly, these example RE build pathways are unlikely to be the best RSA can devise.**
- **Further analysis and stakeholder engagement would be needed to determine what type of pathway is the most feasible and advantageous for the country.**
- **Our primary objective here was to stress test the finding that cost is not a material barrier to achieving ambitious mitigation.**



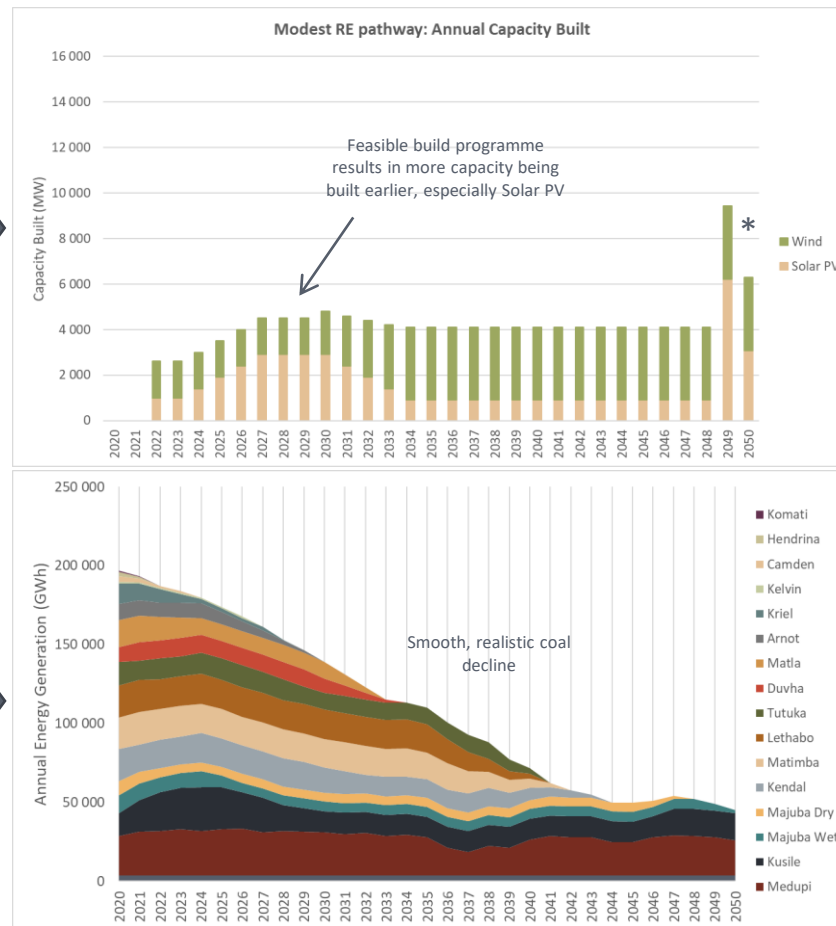
CONSTRUCTING A MODEST RE PATHWAY

USING A MODEST RE BUILD PATHWAY TO KEEP EMISSIONS BELOW 3.5 GT (JUST OUTSIDE PARIS-ALIGNED RANGE)

Initial model output: achieving 3.5 Gt



Modest RE pathway



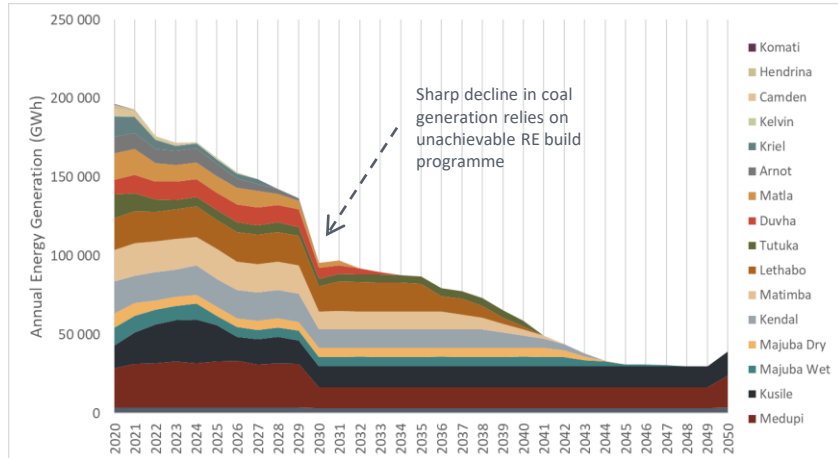
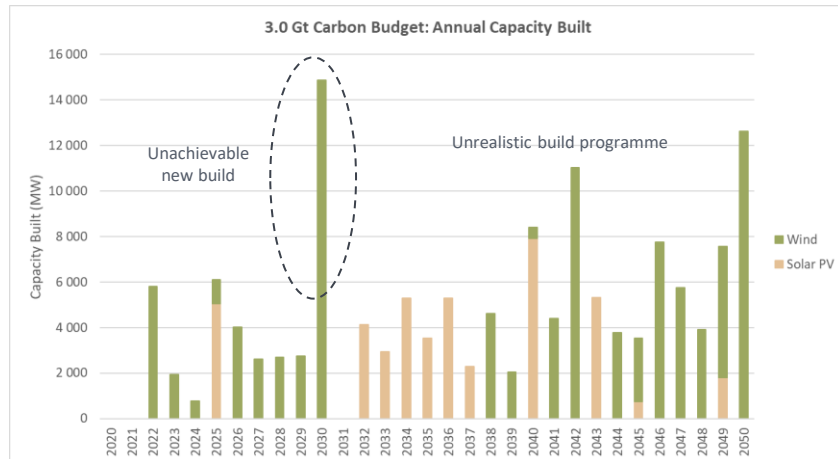
- If real-world constraints are not imposed on the model, achieving a set carbon budget of 3.5 Gt cost-optimally results in an erratic annual RE build profile
- To address this, a minimum build for solar PV and wind is specified for every year to smooth RE build over the planning horizon
- This minimum build is designed to consider an initial industry ramp up rate, potential grid constraints, industry capabilities and to match the total RE energy generated in the erratic RE build profile over the planning horizon
- The model is then re-run with the imposed minimum build to yield a complete optimal system with a realistic 'modest' RE pathway



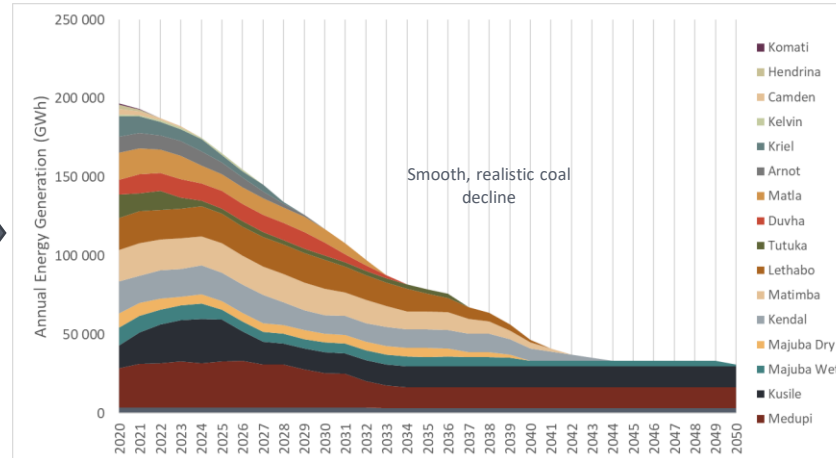
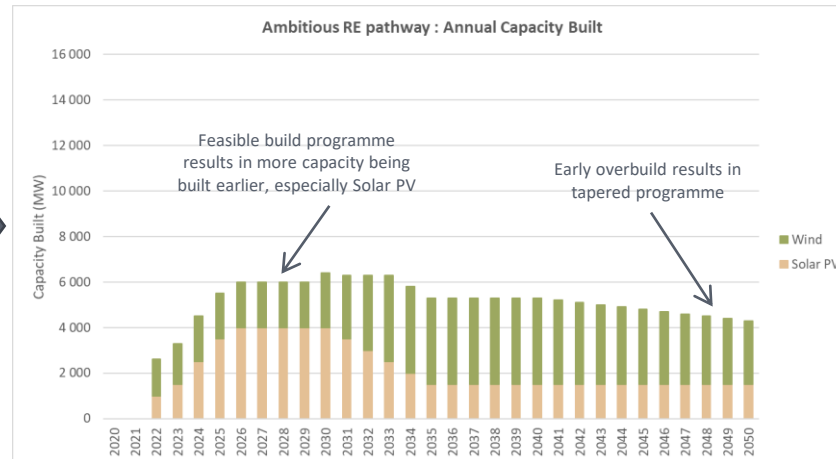
CONSTRUCTING AN AMBITIOUS RE PATHWAY

REQUIRED TO KEEP EMISSIONS IN THE PARIS-ALIGNED RANGE (EMISSIONS TARGET 2.8 GT – 3.0 GT)

Initial model output: achieving 3.0 Gt



Ambitious RE pathway



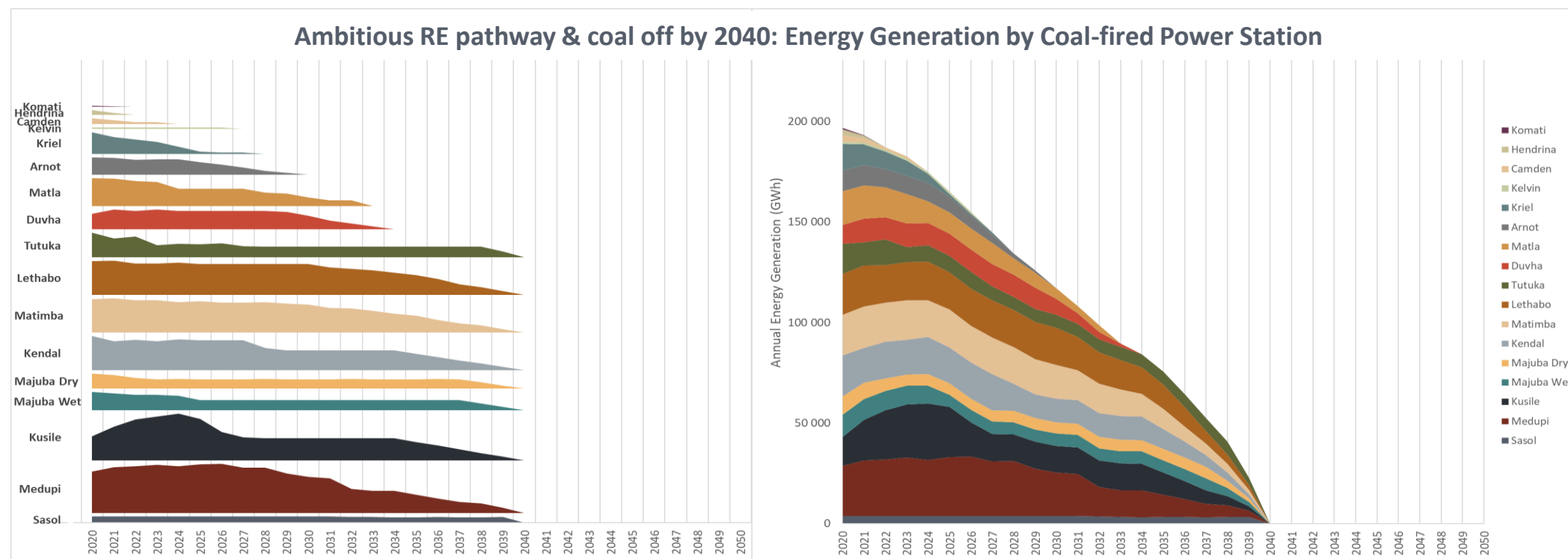
- To achieve emissions that are within the likely 'Paris-Aligned' range, a more ambitious mitigation target of 3.0 Gt is set and the model is optimized, producing an erratic annual RE build
- A revised smoothed minimum annual build profile is developed as per the Modest pathway but designed to match the greater RE energy generated in the 3.0Gt optimised mitigation scenario.
- This yields a more 'ambitious' RE pathway which results in a power system that is likely to be 'Paris-aligned' when the model is re-run with this pathway imposed as a minimum build



