Future CSP in South Africa – A review of generation mix models, their assumptions, methods, results and implications

D. Frank Duvenhage, Omotoyosi O. Craig, Alan C. Brent, and William H. L. Stafford

Citation: AIP Conference Proceedings **2033**, 120002 (2018); doi: 10.1063/1.5067131
View online: https://doi.org/10.1063/1.5067131
View Table of Contents: http://aip.scitation.org/toc/apc/2033/1
Published by the American Institute of Physics

Future CSP in South Africa – A Review of Generation Mix Models, Their Assumptions, Methods, Results and Implications

D. Frank Duvenhage[1,a)], Omotoyosi O. Craig[1,b)], Alan C. Brent[2,3] and William H.L. Stafford[4,5]

[1]*Ph.D. candidates, Engineering Management, Stellenbosch University, Department of Industrial Engineering, Private Bag XI Matieland 7602, Stellenbosch (South Africa.*
[2]*Extraordinary Professor, Department of Industrial Engineering and the Centre for Renewable and Sustainable Energy Studies, Stellenbosch University, South Africa*
[3]*Professor, Sustainable Energy Systems, Engineering and Computer Science, Victoria University of Wellington, New Zealand*
[4]*Extraordinary Associate Professor, Department of Industrial Engineering, Stellenbosch University, South Africa*
[5]*Senior Researcher, Green Economy Solutions, Natural Resources and the Environment Unit, Council for Scientific and Industrial Research, South Africa*

[a)]dfrankduv@gmail.com
[b)]omotoyosicraig@gmail.com

Abstract. South Africa has experienced great uncertainty in its electricity supply sector. Many energy system modeling efforts have been undertaken. This is to determine the most appropriate energy mix and manage uncertainty. We review all available, relevant studies and summarize their results, modeling approaches, and input assumptions. From this, we try to understand their impact on CSP development in South Africa.

INTRODUCTION

South Africa's energy landscape has undergone turmoil after the 2007/'08 power crisis (1). This has prompted government to recognize the value of independent power producers (IPPs). Of particular interest, are those using renewable energy technologies (RETs). Global and local climate change targets contributed to the uptake of RETs (2–4). Furthermore, they are becoming cost-competitive with conventional generation options under constrained supply conditions. This is because the can provide much-needed relief within shorter lead-times (5,6).

Yet, the variability of the renewable energy resources requires more detailed energy planning. Integrated Resource Plans (IRPs), aim to guide government decisions on long-term generation infrastructure expansions. Detailed cost-optimal models, considering various supply options, inform these IRPs (7). Energy system modelling stems from the need to plan for likely future demand scenarios. The aim is to identify reliable electricity generation options, and achieve a high certainty of supply (8). South Africa (SA) promulgated its first IRP in 2010. SA released an update in 2013 (not promulgated), and later in 2016 (currently under review) (9,10). They form the basis of ministerial determinations. These determinations result in energy procurement programs such as the Renewable Energy Independent Power Producer Procurement Program (REI4P). The REI4P has led to the addition of 6,422 MW installed capacity of renewable electricity generation, of which 3,052 MW is operational (11).

Of this capacity, 3,357 MW and 2,292 MW are onshore wind and PV respectively, with concentrating solar power (CSP) constituting 600 MW thereof (11–13). Wind and PV experience great operational variability due to their reliance on natural resources. CSP offers greater stability due to its ability to store thermal energy for dispatchable

SolarPACES 2017
AIP Conf. Proc. 2033, 120002-1–120002-12; https://doi.org/10.1063/1.5067131
Published by AIP Publishing. 978-0-7354-1757-1/$30.00

generation (14). This gives CSP a competitive advantage over other RETs since it can provide peaking, mid-merit or even baseload generation (15–17). Profitable electricity from CSP requires high direct normal irradiance (DNI) and enough thermal energy storage (TES) for the tariff-structure in place (16)(18). Furthermore, CSP offers opportunities for local and national economic growth. This is through investments, job creation, and the localization of CSP manufacturing sectors (19). The lower global adoption rates of CSP, and lower allocations in the REI4P, are a result of its higher Levelized Cost OF Electricity (LCOE) (11,20).

The IRPs are the formal reports produced by the SA Department of Energy (DoE). They inform the desired electricity generation mix for future supply expansions (21). There are, however, other independent studies by research institutions and interested global organizations. These independent studies do not formally contribute to policy-driven decision-making, but provide a benchmark for the IRPs. Furthermore, the results from these studies impact public opinion on generation technologies and influence investments in the electricity sector. Additionally, they often form the basis of assumptions used in further research. In a recent example, a Masters level project used the results of the IRP2013 in its modelling (22). The IRPs impact investor confidence in SA. Since 2015, CSP bidders were experiencing delays in finalizing agreements with the national utility, Eskom (23,24). Additionally, the IRP2016 had no CSP allocations, which lead to an outcry by prospective investors and stakeholders in the media (25–34).

In light of this reaction, and subsequent publication of independent studies in response to the IRP2016, a comprehensive review of electricity supply options for South Africa is necessary. Therefore, this paper presents an objective comparison of all such available studies, for South Africa. An analysis of their methodologies, assumptions, and modelling techniques could provide valuable insights for all stakeholders. This paper focuses primarily on CSP because of its capability to provide stable generation. Furthermore, PV and wind are already commercially established, with CSP still in a young, but growing phase. For faster development of the CSP industry, an understanding of which technical, operational and policy factors will influence its future, is necessary.

ENERGY SYSTEM MODELLING METHODS

The modeling packages and approaches used to find the optimal electricity generation mix for a certain country (or area) varies according to method and purpose (8). Pfenninger et al. discussed the grouping of modeling packages according to the following four paradigms:

1. Energy system optimization models, aiming to determine a variety of possible scenario's based on optimization criteria and goals for all energy sources and demands (scenarios through optimization).
2. Energy system simulation models, aiming to forecast future system developments through simulations, for all energy sources and demands (forecast through simulation).
3. Power systems and electricity market models, aiming to either determine scenarios through optimization or forecasts through simulation, but focused primarily on electricity as a form of energy.
4. Qualitative and mixed-methods scenario's, aiming to produce detailed results (scenario or forecast oriented) for complex energy systems, through a combination of qualitative and quantitative techniques.

These paradigms are not explicit in their boundaries, but are rather fluid in their definitions, approaches, and desired results. Most of the studies reported in this paper focused on finding cost-optimal electricity generation mixes for SA to meet a projected demand (based on separate modeling). Meeting this forecasted demand must take place under certain limitations or constraints; such as meeting future demand at the lowest cost, achieving CO_2 emission reduction targets, and the economies of scale of electricity supply for various generation options. The combinations of these considerations (optimization goals, demands, limitations, and assumptions) constitute "scenarios". These scenarios are then modeled in an appropriate package, and the results are used to understand the implications of the underlying scenario conditions. A simplified representation of the logical process followed to reach final energy mixes in most of the studies is shown in Fig. 1.a. There are many technology-wide energy system modeling packages in use, but the most notable are the PLEXOS and TIMES analysis tools. Industries and research institutions use PLEXOS, and it is the package used by the DoE for the IRPs, and by the National Council for Scientific and Industrial Research (CSIR) for their independent studies and response to the IRP2016. It is a mixed-integer linear programming package with detailed elements for various power plant technologies, the transmission grid and market planning, and with enough detailed input data, is capable of providing analyses at very high resolutions (up to 1- minute detail) (8). Another widely used package is the TIMES model, developed by the IEA ESTAP[a] consortium of researchers from IEA member countries, and is publicly available, with the aim to present possible future developments of national,

[a] International Energy Association - Energy Technology Systems Analysis Program

regional and global energy systems (8). TIMES is generally considered to fall in the paradigm of "energy system optimization models", while PLEXOS is considered part of the "power systems and electricity market models" paradigm (8). Even though these two, among others, might be classified under different paradigms, they can be used in similar ways to determine optimum energy mixes.

The IRPs, the defining regulatory documents used to plan future electricity supply infrastructure builds, uses the outputs of these optimization models to limit the supply capacity of various generation options in a subsequent a competitive bidding process. This relationship between modeling results and its use in national electricity supply planning is shown in Fig. 1.b.

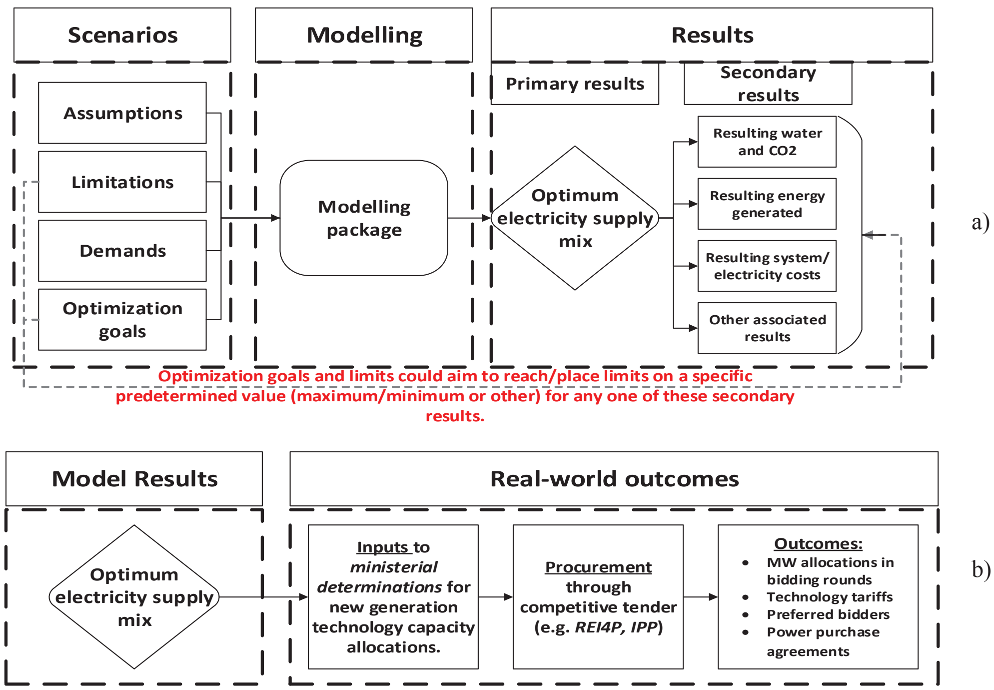


FIGURE1. a) The logical process followed to reach optimized energy mixes for various scenario-specific considerations. b) How the results of modeling for the IRP form the basis of informing future developments.

APPROACH

Since this study focuses on the amalgamation of information from other studies, it must report coherently on a large number of results, without meaningless repetition. Thus, it aims to review studies that determine various electricity generation mixes for South Africa, and which look in particular detail at RETs options, especially CSP. As discussed, the rationale is that such studies inform industry decisions, public opinions, and assumptions for further studies. This means that studies were considered that might influence these three stakeholder groups.

Many studies like these have appeared in recent years, and limitations need to be placed on which are considered in this paper to ensure relevance; the following four criteria were subsequently used:

1. Published during or after 2010 (one exception has been made).
2. Consideration must be given to RETs and CSP in particular.
3. If a global report is considered, particular detail must be available for South African results.
4. Must be publically available.

The sources found to adhere to this criteria are summarized in Table 1, and to cover all available energy mix results for South Africa, their databases were searched for possible contributions to this analysis.

TABLE 1. Sources of potential reports/studies on energy mixes for South Africa.

Resource type	Institution name	Used in analysis
Governmental institutions	South African government gazettes	N
	National Energy Regulator of South Africa (NERSA)	N
	ESKOM	N
	Department of Energy South Africa (DoE)	Y
	The Council for Scientific and Industrial Research (CSIR)	Y
	Department of Science and Technology	N
Global companies and institutions/agencies	International Energy Agency (IEA)	N
	International Renewable Energy Agency (IRENA)	N
	Renewable Energy Policy Network for the 21st Century (REN21)	N
	World Council for Renewable Energy (WCRE)	N
	Solar Energy Industries Association (SEIA)	N
	World Wildlife Fund (WWF)	Y
	Greenpeace	Y
	United Nations Environment Program (UNEP)	N
Research institutions (Academic)	Centre For Renewable and Sustainable Energy Studies (CRSES – Stellenbosch University)	N
	Energy Research Centre (ERC – University of Cape Town UCT)	Y
	Academic publications in general – theses/dissertations and journal papers	N
Research institutions (Industrial)	National Renewable Energy Laboratory (NREL – DoE of the USA)	N
	Plataforma Solar de Almería (PSA - Centre for Energy, Environmental and Technological Research, Spain)	N

The systematic methodology followed to perform the analysis was:

1. Identify appropriate studies according to the four criteria listed above, from the sources listed in Table 1.
2. For each study determine the main objective, modeling approach and package, base scenario, maximum CSP scenario, and minimum CSP scenario.
3. Identify key input parameters, assumptions, limitations, demand profiles, cost profiles/learning curves, forced/relaxed builds, assumed lead times and assumed capacity factors.
4. Find the key results: system costs and/or investment requirements and installed capacities per technology.
5. Enter above information into the database.
6. Analyse trends and correlations according to groupings of CSP development cases.
7. Draw conclusions from above analyses and make informed suggestions.