AMBITIOUS RE BUILD CREATES OPTIONS

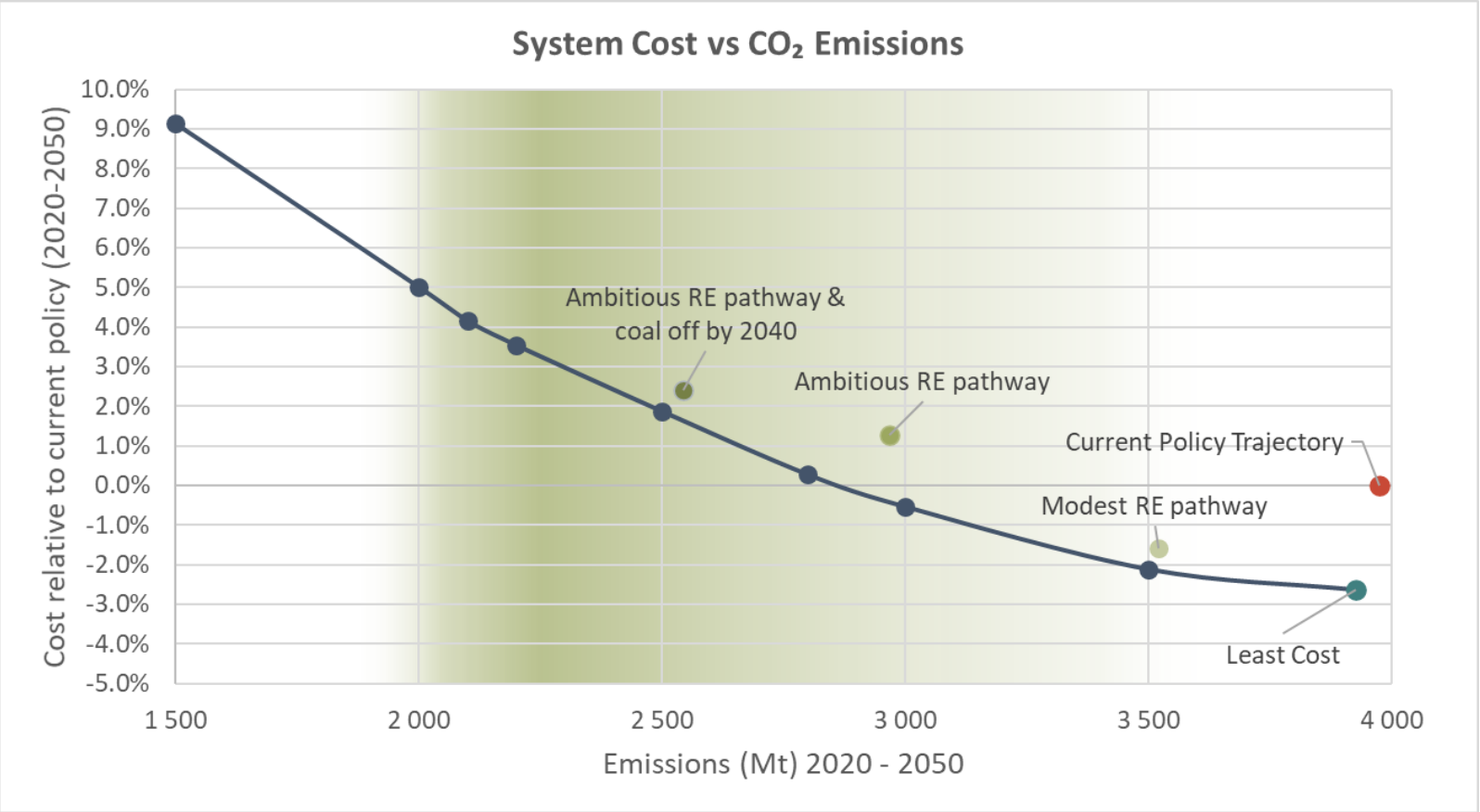
THE SAME BUILD PATHWAY ALLOWS ALL COAL OFF BY 2040

- **Another metric for Paris alignment** other than carbon budgets addresses **the date at which there should be no further coal** in power generation systems.
- This has been argued as being around 2040 according to both international and domestic assessments (ME, 2020b).
- By imposing coal-off-by-2040 as an additional constraint on the Ambitious RE pathway, a final Realistic Mitigation Scenario is defined.
- This scenario generates emissions just greater than 2.5GT, nearly 500MT lower than imposing the ambitious RE pathway alone.
- The RE built in both scenarios is identical meaning that no decision regarding coal-off needs to be taken until the middle of the 2030s.



COST OF MITIGATION

EVEN WITH REAL-WORLD ISSUES CONSIDERED, SIGNIFICANT MITIGATION COMES AT LITTLE OR NO COST COMPARED TO THE CURRENT POLICY



- **Realistic power system pathways can mitigate between 500Mt -1500Mt of CO₂ emissions compared to the current policy.**
- **A modest RE pathway** would mitigate 500Mt whilst costing less than the current policy trajectory.
- **An ambitious RE pathway** would increase the overall system cost by little more than 1% relative to the current policy trajectory, but remove more than 25% of emissions - a reduction of 1000Mt.
- Further mitigation achieved by closing all coal by 2040 reduces emissions by nearly 1500Mt, with a cost increase below 2.5%.
- Whilst the cost differences between the current policy trajectory and these mitigation scenarios are marginal, **the massive mitigation benefits are plainly real.**



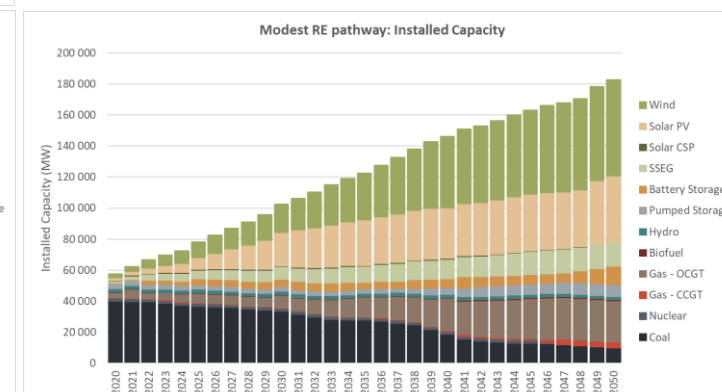
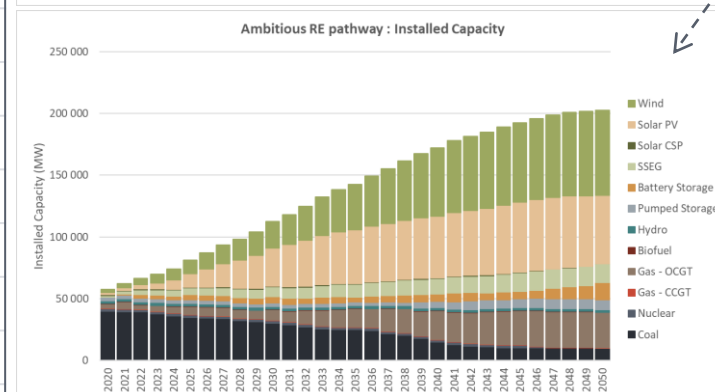
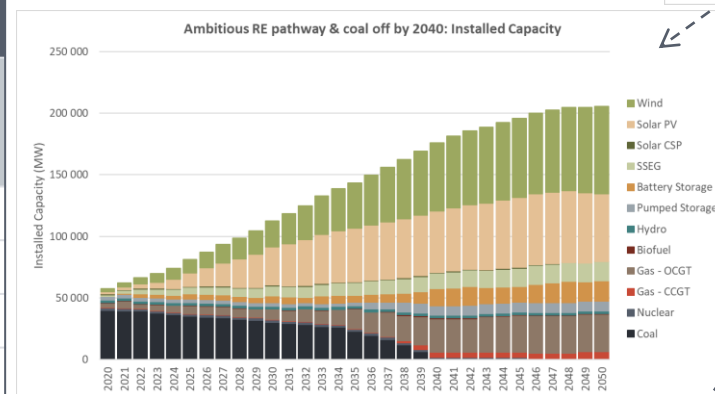
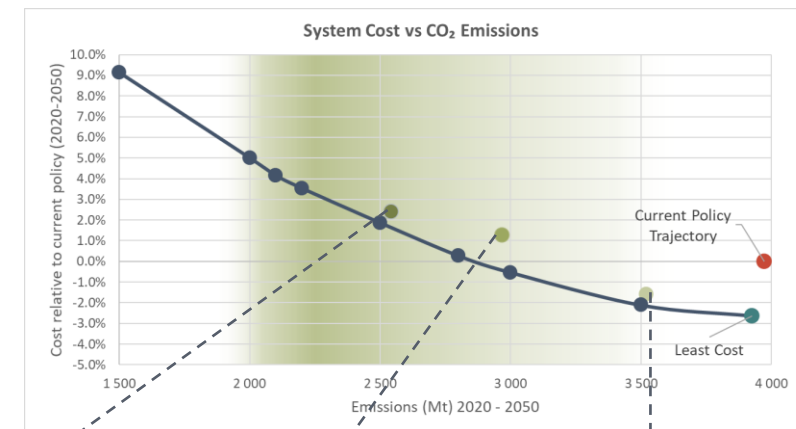
NEW GENERATION CAPACITY

THE CAPACITY MIX FOR REALISTIC TRANSITION TO HIGH RE PENETRATION

In all realistic mitigation scenarios, the majority of new build capacity is wind and solar PV, with gas and battery storage acting as flexible reserve capacity as coal retires. No new coal, nuclear or Hydro is chosen by the optimiser.

Total new capacity built (GW) in each realistic mitigation scenario from 2020 - 2050

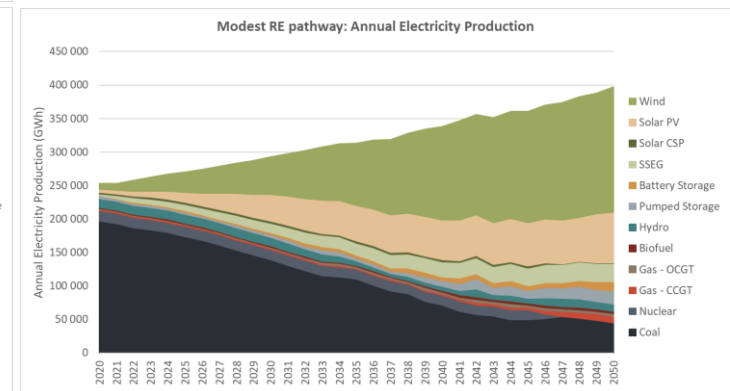
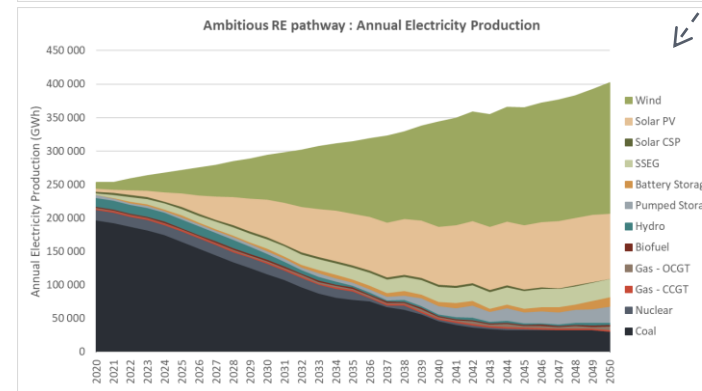
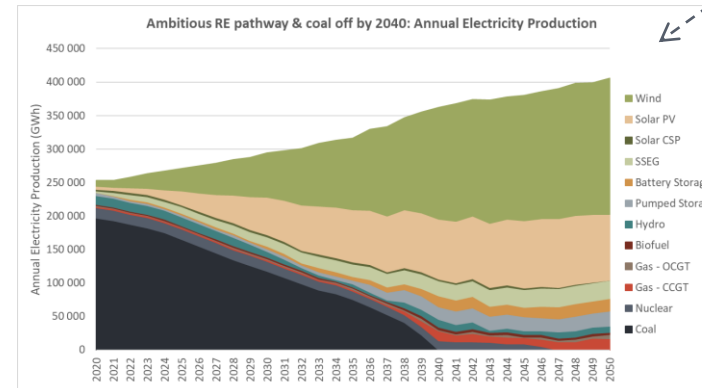
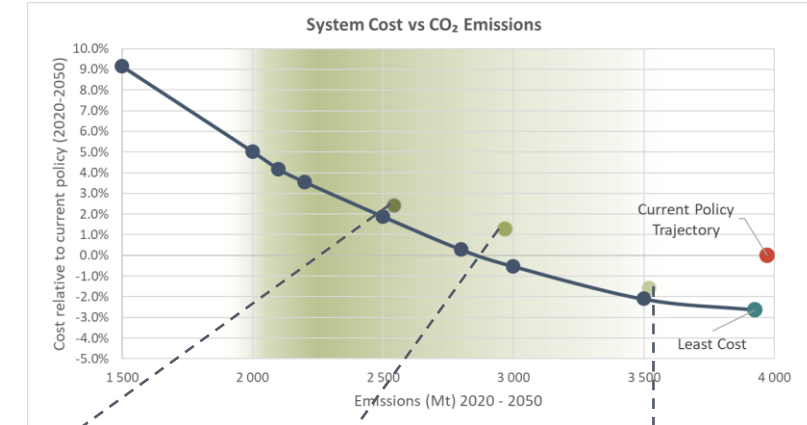
Technology	Ambitious RE pathway & coal off by 2040	Ambitious RE pathway	Modest RE pathway
Wind	88.7	86.8	76.6
Solar PV	63.5	63.5	47.8
Solar CSP	-	-	-
SSEG	17.4	17.4	17.4
Battery Storage	32.9	22.0	19.8
Pumped Storage	5.0	5.0	4.4
Hydro	-	-	-
Biofuel	0.3	-	0.3
Gas – OCGT/GE	32.5	31.1	29.1
Gas – CCGT/GE	6.2	-	3.4
Nuclear	-	-	-
Coal	-	-	-