RESULTS AND DISCUSSION

From the various sources of potential studies listed in Table 1, nine studies were found to adhere to the criteria, and are listed in Table 2. One exception to the criteria was the Greenpeace Energy Revolution report of 2009, since it forms part of a series of two studies, being followed by the Greenpeace Energy Revolution report of 2011.

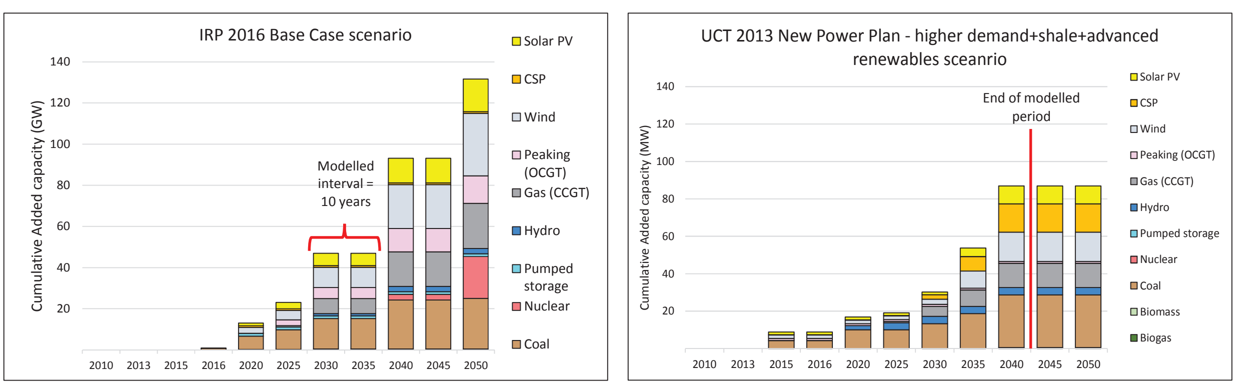
TABLE 2. Reports/studies identified which contribute to determining energy mixes for South Africa.

Report/Study Name	Goal of Study	Optimization Parameter
IRP 2010 (7) and 2016 (10)	Determine how long-term electricity demand should be met by new generating capacity, type, timing, and cost, with a balance between affordability, and a government determined policies.	Cost-optimal (with various limits, forced builds, and relaxed options)
IRP 2013 (9)	Determine how long-term electricity demand should be met by new generating capacity, type, timing, and cost, taking changes in technology costs and forecasted demands into account, and providing a flexible approach to determining investment decisions in contrast to the fixed capacity plan of the IRP 2010 and 2016.	Cost-optimal (with various limits, forced builds, and relaxed options)

TABLE 2. (continued)

Report/Study Name	Goal of Study	Optimization Parameter
CSIR response to IRP 2016 (35)	Part of the IRP update process, industry stakeholder- engagement for comments and inputs prior to final IRP. Aimed to find the least cost, unconstrained electricity mix by 2050, in line with the IRP 2016, to reflect the latest industry-aligned costs and changes.	Cost-optimal (with various limits, forced builds, and relaxed options)
Greenpeace 2009 (36) and 2011 (37) Energy [R]evolution	The only exception made on relevancy-criteria since it forms part of a series of documents, with the next published in 2011. Scenarios based on the global energy scenario produced by Greenpeace demonstrating how energy-related global CO_2 emissions can be at halved by 2050.	Unclear; limits on CO_2, possibly optimized or simulated to reach the goal.
WWF - 50% by 2030 (2010) (38)	Compare the implications of a reference scenario (where capacity is allocated according to the 2007 Eskom investment plan) to that of an alternative, where CO_2 emissions are reduced through more RE to the generation mix by 2030, but still meeting demand requirements.	Simulation performed to reach the goal of 50% installed capacity by 2030
WWF – feasibility of the WWF renewable energy vision 2030 (2015) (39)	Test feasibility and merits of targeting 20% annual electricity generation from RETs by 2030 by performing a spatial-temporal analysis on the complete electrical system of South Africa.	Simulation performed to test goal of 20% installed capacity by 2030
UCT, ERC – Towards a new power plan (2015) (40)	Looks at key assumptions in the IRP 2010 and the impact that updating some of these assumptions will have on a new power plan. The new assumptions considered are lower demand, updated investment costs of renewable and nuclear technologies and the availability of natural gas import options.	Cost-optimal (with various limits, forced builds, and relaxed options)
UCT, ERC - Nuclear build plan technical report (2015) (41)	Analyse the SA Government's commitment to 9.6GW of nuclear power against other supply options. A flexible planning approach in the electricity sector is compared to a commitment to the full nuclear fleet for two different demand scenarios.	Cost-optimal (with various limits, forced builds, and relaxed options)

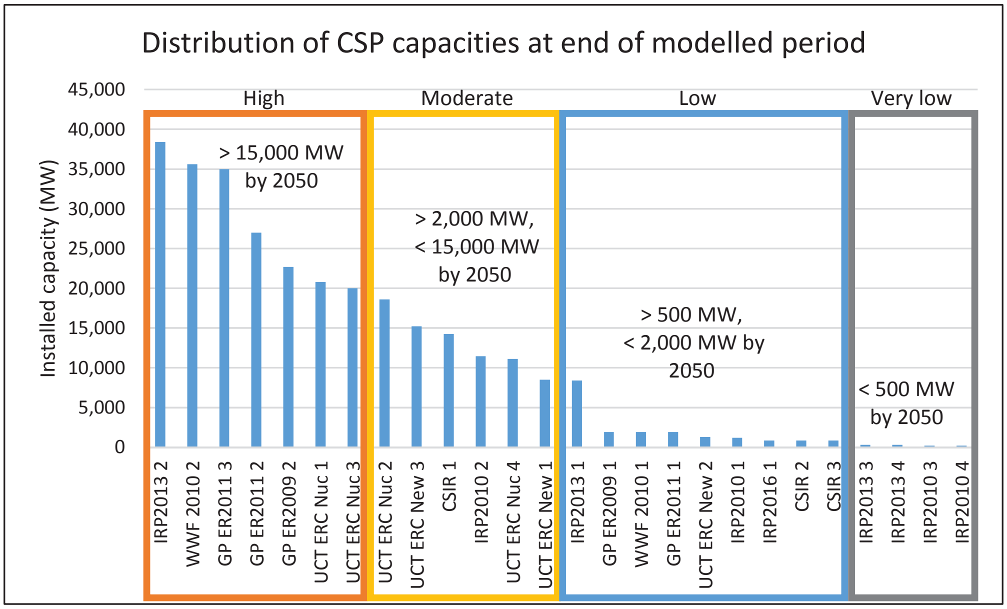
For each study, there are multiple sets of results pertaining to each scenario, for the various technologies considered therein. An example of the IRP 2016 Base Case is shown in Fig. 2. An issue with this data was that each study presented it at different time-scales (every year, five years, ten years, etc.) and in different ways; for example, some studies consider the total installed capacity, some only new added capacity, while others used the cumulative added capacity since the start of the modelling period, the representation of choice for this paper, since it could be calculated from the previous two presentation styles. From Fig. 2 one can see that factors, such as time-scales, modeling period and the sheer amount of information relating to the energy mixes, namely capacity per technology, complicate the representation of this data for multiple scenarios.



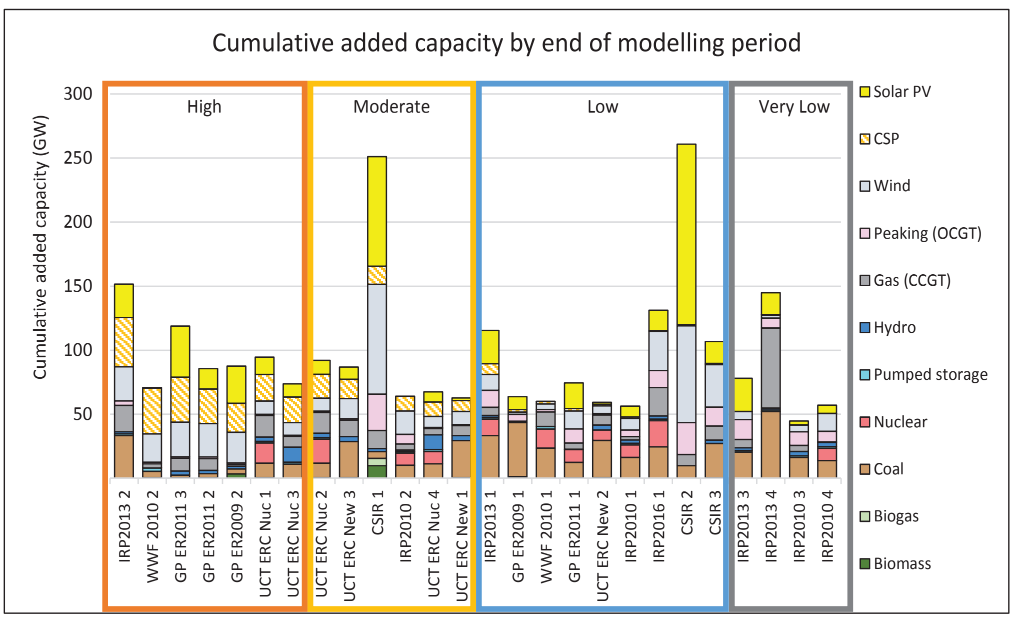
(a) (b)

FIGURE 2. Cumulative new added capacity for the (a) IRP 2016 and (b) UCT New Power Plan of 2013.

Yet, it is also important to see the capacity allocated to CSP in light of capacities allocated to other technologies to understand how the demand is met by the combination of technologies. For this reason, it was decided to show the CSP build-plan over the entire modeling period, as well as the final total energy mix by the end of the modeling period of each scenario reviewed. Since the aim of this paper is to understand the impact of modeling considerations on the projected development of CSP in South Africa, the scenarios covered in this analysis will be compared to each other on the basis of CSP capacity allocations. Figure 3.a shows that there are four distinct groups of CSP development cases stemming from the capacity allocations; high, moderate, low, and very low. Figure 3.b shows the entire energy mix of each of these scenarios by the end of the modeling period. The full names of each of the scenarios in Fig. 3 are given in Appendix A.



a)



b)

FIGURE 3. (a) Distribution of capacities allocated to CSP by the end of each scenario's modeling period. (b) Total energy mix by the end of each scenario's modeling period

Another key result of these models is the associated total system cost, or calculated average tariff resulting from the energy mix modeled. This information is very relative in nature for each study across the various scenarios aiming to compare relative costs within a study, and not necessarily explicitly predicting the actual future costs. They are also relative across different studies from different countries (currency), different publishing years (inflation), and different input cost data origins (2005 USD for example). This complicates comparing the impact that each energy mix from each scenario has on system costs between different studies. Therefore, the average cost-results over the modeled period for each scenario in a study are normalized to the lowest average cost over the same modeling period within that study and expressed as a factor greater than the lowest average cost between all the scenarios within a study. This will provide insight into how each scenario compares to the others in the same study, and relatively to those from other studies. It should be noted that a value of one, in Fig. 4, refers to the scenario in that study with the lowest system cost, and values greater than one indicates how many times more costly than the least costly energy mix a certain scenario is. This makes the total system costs more comparable between different studies, showing that the higher contribution by CSP does not always result in a higher total system cost.

However, in general, greater CSP allocations lead to slightly higher system costs when compared to the costs resulting from the other scenarios in the same studies. This is an apparent result of the higher LCOE of CSP, resulting mainly from the current and projected high capital costs. It is furthermore greatly dependent on tariff structures offered by government and bids offered by CSP developers, which are not considered in the modeling. That being said, if the conclusions reached later were systematically implemented, bidding would be more competitive between CSP developers, and tariffs would be lower, resulting in the desired overall lower system cost-implications by CSP.