ENERGY GENERATION MIX

GAS PROVIDES CAPACITY SUPPORT, BUT VERY LITTLE ENERGY

- A Modest RE pathway requires CCGTs to be cost-optimal, but an Ambitious RE pathway does not
- **An Ambitious pathway creates a sufficient supply of energy** – capacity issues are resolved with OCGTs (a miniscule fraction of all energy generated <1%) and storage
- Coal-off-by-2040 is achieved with the same Ambitious RE build pathway, however, coal energy is swapped for CCGT gas after 2040
- **Critically, an Ambitious RE pathway creates options to achieve future mitigation milestones**, the gas decision can be delayed for at least 15 years
 - Gas is only required in volume in the late 2030s
 - Gas infrastructure for power generation if/when required could be coast-located, avoiding a necessity for long pipeline lead-times
 - Liquid fuel-fired turbines can adequately provide support in the interim (more detail on this later)



WHAT DO THESE FINDINGS MEAN FOR RSA?



ACHIEVING POLICY PRIORITIES IN THE RSA POWER SECTOR

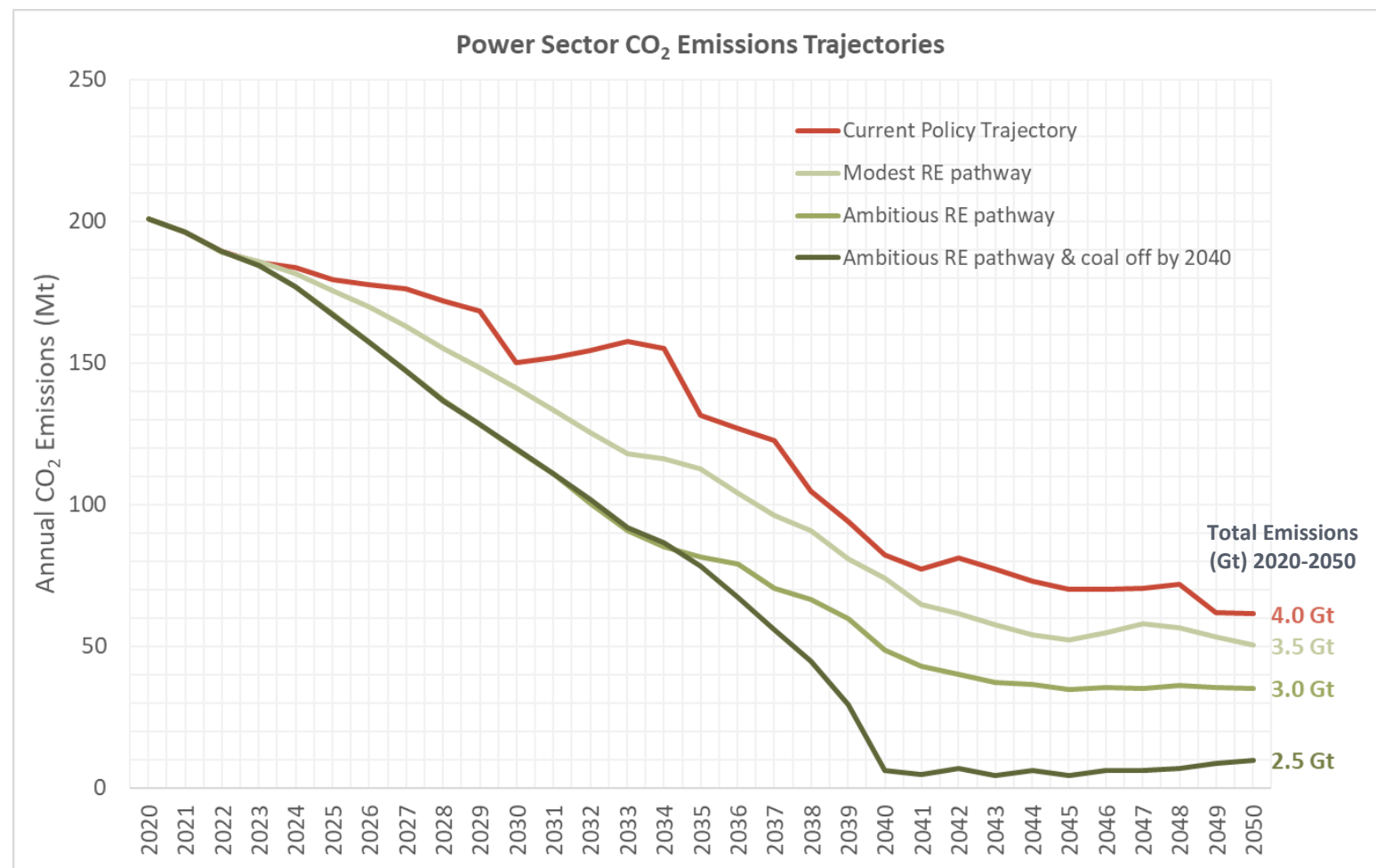
WHAT ARE THE QUESTIONS WE SHOULD NOW BE ASKING?

- Our work has shown that an accelerated RE build pathway does not cost materially more than either the Current Policy Trajectory nor Least Cost Optimisation scenario, even when accommodating real world constraints
- The question about the cost of mitigation is no longer relevant
- **What then are the questions we need to ask and answer?**
- We propose **these are about specifying the RE build pathway that best responds to the sector and country's policy priorities**
- Whilst not the focus of this work, our analysis has uncovered a number of issues relevant to these policy priorities, including:
 - Achieving our domestic and international mitigation targets
 - Enabling sizeable and sustained investment
 - Supporting localisation and industrialisation; highly relevant to job creation and RSA's Covid recovery
 - Decreasing local environmental pollutants
 - The value of deferring decisions around gas
 - The value of maintaining an option for retiring coal earlier than currently planned
- We explore each of these over the next few slides



HOW CAN RSA MEET ITS MITIGATION COMMITMENTS?

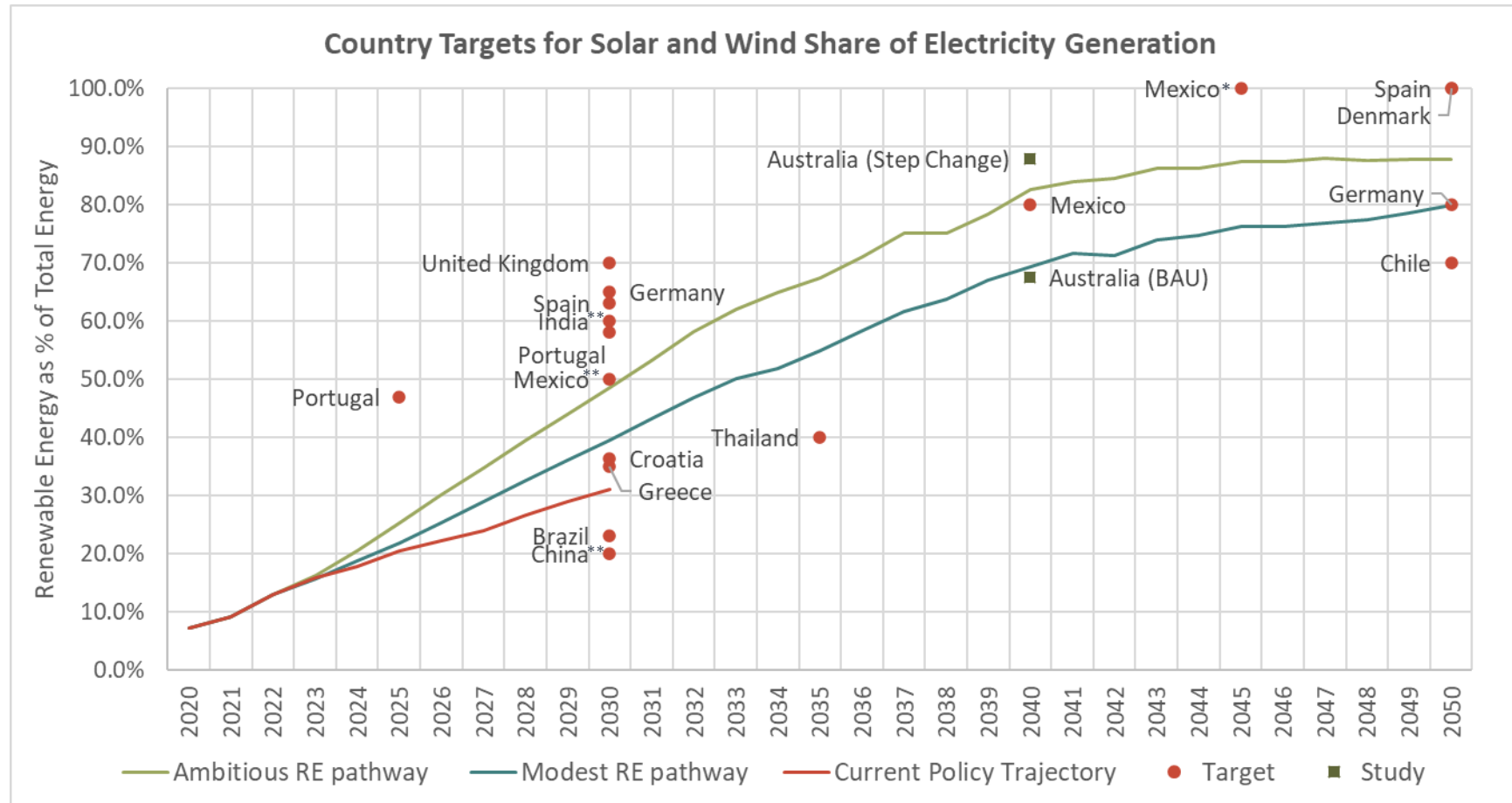
AN IMMEDIATE AND AMBITIOUS RE BUILD PATHWAY IS REQUIRED



- An emissions trajectory in the region of the Ambitious or Coal-Off-by-2040 RE pathways **will be required for the rest of the RSA economy to mitigate cost-effectively** (within the Paris-aligned range).
- The Ambitious and Coal-off-by-2040 RE pathways track the same RE build pathway and emissions for the first decade.
- Following the Ambitious RE pathway's RE build **provides a valuable option** to shift to Coal-off-by-2040 should increased decarbonisation be required in the future.
- An ambitious RE build in the first decade will also **support low carbon options in other sectors, for example electric vehicles, green hydrogen and industrial electrification.**