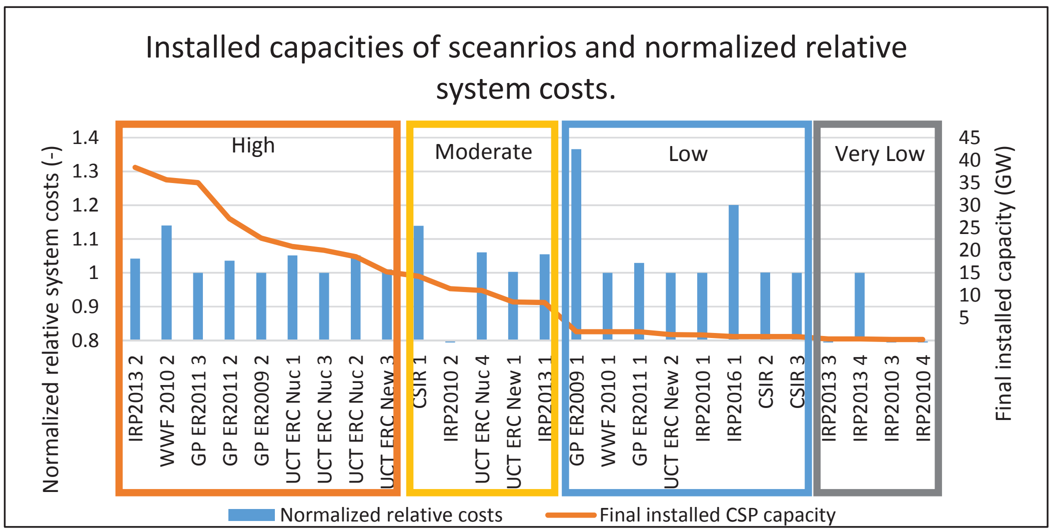


FIGURE 4. Final installed capacities of each scenario compared to normalized relative system costs.

Greenhouse gas emissions and water consumption are other key considerations for electricity supply planning and modeled energy mixes; to understand the impact of different electricity generation options on natural resources. In all of the studies analyzed in this paper, emissions are, however, not used as an optimization parameter, but rather as a limit imposed on the resulting energy mix. For this reason, the presence and magnitude of these limits will be used to analyze impacts on generation technology selections.

The assumptions discussed above can be described as being part of three groups: the attributes of CSP (costs, technical parameters, etc.), the attributes of other electricity generation options (nuclear, coal, PV, etc.), and the attributes of the system itself. When considering the results of these 26 scenarios, their impact on the capacity allocated to CSP cannot be taken in isolation, but need to be addressed as a group. There is very little to no mathematic correlation when, for example, plotting the final CSP capacities against final projected system demand, or any other assumed input parameter. This is because while one assumption in a scenario might be advantageous to CSP (like strict CO_2 limits), another might favor nuclear or PV (lower nuclear costs or lower projected demand growth). For this reason, the assumptions identified as key driving forces of CSP development/inhibition, are CSP capital costs (relative to alternative generation options; in particular PV and nuclear), CSP learning rates (total reduction over modelling period), demand (final system demand at end of modelling period), meeting greenhouse gas emission reduction targets (final CO_2 emissions goal by end of modelling period) and the inclusion of scenario-specific assumptions of other electricity generation options. For this reason, the parameters used to compare the scenarios' were plotted on radar graphs. Since radar graphs can only compare values of the same scale or order to each other, the values are normalized as far as possible. The maximum CSP CAPEX refers to the initial overnight capital costs reported in the studies and is compared to the initial CAPEX of PV and nuclear to illustrate the relative cost of CSP used in the model (higher values indicate that CSP is comparatively more expensive). The cost reduction reported is the total reduction due to learning used in the model, normalized to the average of all the different scenario cost reductions (higher values indicate greater cost reductions). The end-of-period demand is normalized to the minimum demand projected for all the scenarios considered from all studies, thereby giving an idea as to how many times the demand for a certain scenario is greater than the lowest projected demand (higher values indicate greater projected demands). The end-of-period CO_2 emissions limit of each of the scenario are normalized to the average CO_2 emissions limit set for the last year of modeling of all the scenarios considered (higher values indicate more relaxed limits on CO_2).

Figure 5 shows that each of the CSP development cases has different development paths or rates at which CSP is added to the generation fleet. This is partly due to further assumptions, such as decommissioning schedules of existing fleets, carbon emission reduction target years, and projected demand growth rates. Some of the development paths seem to increase too rapidly, but this is due to time-resolution differences between the original report (reporting, for example, every 1 year) and the resolution used for this report (every five years after 2020).

From the High CSP Development Cases, it can be seen that greater technology cost reductions and higher greenhouse gas emission reduction targets to aid in driving the more rapid adoption of CSP into the energy mix. The only exceptions are the three UCT scenarios, which do not report in their published studies that any limits are placed on CO_2 emissions in their models, hence the apparent high levels of CO_2 allowed.

From the Moderate CSP Development Cases, it is clear that the assumption resulting in the slightly lower adoption of CSP is primarily cost-related, with higher CSP/PV and CSP/nuclear costs being used in the models, with generally less strict CO_2 limits placed on emissions. The CSP/PV cost that appears to exceed the maximum bound of the radar graph is that of the CSIR response to the IRP2016, which assumes the highest overnight capital cost for CSP at around 131 R/W, and a much lower PV cost of around 9 R/W. Even though CSP is much more capital intensive in these scenarios, due to the strict CO_2 limits imposed therein, CSP is allocated a large portion of the energy mix.

From the Low CSP Development Cases, it can be seen that the high comparative cost of CSP/nuclear (or lower cost of nuclear compared to CSP) results in CSP being allocated a smaller portion of the generation mix over the modeling period. Here it should also be said that the three cases with the highest final CSP capacities (the two Greenpeace and WWF reference scenarios) appear to not have been optimised as is the case for the IRPs, and CSIR- and UCT studies, since they aim to serve as a projected simulation of the current trends in the electricity generation sector, as brought forward in previous Eskom build plans and the original IRP2010. It is therefore insightful to note that the CO_2 limits have been removed for these scenarios, resulting in lower CSP capacities required, since emissions reductions are not prioritized. It is important to note that the IRP2016 falls in this group, with no CSP learning and very high comparative costs assumed.

In the graphs showing the Very Low CSP Development Cases, the first noticeable characteristic is that there are only four scenarios (out of a total of 26) It is also important to note that maximum end-of-period capacities allocated to CSP have already been surpassed by the current actual installed, and under-construction, CSP projects in South Africa, totalling 500 MW by end-2018. The four of these scenarios form part of the IRP2013 and IRP2010 studies, where very specific conditions are tested, namely a carbon tax instead of CO_2 limits for "IRP 2013 3", large regional and local gas developments for "IRP 2013 4", very low economic growth and thus low electricity demand in "IRP 2010 3" and finally high coal and gas costs (with consistently high CSP/PV and CSP/nuclear costs) in the "IRP 2010 4".

The future electricity demand does not appear to influence the CSP potential installed capacity (Fig. 5) as demand is met by the supply mix in all studies and scenarios examined. The opinion of the author is that if the other driving forces were more favorable to CSP (lower CAPEX costs and greater reductions, and stricter CO_2 limitations), irrespective of future demand, CSP would play a greater role in the energy mix. Mention should also be made of the importance of not forcing any annual new-build capacity restrictions on any technology. This was done in all the IRPs, where PV and wind are restricted to 1000 MW/a, and 1600MW/a, respectively. In the initial IRP2010, restrictions were also imposed on CSP, to the order of 500 MW. Since no restrictions are imposed in any of the other studies, they are not used as a basis of comparison.

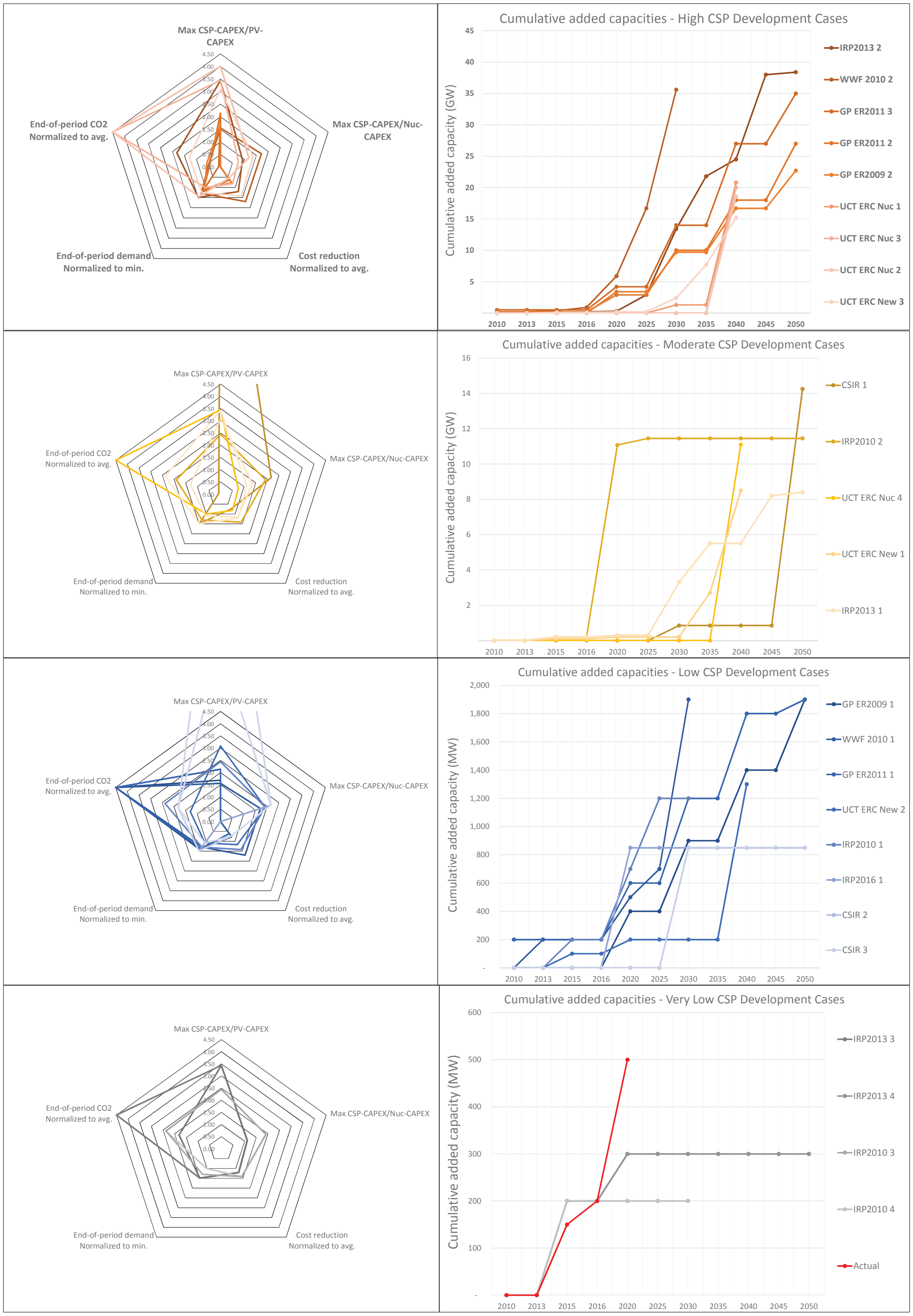


FIGURE 5. Radar graphs of key drivers and CSP build plans over modeling period for all CSP development cases.

CONCLUSION

From the graphs in Fig. 5, and in light of the actual CSP developments (500 MW to be installed by end 2018), as well as the state of other electricity generating industry related factors to date (such as lower than expected economic growth), the conditions that would favour higher CSP development in South Africa, and the responsible stakeholder (in brackets), are summarised as:

- Lower CSP-related costs, in particular, technology-related capital costs. (CSP Industry)
- Increase CSP allocations in subsequent bidding rounds, to improve CSP learning, making contractors and financiers more familiar and comfortable with CSP construction and operational phases, thereby addressing non-technology specific costs associated with financing and investment uncertainties. (Government)
- Greater energy greenhouse gas emissions restrictions imposed by the government as a national policy. (Government)
- Increase localized manufacturing of CSP plant components by existing, mature industries (car manufacturing, local metal workers, and boilermakers etc.) to reduce capital costs and create another, non-generation related, national economic benefit. (Government+CSP Industry)
- Ensure greater national economic growth is facilitated by the government through incentivizing better private sector development to motivate greater electricity demand. (Government)
- Better CSP tariff incentives for larger TES- and installed capacities, will increase capacity factors and aid in lowering costs of electricity production, and drive down final sales tariffs to Eskom. (Government)

For energy system modeling, however, it must be emphasized that the models and associated input parameters and assumptions are as impartial as possible. Modelers need to not only to ensure the most realistic technology and demand assumptions are made but also guarantee that least-cost technology selections by the model are made as accurately as possible, preventing modeler bias, leaving the model and its results “technology-agnostic”. This is crucial, since future expansion plans must be based on scientific, objective model results, combined with strategic policy determinations, to ensure new-build options selected do result in the lowest system-costs for the end-consumer.