AN AMBITIOUS PATHWAY ENABLES RSA TO KEEP PACE WITH INTERNATIONAL RE TARGETS



- Many countries are committing to increasing the share of renewable energy within their power systems, largely owing to climate concerns
- An Ambitious pathway allows RSA to commit to ambitious targets aligned with its international peers

*includes hydro

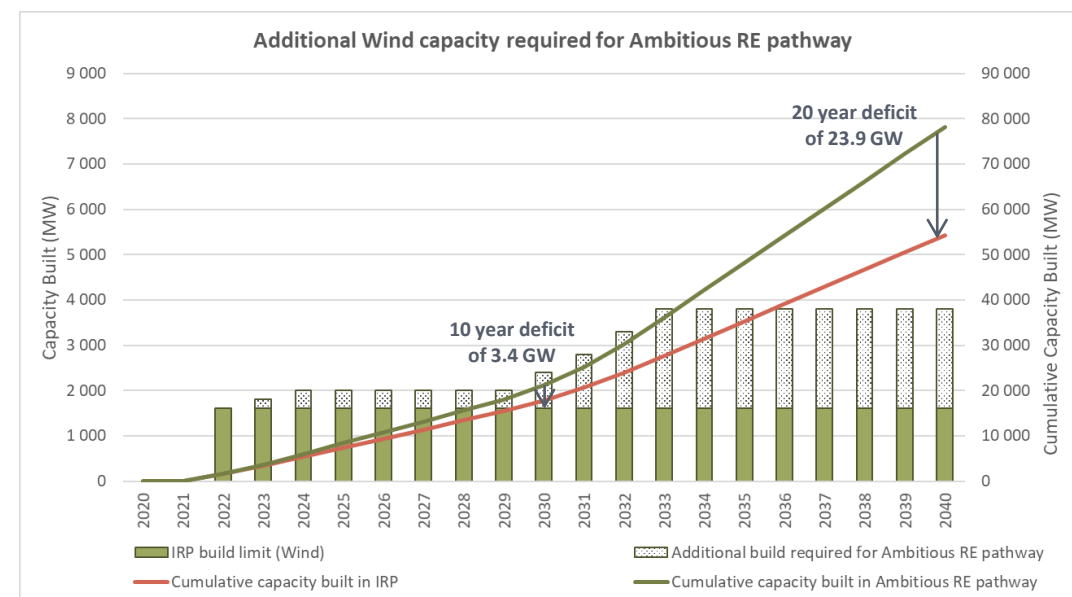
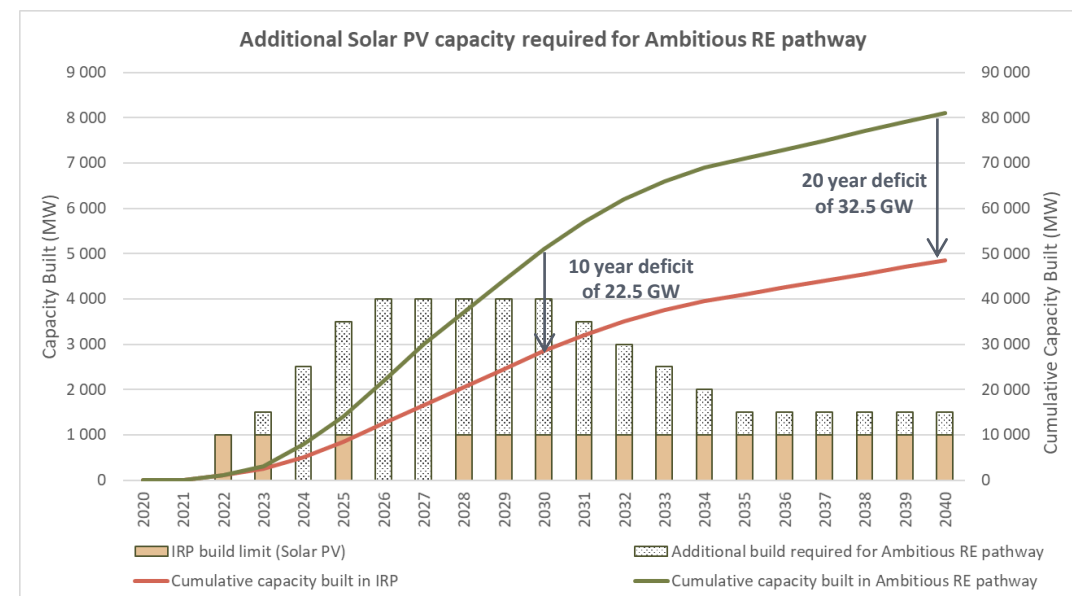
** includes hydro and nuclear



AMBITIOUS RE PATHWAYS PROVIDE AN ENORMOUS INDUSTRY LOCALISATION OPPORTUNITY

WHAT IS REQUIRED OVER AND ABOVE THE IRP BUILD PLAN?

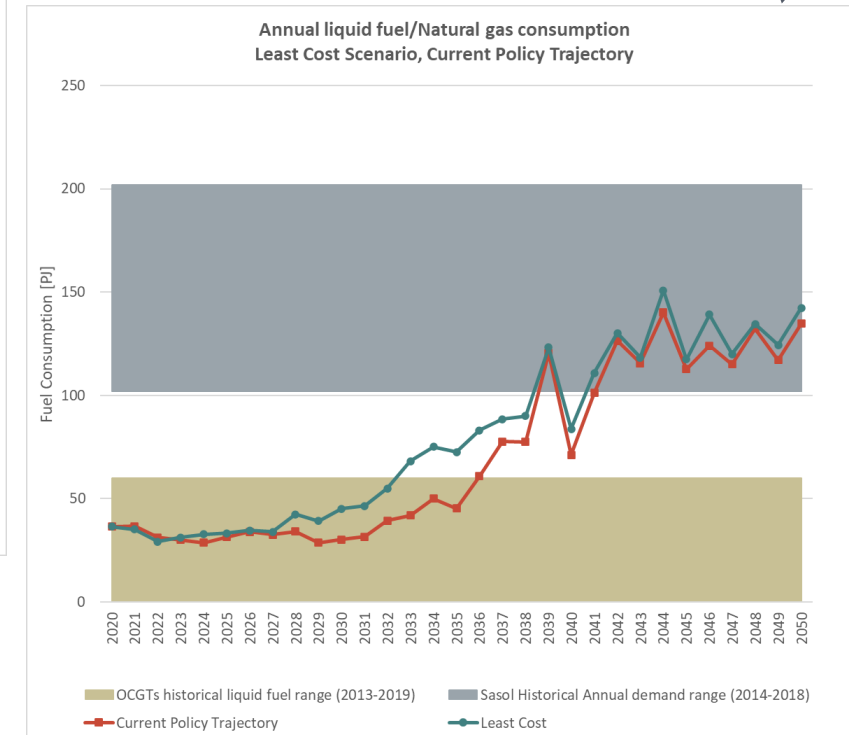
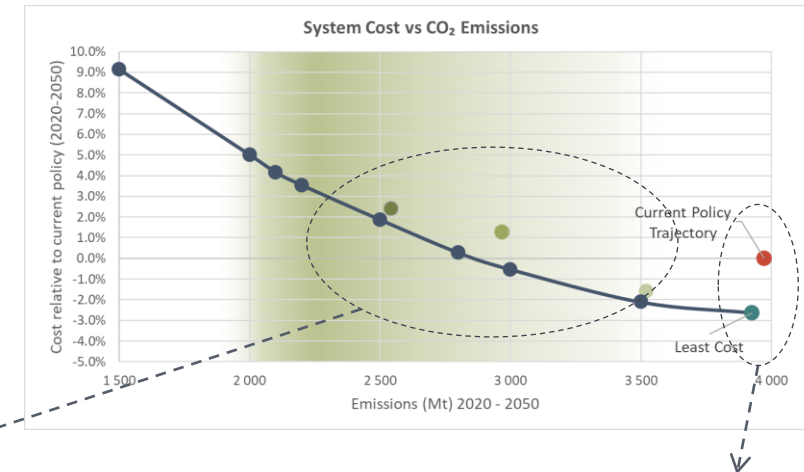
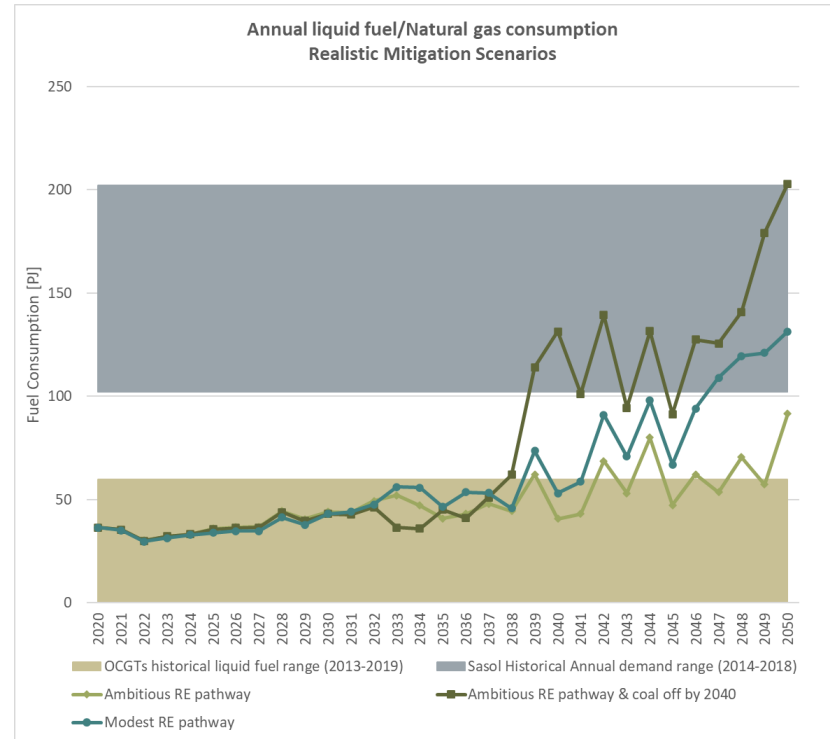
- **Ambitious** mitigation will require RSA to build more renewables, earlier
- Following the IRP build profile leaves RSA playing catch-up – needing to build an additional 3.4 GW of wind and 22.5 GW of solar PV in 2030 to get on track to achieve a Paris-aligned power sector
- This will be practically impossible for a local industry, and would likely require external assistance from countries that are in the process of establishing competencies throughout the RE value chain
- Hence, delaying the start of an accelerated build will mean that RSA misses out on the opportunity to establish a thriving local industry which would enable it to meet its climate commitments through its own domestic skills and capabilities



THE ROLE OF GAS IN THE RSA POWER SECTOR

WHEN MUST WE DECIDE?

- Gas accounts for less than 3% of energy generation in all scenarios investigated – mostly in the range from 1.5% - 2.5%
- Peaking requirements can be provided by liquid fuels for at least the next 10 years in all scenarios
- In all realistic mitigation scenarios, liquid fuels can provide the necessary fuel capacity for at last a further 5 years into the late 2030s.
- Even the coal-off-by-2040 scenario, which relies on mid-merit capacity to replace coal, has annual fuel consumption until late 2030s in the historic range of existing OCGT liquid fuel usage
- RSA does not need to expand gas infrastructure to support the power sector for the foreseeable future
- Such a decision can wait for 10 – 15 years
- The **option** to delay this decision has **immense value** for the country – we do not need to lock into long term gas commitments for the power sector now



Source: CSIR (2020)



THE RESULTS SHOW THAT THE QUESTION *IS NOT* ABOUT THE COST OF POWER SECTOR DECARBONIZATION

- **RSA faces huge economic challenges: post-corona recovery, restoring power sector reliability, growing climate obligations**
- **This study has shown that it is possible for RSA to drastically accelerate its energy transition and trigger a large investment programme at no additional cost to the power system.**
 - This finding is strengthened through the use of conservative assumptions; and
 - Stands even when scenarios are adjusted for practical constraints.
- **The scenarios demonstrate that the 1 - 2Gt emissions reduction (over and above the IRP 2019 Current Policy Trajectory) required for power sector Paris-alignment is achievable without significant cost impact.**
- **All lowest cost electricity sector trajectories for RSA involve an immediate and substantial RE build programme**
 - Despite being included as options, no new coal or nuclear plant is chosen in any optimal scenario investigated. These technologies are too expensive and not required for grid adequacy (reliability of supply).
 - The cost of new RE, storage and smart grid technologies have fallen precipitously in the last decade and will continue to drive disruptive change in energy systems globally.
- **All initial work in the area suggests that the socio-economic benefits of an ambitious RE-build out are immense**, including significant job creation, local air pollutant reduction, foreign and domestic investment, Mpumalanga economic recovery, reduction in the carbon intensity of exports, opportunities to export RE components into Africa, mitigating coal financing risk and enabling future growth areas such as electric vehicles and green hydrogen.



THE QUESTION IS ABOUT HOW TO OPTIMALLY SPECIFY RSA'S RE BUILD PROGRAMME

- In order to **stress test the study's main finding** (that cost is no longer a barrier to an accelerated energy transition) we considered three examples of 'realistic' scenarios: 'Modest RE pathway', 'Ambitious RE pathway' and 'coal-off by 2040'
 - Even with these 'reality-adjustments' the scenarios support the study's main finding – cost is not a material barrier
- **What then does the optimal 'realistic' build programme look like? This is the real question RSA should be concerned with now:**
 - **It should be as close to the theoretically optimal scenarios as possible whilst accommodating realistic constraints and policy objectives**
 - Speeding up Tx infrastructure upgrade processes to enable an optimal mix should be prioritised in order to lower the system cost
 - Targeting development in declining mining regions and addressing the need for localisation and sector transformation
- **The major constraints on the RE industry are policy uncertainty and regulatory restrictions** – these can be addressed through political commitment and sector reforms
- **We know that the RE build must be immediate and ambitious**
 - A slow start means we are highly unlikely to achieve Paris-alignment and economic competitiveness in the low carbon global future. Emissions over the long-term are most easily and cost-effectively achieved by initiating coal phase down immediately, and allowing it to proceed steadily
 - For a similar level of costs, a more ambitious RE build pathway delivers valuable options for more rapid future decarbonisation if required, and
 - scaling up of the associated economic stimulus and socio-economic benefits (especially in areas which will be most impacted by reduced coal-burn), in a rapidly changing world.



A RESEARCH AGENDA

PROPER PLANNING REQUIRES ADDITIONAL INFORMATION AND RESEARCH

1. The need for a **Just Transition** for existing power station and coal workers will be critical. This includes investigation into the employment and investment potential of an ambitious RE build pathway and associated industrialisation plan.

2. Further analysis is needed to confirm how an accelerated energy transition would fare in the context of **uncertainty about future electricity demand**.

3. **Existing coal fleet refurbishment costs** (ignored in this analysis) could be substantial but are currently unknown. This will influence timing of plant phase out and associated cost savings.

4. A faster decline in coal burn indicates **reduced local air pollution**. How could this finding support a win-win solution to the current stand-off regarding Eskom's environmental regulatory compliance?

5. **Investigating alternative models of ownership** to enable broader participation in and contribution to South Africa's energy transition, especially by communities and municipalities.
6. **The utilisation profile of individual coal plant under an ambitious RE build scenario** suggests opportunity for strategic decision-making to save costs. This needs to be understood at a plant level to determine cost and feasibility of running coal plant at reduced capacity factors.

7. Further understanding of how the **development of Transmission infrastructure** can best be aligned with an accelerated energy transition.

8. A grid dominated by RE looks very different to a grid dominated by coal or nuclear. **What is the most appropriate industry structure, institutions, regulatory and market rules going forward?**

9. New arrangements for financing and absorbing counterparty risk need investigating given the current vulnerability of the State's balance sheet, and the impact of COVID locally and internationally.

10. **Strategies for providing investor certainty** to ensure maximum industrialisation and localisation need examining



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GLOSSARY OF TERMS, ACRONYMS AND ABBREVIATIONS

ATB	Annual Technology Baseline
CCGT/GE	Combined Cycle Gas Turbine / Gas Engine
CCS	Carbon Capture and Storage
CF	Capacity Factor
CO₂	Carbon Dioxide
CSIR	Council of Scientific and Industrial Research
CSP	Concentrated Solar Power
DEFF	Department of Environment, Forestry and Fisheries; main coordinating agency responsible for establishing overall targets and frameworks for policy implementation of South Africa's climate objectives
DMRE	Department of Mineral Resources and Energy; responsible for energy policy and for the implementation of the Integrated Resource Plan
EAF	Energy Availability Factor
FOM	Fixed Operations and Maintenance
FBC	Fluidised Bed Combustion
GW	Gigawatt (1 000 000 000 W)
GWh	Gigawatt hour (1 000 000 000 Wh)
IRP	Integrated Resource Plan
LCOE	Levelized Cost of Electricity
MES	Minimum Emission Standard
NO₂	Nitrogen Dioxide



GLOSSARY OF TERMS, ACRONYMS AND ABBREVIATIONS

NREL	National Renewable Energy Laboratory
OCGT/GE	Open Cycle Gas Turbine / Gas Engine
Paris Agreement	The Paris Agreement provides a global framework for avoiding dangerous climate change by limiting global warming to well below 2°C above pre-industrial levels and pursuing efforts to limit it to 1.5°C
PLEXOS Model	Plexos is an integrated optimisation model used for long-, medium-, and short-term energy market analysis to inform power system planning
PM	Particulate Matter
PPD	Peak-Plateau-Decline
Precautionary Principle	The UNFCCC specify in Article 3 (3) of the Paris Agreement that signatory Member States should take precautionary measures to anticipate, prevent or minimise the causes of climate change and mitigate its adverse effects
PV	Photovoltaic
REDZ	Renewable Energy Development Zones (see Additional Information)
REIPPPP	Renewable Energy Independent Power Producer Procurement Programme; South Africa's renewable energy auction process launched in 2010 as part of a set of interventions to enhance South Africa's electrical power generation capacity (see Additional Information)
RSA	Republic of South Africa
SEA	Strategic Environmental Assessment
SO₂	Sulphur Dioxide
SSEG	Small-Scale Embedded Generation
UNFCCC	United Nations Framework Convention for Climate Change
VOM	Variable Operations and Maintenance



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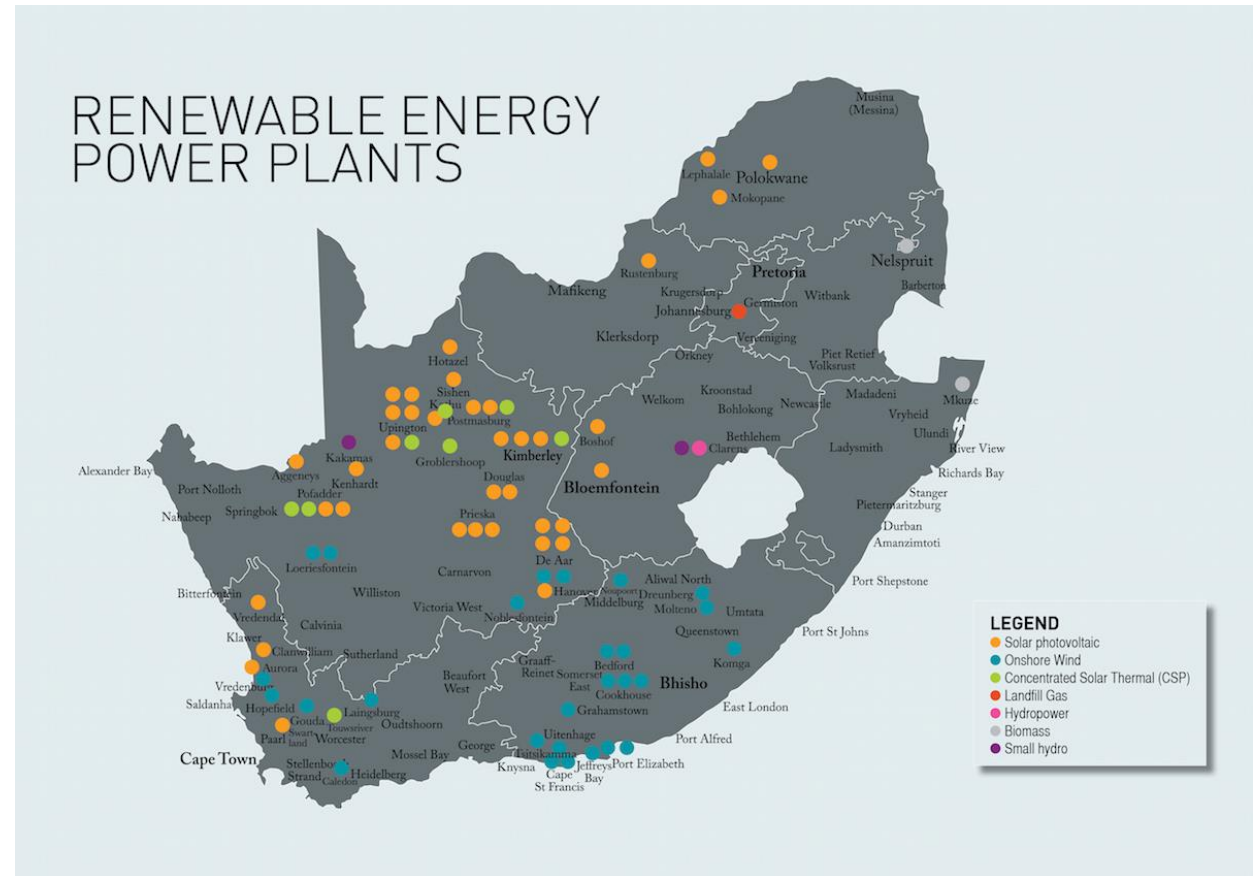
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ADDITIONAL CONTEXT: RE DEPLOYMENT IN RSA

THE RENEWABLE ENERGY INDEPENDENT POWER PRODUCER PROGRAMME (REIPPPP)

- The REIPPPP was launched in 2010 as part of a set of interventions to enhance South Africa's electrical power generation capacity. It is comprised of a competitive tender process, structured into rolling bid-windows (BW) and aimed at attracting sustained market interest and reduced prices for renewable energy projects (Eberhard and Naude, 2017).
- REIPPPP bid windows ran over a 5-year period (BW1 = Nov 2011; BW2 = Mar 2012; BW 3 = Aug 2013; BW 4 = Aug 2014; BW 4 (Expedited) = Nov 2015) and resulted in the procurement of 2.3 GW solar PV and 3.4 GW wind energy, almost all of which is operational today (IPP Office, 2020). After a lengthy period of no procurement, the next bid window is expected to open in 2020/2021.
- Bids are evaluated on the basis of price as well as economic development criteria including socio-economic development (SED) and enterprise development (ED), aimed at direct funding in such a way that IPP projects have a positive socio-economic impact (Eberhard & Naude, 2017).