ACKNOWLEDGMENTS

Thanks go out to Stellenbosch University’s STERG and the National Research Foundation of South Africa, for funding my registration and attendance of SolarPACES ’17, to my supervisor Professor Alan Brent, to Greg Prentice for presenting this work at another symposium, to my pears (E.P Dall and M.D. Sklar-Chik) for reviewing the work, and to my Heavenly Father.

REFERENCES

1. Financial Mail. South Africa’s Energy Crisis: Eskom 2008-2005 [Internet]. Rosebank: Times Media Books 2015; 2015. Available from: http://cdn.bdlive.co.za/ebooks/Eskom and the SA energy crisis.pdf
2. United Nations Framework Convention on Climate Change. United Nations Framework Convention on Climate Change. Review of European Community and International Environmental Law. 1992.
3. United Nations Framework Convention on Climate Change. Kyoto Protocol To the United Nations Framework Kyoto Protocol To the United Nations Framework. Review of European Community and International Environmental Law. 1998.
4. United Nations Framework Convention on Climate Change. Paris Agreement. 2015.
5. Haffejee Y. Renewable Energy IPP Program South Africa. Abu Dhabi: IRENA; 2013.
6. Walwyn DR, Brent AC. Renewable energy gathers steam in South Africa. Renew Sustain Energy Rev. Elsevier; 2015;41:390–401.
7. Republic of South Africa Department of Energy. Integrated Resource Plan For Electricity 2010. Pretoria; 2010.
8. Pfenninger S, Hawkes A, Keirstead J. Energy systems modeling for twenty-first-century energy challenges. Renew Sustain Energy Rev. Elsevier; 2014;33:74–86.
9. Republic of South Africa Department of and Energy. Integrated Resource Plan for Electricity (IRP update 2013). Update Report. 2013.
10. DoE. Integrated Resource Plan [Internet]. 2016 [cited 2017 Mar 28]. Available from: http://www.energy.gov.za/IRP/irp-2016.html

11. Independent Power Producer Office. Independent Power Producers Procurement Programme (IPPPP) An Overview. Centurion; 2017.
12. Eberhard A, Naude R. The South African Renewable Energy Independent Power Producers Procurement Programme (REIPPPP) – Lessons Learned. J Energy South Africa. 2016;27(November 2016):1–14.
13. DoE. Renewable Energy IPP Procurement Programme (REIPPPP) for South Africa. 2015.
14. Gauché P, Rudman J, Mabaso M, Landman WA, von Backström TW, Brent AC. System value and progress of CSP. Sol Energy. 2017;
15. Silinga C, Gauché P. Scenarios for a South African CSP peaking system in the short term. Energy Procedia. Elsevier B.V.; 2013;49:1543–52.
16. Silinga C, Gauché P, Rudman J, Cebecauer T. The South African REIPPP Two-tier CSP Tariff: Implications for a Proposed Hybrid CSP Peaking System. Energy Procedia. 2015 May;69:1431–40.
17. Desideri U, Campana PE. Analysis and comparison between a concentrating solar and a photovoltaic power plant. Appl Energy. Elsevier Ltd; 2014;113:422–33.
18. IRENA. Renewable Energy Technologies Cost Analysis Series: Concentrating Solar Power. Comprehensive Renewable Energy. 2012.
19. Gauché P, Backström TW Von, Brent AC. A concentrating solar power value proposition for South Africa. J Energy South Africa. 2013;24(1):67–76.
20. IRENA. The Power To Change : Solar and wind cost reduction potential to 2025. 2016.
21. Wright J, Bischof-Niemz DT, Calitz J, Mushwana C. Least-cost electricity mix for South Africa by 2040. Cape Town; 2016.
22. Auret C. Scenario modeling for short to the long-term rollout of concentrating solar power in South Africa by. 2015;(March).
23. Omarjee L. Eskom postpones IPP signing with Redstone Fin24 Tech [Internet]. Fin24. 2016 [cited 2017 May 10]. Available from: http://www.fin24.com/Economy/Eskom/eskom?postpones?ipp?signing?with?redstone?20160728
24. Tsanova T. Eskom again avoids signing PPA for 100 MW CSP park - report [Internet]. Renewables Now. 2016 [cited 2017 May 10]. Available from: https://renewablesnow.com/news/eskom-again-avoids-signing-ppa-for-100-mw-csp-park-report-538099/
25. Yelland C. Analysis : The Draft 2016 Integrated Resource Plan – lightweight, superficial and downright dangerous [Internet]. The Daily Maverick. 2016 [cited 2017 Mar 13]. Available from: https://www.dailymaverick.co.za/article/2016?11?30?analysis?the?draft?2016?integrated?resource?plan?light weight?superficial?and?downright?dangerous/
26. Yelland C. Money Talk on Radio 2000 CSIR’s outlook for South Africa’s future electricity mix [Internet]. Moneyweb. 2016 [cited 2017 Apr 6]. Available from: https://www.moneyweb.co.za/news/industry/csir?presents?its?outlook?for?south?africas?future?electricity?mi x/
27. Ndebele P. Comments for submission to the DOE on the IEP and Draft IRP 2016 Base Case. 2017.
28. Pierce W, Bischof-Niemz T, Mehos M, Badeda J, Gauche P. The Role and Value of CSP in the South African Power System - CONSENSUS STATEMENT. Pretoria; 2017.
29. Wright J, Bischof-niemz T. Comments on the Integrated Resource Plan 2016 Draft South African Integrated Resource Plan 2016 public hearing. 2016.
30. Martin B. South African Renewable Energy Council (SAREC) Response To The Integrated Resource Plan 2016 Update. 2017.
31. Lilley R, Yelland C. DoE’s draft IRP 2016 roasted [Internet]. Moneyweb. 2017 [cited 2017 May 10]. Available from: https://www.moneyweb.co.za/news/industry/does?draft?irp?2016?roasted/
32. Eberhard A. Structure of the market needs to be revised to ensure least-cost energy [Internet]. Businesslive. 2017 [cited 2017 May 10]. Available from: https://www.businesslive.co.za/bd/opinion/2017?05?09?structure?of?the?market?needs?to?be?revised?to?ensu re?least?cost?energy
33. Creamer T. As DoE prepares to release IRP, all eyes will be on nuclear [Internet]. Engineering News. 2017 [cited 2017 May 10]. Available from: http://www.engineeringnews.co.za/article/as-doe-prepares-to-release-irp-all-eyes-will-be-on-nuclear-2016-11-17/rep_id:4136
34. Njobeni S. Government erred in IRP draft [Internet]. IOL. 2017 [cited 2017 May 10]. Available from: http://www.iol.co.za/business?report/energy/government?erred?in?irp?draft?8413556
35. Wright JG, Bischof-Niemz T, Calitz J, Mushawana C, van Heerden R, Senatla M. Formal comments on the