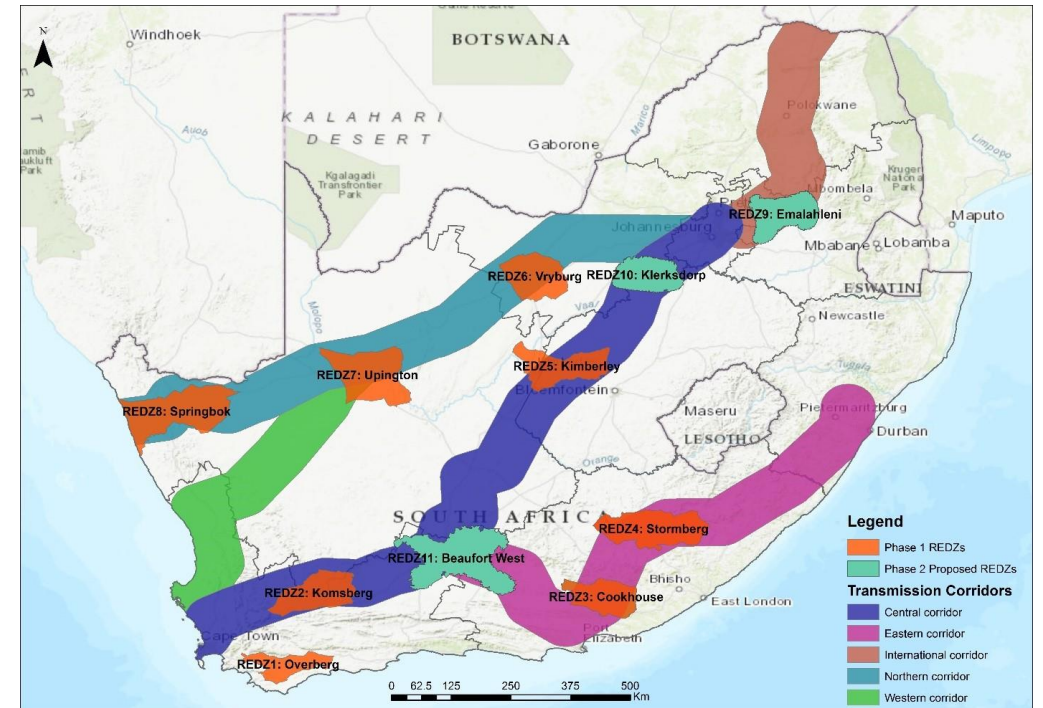
Map of REIPPPP projects (Energy Intelligence, 2016)



ADDITIONAL CONTEXT: RSA INFRASTRUCTURE DEVELOPMENT

STRATEGIC ENVIRONMENTAL ASSESSMENT (SEA) FOR ELECTRICITY GRID INFRASTRUCTURE AND RENEWABLE ENERGY PROJECTS

- South Africa's Department of Environmental Affairs (DEA) embarked on a process of identifying ways to act streamline environmental authorisations for major infrastructure build programmes in South Africa – including those related to the development of transmission grid infrastructure and renewable energy projects
- In 2016, government approved the gazetting of 8 Renewable Energy Development Zones (REDZ) and 5 'Power Corridors'. These were established through collaborations between the Department of Environmental Affairs, CSIR, Eskom and the South African National Biodiversity Institute.
- 'Power Corridors' were identified as suitable routes for the expansion of key strategic transmission infrastructure to satisfy national transmission requirements.
- REDZ were established based on criteria of high resource potential, access to planned transmission infrastructure corridors and distance from ecologically sensitive areas.
- Within these identified areas, wind and solar PV technologies are incentivised and 'deep' grid expansion upgrades may be expedited through the streamlining of regulatory processes and relaxation of environmental authorisations (DEA, 2016).
- In the second phase of the SEA, three additional REDZ for wind and solar PV energy projects were proposed (DEFF, 2019), have recently been gazetted (July 2020) and are out for public comment.

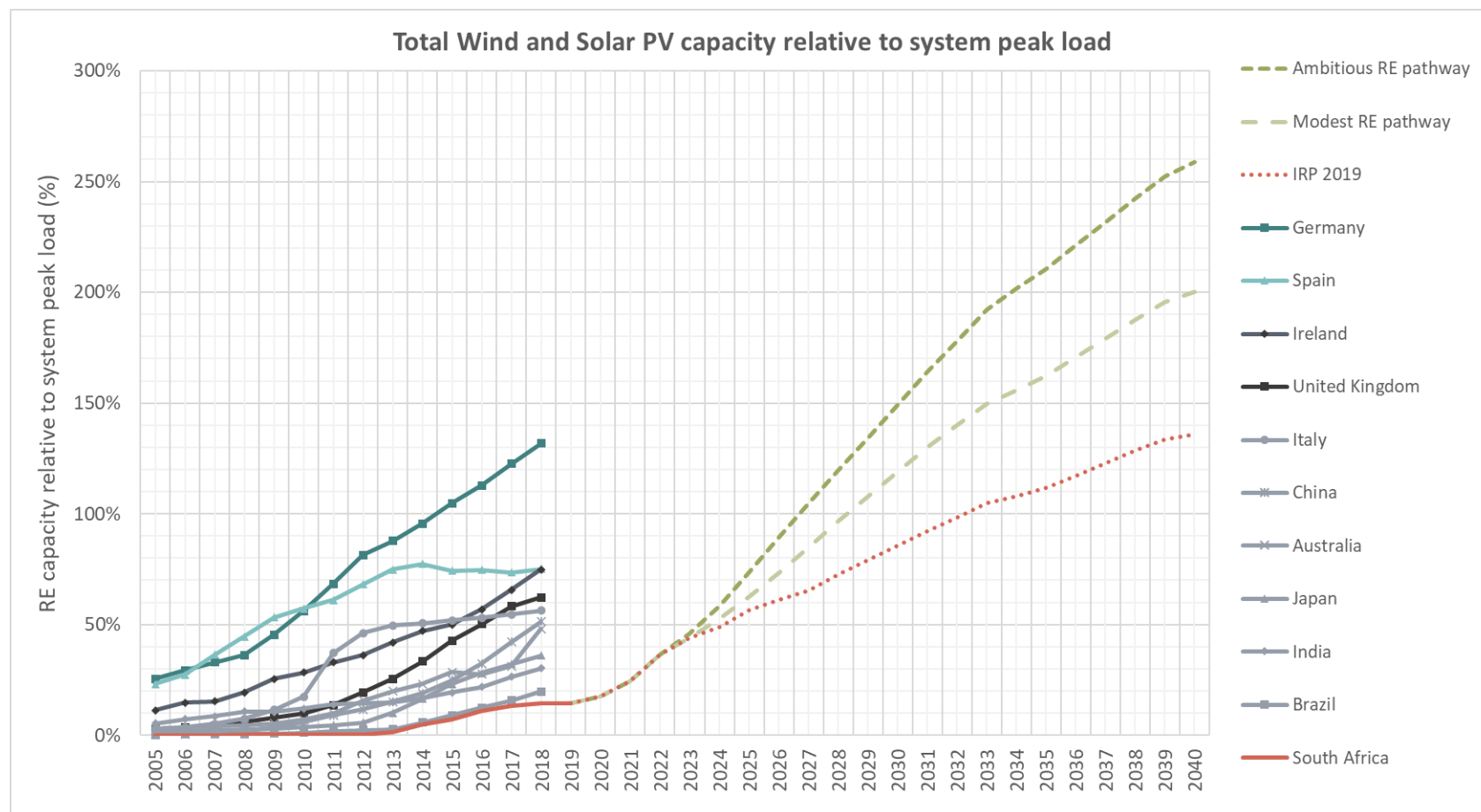


"Phase 2 Wind and Solar PV SEA aims to identify REDZs in previously mined areas to enable the rehabilitation of abandoned mines and to contribute towards the planning of the Just Energy Transition framework by strategically planning large scale wind and solar PV developments in areas where job losses may occur from closure of mines such as coal, diamond and gold mines." (DEFF, 2019)



ADDITIONAL CONTEXT: RE PATHWAYS COMPARED TO GLOBE

AN ACCELERATED RE BUILD PROGRAMME IS ACHIEVABLE BASED ON INTERNATIONAL EXPERIENCE



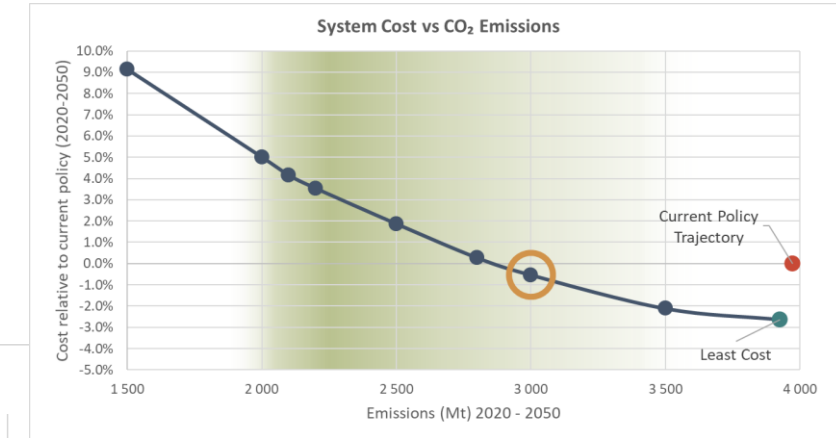
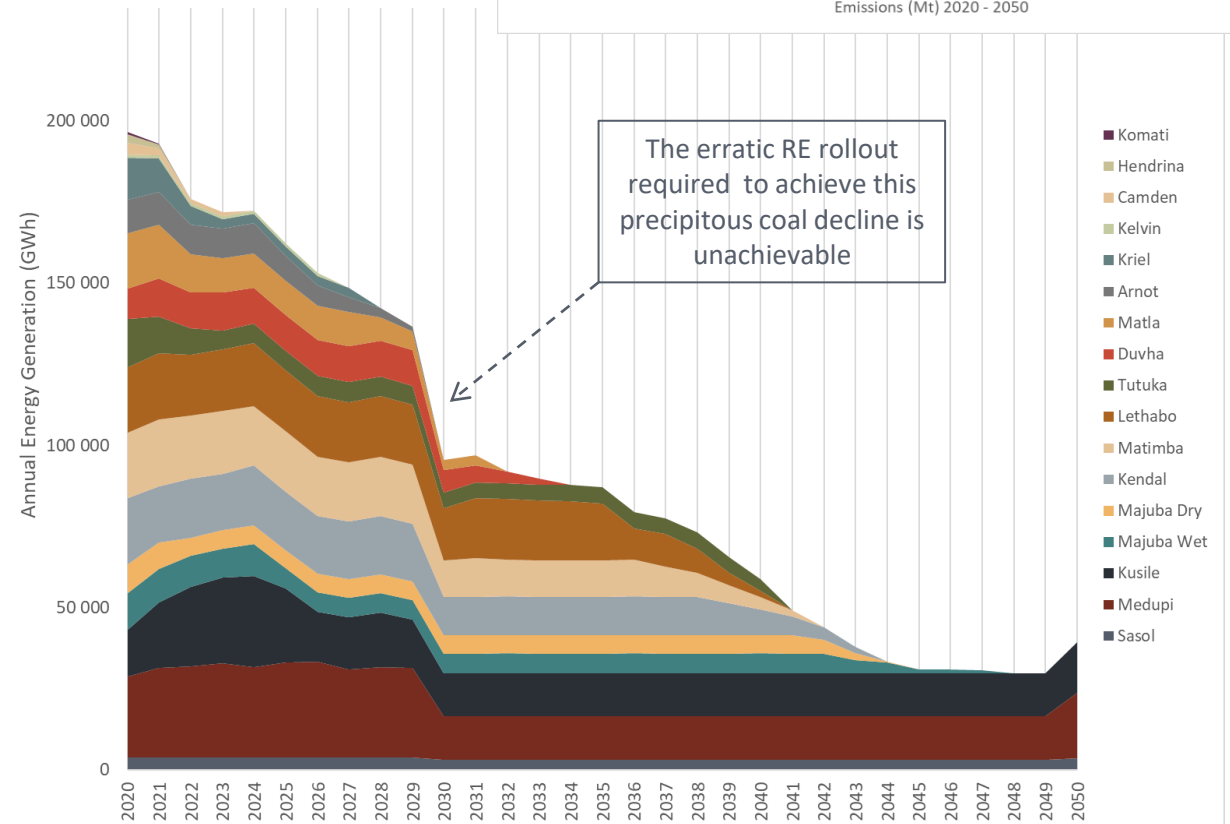
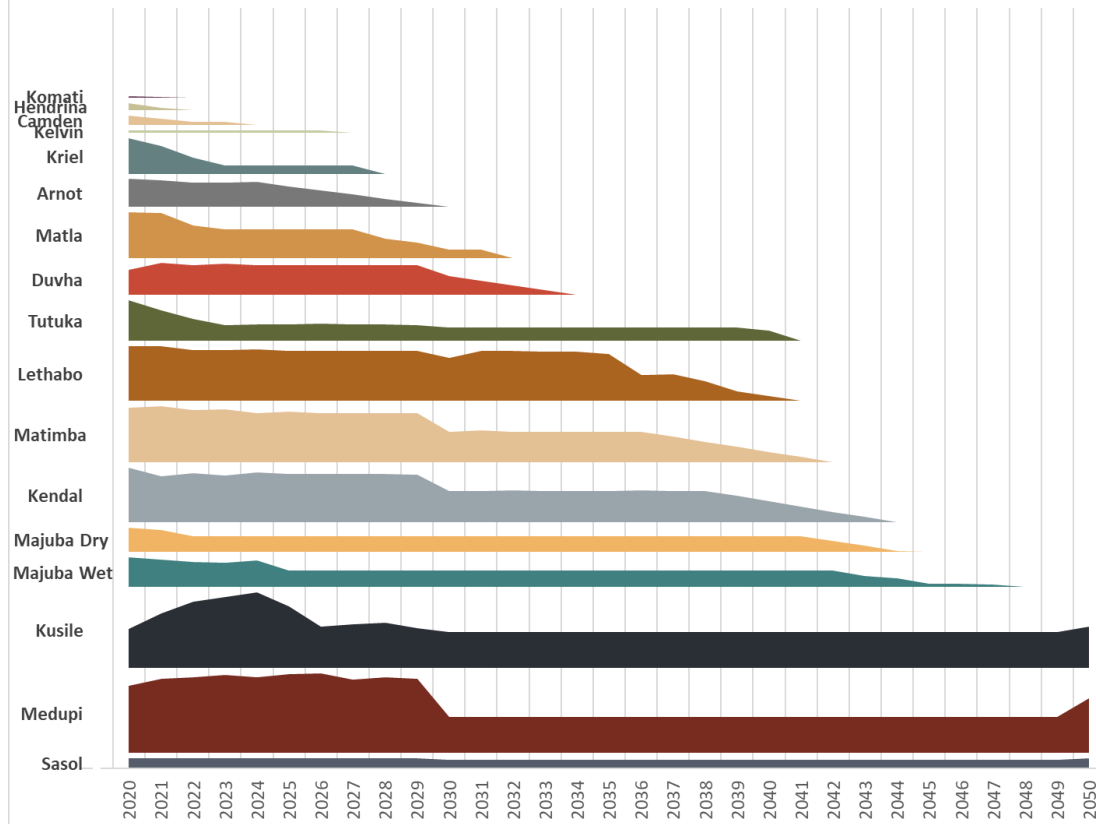
- Higher RE build rates have been achieved in other countries
- RSA is significantly behind other countries, especially considering its RE resource
- Even with an ambitious programme RSA RE penetration will still lag Germany by 10 years
- Sustained build within the IRP build limits would see RSA lag Germany by more than 20 years