Integrated Resource Plan Update Assumptions, Base Case results and Observations 2016. Pretoria; 2017.
36. Teske S. energy [r] evolution: A sustainable South Africa energy outlook. 2009.
37. Teske S. The advanced energy [r] evolution: A sustainable energy outlook for South Africa. 2011.
38. du Plessis M, Worthington R, Fakir S, Tyrer L, Cox J. 50% by 2030: Renewable Energy in a Just Transition to Sustainable Electricity Supply. Rosebank; 2010.
39. WWF. Feasibility of the WWF Renewable Energy Vision 2030 – South Africa: A spatial-temporal analysis of the WWF Renewable Energy Vision 2030 – South Africa. 2015.
40. ERC. Towards a new power plan. 2013;(April):21.
41. Energy Research Centre. South Africa's proposed nuclear build plan: an analysis of the potential socioeconomic risks. Technical Report. Cape Town; 2015.

Appendix A

Short name	Study	Scenario name	Brief description
IRP 2013 2	IRP 2013	High Nuclear Cost	Investigated impact of higher nuclear costs on energy mix.
WWF 2010 2	WWF - 50% by 2030 (2010)	Alternative	Investigates the impact of pushing for an energy mix with 50% renewables by 2030.
GP ER 2011 3	Greenpeace Energy Revolution 2011	Advanced Energy Revolution	Aims to reduce carbon emissions to 80% below 1990 levels by 2050.
GP ER 2011 2	Greenpeace Energy Revolution 2011	Energy Revolution	Aims to reduce carbon emissions to 50% below 1990 levels by 2050.
GP ER 2009 2	Greenpeace Energy Revolution 2009	Energy Revolution	Aims to reduce carbon emissions to 54% below 1990 levels by 2050.
UCT ERC Nuc 1	UCT ERC Nuclear build plan technical report	Future 1 - Flexible Build Plan	"Best case for nuclear" conditions; high demand, low nuclear costs and higher RE costs, with a flexible build plan.
UCT ERC Nuc 3	UCT ERC Nuclear build plan technical report	Future 2 - Flexible Build Plan	"Worst case for nuclear" conditions; low demand, high nuclear costs and lower RE costs, with a flexible build plan.
UCT ERC Nuc 2	UCT ERC Nuclear build plan technical report	Future 1 - Committed Build Plan	"Best case for nuclear" conditions; high demand, low nuclear costs and higher RE costs, with a committed nuclear build plan.
UCT ERC New 3	UCT ERC New power plan	High Demand, Shale, and Optimistic RE	Explore impact of higher demand, greater local and regional shale gas developments and aggressive RE learning rates.
CSIR 1	CSIR response to IRP	Decarbonized Scenario	Response to IRP2016, part of public participation process. Aims to reduce CO_2 emissions by 90% by 2050.
IRP 2010 2	IRP 2010	Emissions 3 Scenario	Strict CO_2 emissions limits imposed on electricity sector (220 MT/a from 2020 onwards)
UCT ERC Nuc 4	UCT ERC Nuclear build plan technical report	Future 2 - Committed Build Plan	"Worst case for nuclear" conditions; low demand, high nuclear costs and lower RE costs, with a committed nuclear build plan.
UCT ERC New 1	UCT ERC New power plan	New Power Plan	Aims to provide a new power plan as an alternative to the IRP 2013, with updated input assumptions.
IRP 2013 1	IRP 2013	Base Case Scenario	Aims to provide a base case scenario with lowest system costs for national planning.
GP ER 2009 1	Greenpeace Energy Revolution 2009	Reference Scenario	Reference scenario for comparing 50% RE against. Based on latest (2007) Eskom builds plans and energy sector conditions.
WWF 2010 1	WWF - 50% by 2030 (2010)	Reference Scenario	Reference scenario for comparing 50% RE against. Based on latest (2007) Eskom builds plans and energy sector conditions.
GP ER 2011 1	Greenpeace Energy Revolution 2011	Reference Scenario	Reference scenario for comparing 50% RE against. Based on the IRP2010 Policy Adjusted scenario.
UCT ERC New 2	UCT ERC New power plan	Cheaper Nuclear	Explores the impact of lower nuclear costs on the energy mix.
IRP2010 1	IRP 2010	Policy Adjusted Scenario	Serves as the basis for current ministerial determinations and national build plans.
IRP 2016 1	IRP 2016	Base Case Scenario	The proposed update to IRP 2010, also to serve as the basis for new ministerial determinations and national build plans.
CSIR 2	CSIR response to IRP	Least cost with expected costs	Response to IRP2016, part of public participation process. Updated cost input parameters for RETs and is cost-optimal.
CSIR 3	CSIR response to IRP	Base Case with low demand	Response to IRP2016, part of public participation process. Same input parameters as IRP2016, with lower demand.
IRP 2013 3	IRP 20133	Carbon Tax Scenario	Investigate the impact of removing CO2 limits and imposing a stricter carbon tax on the electricity sector.
IRP 2013 4	IRP 2013	Big Gas Scenario	Investigate the impact of greater local and regional gas developments on energy mix.
IRP 2010 3	IRP 2010	Low Growth Scenario	Investigates appropriate energy mix associated with lower economic growth.
IRP 2010 4	IRP 2010	Peak Oil Scenario	Investigates appropriate energy mix associated higher coal and gas costs.