IMPACT OF REAL-WORLD CONSTRAINTS

OPTIMISED 3.0 GT SCENARIO, DOES NOT EXIST IN THE REAL WORLD

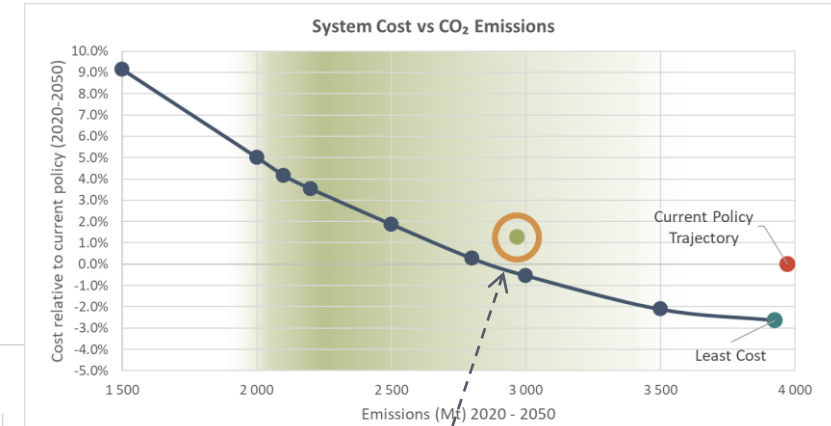
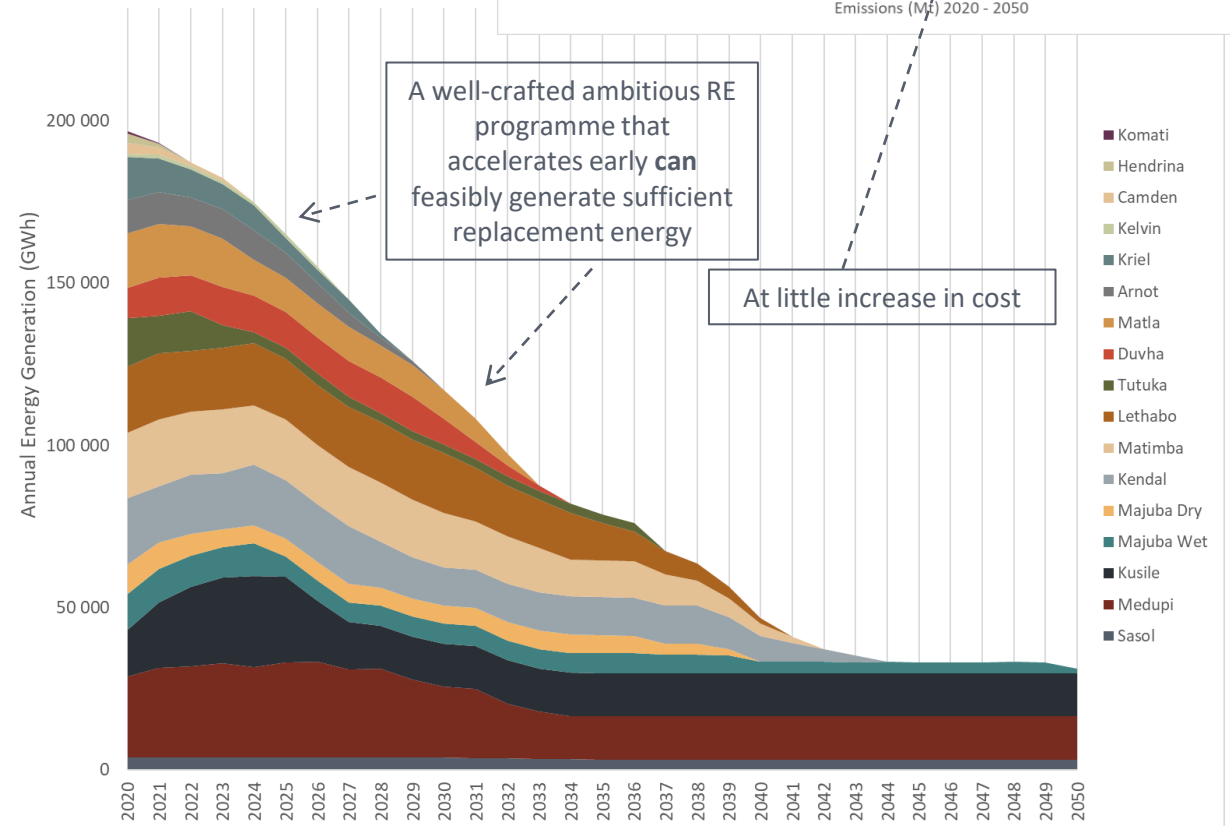
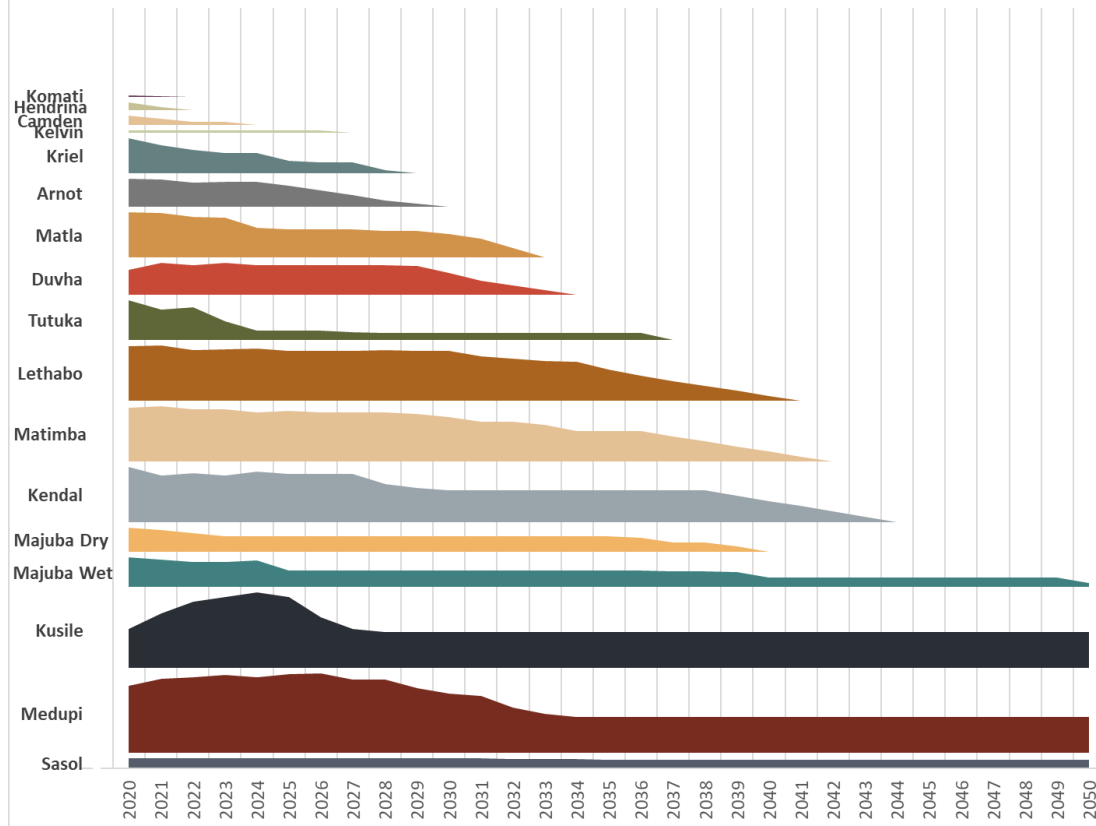
3.0 Gt Carbon Budget: Annual Energy Generation by Coal-fired Power Station



ACHIEVABLE, AMBITIOUS SCENARIO

EMPHASIZES NECESSITY TO AVOID DELAY IN RE ACCELERATION

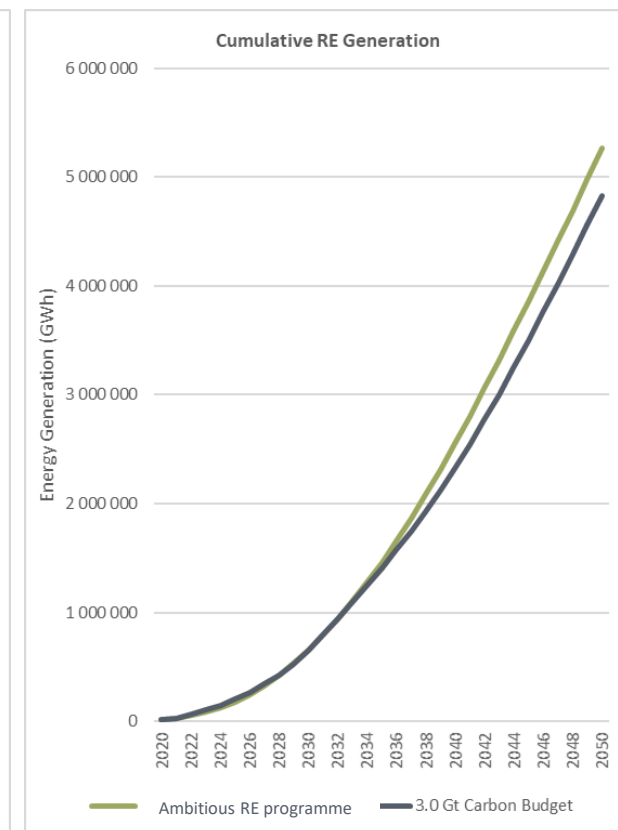
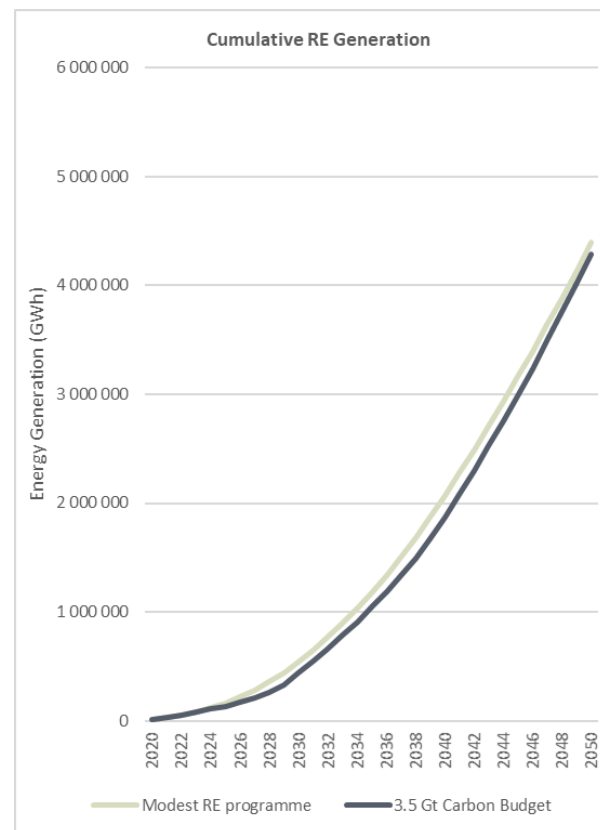
Ambitious RE Industrialisation: Annual Energy Generation by Coal-fired Power Station



ADDITIONAL TECHNICAL NOTES

PLEXOS MODELLING APPROACH, AND CONSTRUCTING RE PATHWAYS

- Power System plans were developed using the Plexos “Long Term (LT)” model – a simplified version of the multi-decade forecast period using 15 representative days for each year.
- Optimal power systems were then tested for system adequacy using the Plexos “Short Term (ST)” model – an hourly dispatch model that tests the power system plan for system adequacy through every hour of each year in the forecast period.
- Power system inadequacies were resolved by imposing a stringent capacity reserve margin requirement in the LT optimisation.
- Short term load balancing, grid stability, frequency control issues etc are not addressed in this modelling.
- Realistic mitigation scenarios are constructed through imposing a minimum annual new build RE capacity and re-running the optimisation. Cumulative RE generation needed to match or slightly exceed two optimised power system plans – 3 Gt and 3.5 Gt Carbon Budgets (see figures).



ASSUMPTION DETAIL

ASSUMPTIONS REGARDING THE ABATEMENT OF LOCAL AIR POLLUTANTS

- Coal fired power stations release local air pollutants, including Particulate Matter (PM), Nitrogen Dioxide (NO₂) and Sulphur Dioxide (SO₂) which impact the local environment and human health. The Environment Department (DEFF) regulates these pollutants under the Air Quality Act by setting Minimum Emission Standards and requiring individual power plants to hold Atmospheric Emissions Licences in relation to these Standards in order to operate.
- Pollutant specific abatement technologies can be retrofit in power plants to reduce local air pollutants, some at significant cost and with associated plant downtime. This is primarily why local abatement technologies are relevant to this study; they are material to how the model optimises.
- Plausible assumptions around local air pollutant abatement costs needed for the modelling include: **what technology will be retrofit, at which station, when, how much it will cost (opex and capex), and what implications there are for plant downtime.**
- We note that whilst it is not the focus of our study, the issue of local air pollutants is highly contentious, increasingly litigated, and with significant moral and ethical hazard.
- It is therefore particularly important that assumptions used for the baseline must - as far as possible - be **credible, based on publicly available data, internally consistent, and applicable across scenarios.**



ASSUMPTION DETAIL

ESTABLISHING A BASELINE LOCAL AIR POLLUTANT MITIGATION PROFILE FOR THE COAL FLEET

1. Abatement technology and timeframe : What can we assume will be retrofit when?

- Here, a distinction is recognised between regulatory compliance and Eskom's planned retrofit schedule - which is not fully compliant with the Air Quality Regulations (Eskom, 2019b). In the study we opt for the latter, to be consistent with the 2019 IRP* and therefore to ensure consistency across baseline and scenarios. It is worth noting that this is a conservative assumption in the context of the study, as full compliance assumes greater coal fleet cost, increasing the cost of the baseline versus the mitigation scenarios.
- The technologies retrofit at each plant, including retrofit dates are taken from Eskom's committed retrofit schedule (Eskom, 2019b). It was assumed that no downtime outside the ordinary maintenance schedule was required for retrofits**.

2. Costs : How much will these retrofits cost?

- Capital and operating costs associated with each abatement technology are Eskom's (Naledzi, 2018). The Flue Gas Desulphurisation (FGD) costs in particular have been critiqued as being inflated*** & ****
- MES shown includes MES Opex as well as CAPEX annualised from the date spent to the closing date of the station in the reference scenario (IRP)

Note: Eskom's public documents underpinning the local air pollutant profile are difficult to navigate. The assumptions upon which each document builds are not always clearly spelled out. Whilst we only rely on information in the public domain, our interpretation of this frequently required clarification with Eskom's Environmental Management Unit.

*The 2019 IRP assumes the 'MES 1' scenario developed by Eskom and used in the *Medium Term System Adequacy Outlook, Eskom, 30 October 2019*. The MES 1 scenario is that contained in the *2019 Applications for suspension, alternative limits and/or postponement of the MES compliance timeframes for Eskom's coal and liquid fuel fired power stations* dated March 2019 (Eskom ENV18-245 rev 2.1). (Confirmed by Deidre Herbst, personal communication, 2019).

**Personal communication CSIR 2019; Sahu email 09-11-2019. We note that this is different to Eskom's assumption in the MTSOA 2019, where MES 1 increases planned outages.

***Personal communication with various international experts (Myllyvirta, Rosenberg)

****FGDs increase CO₂ emissions slightly due to the addition of limestone into the boiler. The technology also reduces energy output, in the region of a percent. Neither of these aspects were included in the modelling, as neither was held to be materially significant.



ASSUMPTION DETAIL

TECHNOLOGY COST DETAIL - CONVENTIONAL

Property			Conventionals								
			Coal (PF)	Coal (FBC)	Coal (PF with CCS)	Coal (IGCC)	Nuclear (DoE)	OCGT	CCGT	CC-ICE	Demand response
Rated capacity (net)		[MW]	4 500	250	4 500	644	1 600	132	732	230	500
Overnight cost per capacity	2019	[ZAR/kW]	43 453	52 450	84 054	67 454	75 728	10 015	10 997	10 833	0
Construction time		[a]	9	4	9	4	6	2	3	1	1
Capital cost (calculated) ¹	2019	[ZAR/kW]	48 188	58 023	90 632	74 622	93 964	10 754	12 199	10 833	0
	2030	[ZAR/kW]	48 188	58 023	76 435	74 622	91 968	10 754	12 199	10 833	0
	2050	[ZAR/kW]	48 188	58 023	76 435	74 622	91 968	10 754	12 199	10 833	0
Fuel cost		[ZAR/GJ]	34	17	34	34	10	147	147	147	0
Heat rate		[GJ/kWh]	9 812	10 788	14 106	9 758	10 657	11 519	7 395	7 300	4
Fixed O&M		[ZAR/kW/a]	1 133	762	1 932	1 743	1 187	196	203	183	10
Variable O&M		[ZAR/MWh]	98	212	181	92	45	3	27	80	1 593
Load factor (typical)		[./.]	85%	85%	85%	85%	90%	8%	36%	55%	2%
Economic lifetime		[a]	30	30	30	30	60	30	30	30	1
			2%		2%						
			6%		6%						
			13%		13%						
			17%		17%		15%				
Capital phasing		[%/a]	17%		17%		15%				
			16%	10%	16%	10%	25%				
			15%	25%	15%	25%	25%		40%		
			11%	45%	11%	45%	10%	90%	50%		
			3%	20%	3%	20%	10%	10%	10%	100%	100%

¹ From capital phasing, discount rate and economic lifetime.

All costs in Jan-2019 Rands



ASSUMPTION DETAIL

TECHNOLOGY COST DETAIL - RENEWABLES

Property		Renewables														
		Wind	Solar PV (tracking)	Solar PV (fixed)	CPV	CSP (trough, 3h)	CSP (trough, 9h)	CSP (tower, 3h)	CSP (tower, 9h)	Biomass (forestry)	Biomass (MSW)	Landfill Gas	Biogas	Bagasse (Felixton)	Bagasse (gen)	Inga
Rated capacity (net)	[MW]	100	10	10	10	125	125	125	125	25	25	5	5	49	53	2 500
Overnight cost per capacity	2019 [ZAR/kW]	15 016	16 371	15 582	61 724	105 988	160 519	94 574	63 862	61 945	175 224	19 468	94 700	19 700	37 768	50 156
Construction time	[a]	4	2	1	1	4	4	4	4	4	4	1	1	2	3	8
Capital cost (calculated) ¹	2019 [ZAR/kW]	14 652	15 845	9 937	61 724	103 649	156 976	92 487	62 453	68 527	193 842	19 468	94 700	20 233	39 342	74 340
	2025 [ZAR/kW]	12 708	14 030	8 619	61 724	101 386	153 548	90 467	61 089	68 527	193 842	19 468	94 700	20 233	39 342	74 340
	2030-2050 [ZAR/kW]	12 708	14 030	8 619	61 724	101 714	154 046	90 760	61 287	68 527	193 842	19 468	94 700	20 233	39 342	74 340
Fuel cost	[ZAR/GJ]	-	-	-	-	-	-	-	-	39	-	-	-	90	90	-
Heat rate	[GJ/kWh]	-	-	-	-	-	-	-	-	14 243	18 991	12 302	11 999	26 874	19 327	-
Fixed O&M	[ZAR/kW/a]	742	347	328	384	1 253	1 320	1 153	1 236	2 028	7 927	2 907	2 378	190	431	484
Variable O&M	[ZAR/MWh]	-	-	-	-	1	1	1	1	81	140	76	62	10	30	0
Load factor (typical)	[./.]	36%	25%	20%	22%	32%	46%	38%	60%	85%	85%	74%	85%	55%	50%	67%
Economic lifetime	[a]	20	25	25	25	30	30	30	30	30	30	30	30	30	30	60
																20%
																25%
																25%
Capital phasing	[%/a]															10%
		5%				10%	10%	10%	10%	10%	10%					5%
		5%				25%	25%	25%	25%	25%	25%				10%	5%
		10%	10%			45%	45%	45%	45%	45%	45%			33%	30%	5%
		80%	90%	100%	100%	20%	20%	20%	20%	20%	20%	100%	100%	67%	60%	5%

¹ From capital phasing, discount rate and economic lifetime
All costs in Jan-2019 Rands



ASSUMPTION DETAIL

TECHNOLOGY COST DETAIL - STORAGE

Property			Storage technologies			
			Pumped Storage	Battery (Li-Ion, 1h)	Battery (Li-Ion, 3h)	CAES (8h)
Rated capacity (net)		[MW]	333	3	3	180
Overnight cost per capacity	2019	[ZAR/kW]	24 680	12 119	29 777	30 009
	2030-2050	[ZAR/kW]	24 680	5 757	14 144	30 009
Construction time		[a]	8	1	1	4
Capital cost (calculated) ¹	2019	[ZAR/kW]	30 777	11 141	27 372	33 906
	2030-2050	[ZAR/kW]	30 777	5 757	14 144	33 906
Fuel cost		[ZAR/GJ]	-	-	-	147
Heat rate		[GJ/kWh]	-	-	-	4 465
Round-trip efficiency		[%]	78%	89%	89%	81%
Fixed O&M		[ZAR/kW/a]	222	757	757	261
Variable O&M		[ZAR/MWh]	0	4	4	3
Load factor (typical)		[./.]	33%	4%	12%	22%
Economic lifetime		[a]	50	10	10	40
			1%			
			1%			
			2%			
			9%			
Capital phasing		[%/a]	16%			
			22%			25%
			24%			25%
			20%			25%
			5%	100%	100%	25%

All costs in Jan-2019 Rands

¹ From capital phasing, discount rate and economic lifetime.

