MASTER'S THESIS

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Development of a Renewable Energy Power Supply Outlook 2015 for the Republic of South Africa

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FACHHOCHSCHULE TECHNIKUM WIEN

Declaration

I, Sebastian GIGLMAYR, hereby declare on oath that this master's thesis is a presentation of my original research work and that it has not been submitted anywhere for any award. Wherever external contribution and other sources were implied, every attempt was made to emphasise this clearly by indicating references to the literature.

Place, Date | Signature

Abstract

South Africa's electricity supply is characterised by outdated structures that cannot meet contemporary requirements. The distribution is centralised and mostly unidirectional, while the generation is based on the use of such fossil fuels as coal. A current substantial backlog of electricity supply occurred, since the demand rose faster than the generation capacities increased. During the last decade, the government has implemented a variety of mid- and long-term programmes to enable further capacities, and to ensure onward sustainable development. A meaningful part thereof is a subsidy mechanism for large-scale and grid-connected renewable energy systems to promote an increase of installed capacities by independent power producers.

The framework of the thesis includes a literature research to highlight the current challenges and to justify the need for a sufficient forecast method regarding an increased amount of renewable energies. A 2015 annual time series simulation of every approved project until mid-2013 is undertaken, assuming that every plant will be on grid by the end of 2014. The model's methodology is split into four different approaches regarding four different technologies, including solar photovoltaic, wind, hydropower, and concentrated solar power. Hourly based annual load behaviour results throughout in the achievement of a prospective amount of electricity contribution. As a consequence, knowledge about system loads behaviour, such as evaluations regarding high-demand scenarios and fluctuation bandwidths, is developed. The result contains a variety of information about the prospective supply, which might serve for trendsetting decision-making.

Keywords

Renewable energy in South Africa, policy framework, forecast, time series simulation

Kurzfassung

Die Infrastruktur zur Stromerzeugung bzw. zur Verteilung in Südafrika ist veraltet und wird die zukünftigen Anforderungen nicht erfüllen können. Das System ist stark zentralisiert, unflexibel und hat einen außergewöhnlich hohen Anteil an fossilen Energieträgern. Angesichts des stetig anwachsenden Verbrauchs und des Mangels an zusätzlichen Versorgungskapazitäten, erhöht sich die Wahrscheinlichkeit einer Unterversorgung. Um den zukünftigen Aufgaben gerecht werden zu können, wurden innerhalb der letzten Jahre lang- und mittelfristige Programme geschaffen, die unter Anderem dazu dienen, erneuerbare Energieträger zu unterstützen.

Die Arbeit beinhaltet eine ausführliche Literaturrecherche, welche aktuelle Problematiken im Bereich der Stromerzeugung bzw. Verteilung aufzeigt und begründet. Das Hauptaugenmerk gilt jedoch der Erstellung einer Zukunftsprognose für 2015 in welcher alle genehmigten und geförderten Projekte mit einer Anschlussleistung größer 1MW bis 2013 berücksichtigt werden. Ein auf Zeitserien basierendes Modell beinhaltet vier verschiedene Vorgehensweisen, entsprechend der eingesetzten Technologien.

Das Resultat umfasst eine jährliche Menge an eingespeistem Strom, das Lastverhalten der Kraftwerke und eine Bewertung des Beitrags zur Verbrauchsspitzen bzw. Fluktuationseigenschaften um Entscheidungsträgern einen Ausblick der erneuerbaren Stromversorgung zu gewährleisten.

Schlagwörter

Erneuerbare Energien in Südafrika, politische Rahmenbedingungen, Prognose, Zeitseriensimulation

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Acronyms and abbreviations

ANC	African National Congress
CCGT	closed-cycle gas turbine
CF	capacity factor
CORDIS	Community Research and Development Information Service
CPV	concentrated photovoltaic
CR	central receiver
CRSES	Centre for Renewable and Sustainable Energy Studies
CSIR	Council for Scientific and Industrial Research
CSP	concentrated solar power
DEA	Department of Environmental Affairs
DHI	diffuse horizontal irradiance
DME	Department of Minerals and Energy
DNI	direct normal irradiance
DoE	Department of Energy
DR	demand response
DSM	demand-side management
DWA	Department of Water Affairs
EAF	energy availability factor
ECS	energy conservation scheme
EIA	environmental impact assessment
ESKOM	Elektrisiteitsvoorsienings-kommissie (prev. ESCOM Electricity Supply Commission)
GDP	gross domestic product
GHI	global horizontal irradiance
GTI	global tilted irradiance
IEP	Integrated Energy Plan
IPP	independent power producer
IRP	Integrated Resource Plan
ISMO	Independent System and Market Operator
MAE	mean absolute error
MAPE	mean absolute percentage error
ME	mean error
MTPPP	medium-term power purchase programme
MTRM	Medium Term Risk Mitigation
MYPD	Multi-Year Price Determination
NEA	National Energy Act
NERSA	National Energy Regulator of South Africa

NREL	National Renewable Energy Laboratory
OCGT	open-cycle gas turbine
PFMA	Public Finance Management Act
PPA	power purchase agreement
RBS	Revised Balanced Scenario
REBID	Renewable Energy Bid
REFIT	Renewable Energy Feed-In Tariff
REIPPPP	Renewable Energy Independent Power Producer Procurement Programme
RFP	Request for Proposal
RMSE	root mean square error
RoD	Record of Decision
SAM	System Advisor Model
SANEDI	South African National Energy Development Institute
SAPIA	South African Petroleum Industry Association
SAPVIA	South African Photovoltaic Industry Association
SAWEA	South African Wind Energy Association
SBO	Single Buyer Office
SD	standard deviation
SESSA	Sustainable Energy Society of Southern Africa
SO	system operator
SSA	Statistics South Africa
STC	standard test conditions
STERG	Solar Thermal Energy Research Group
SVC	static VAR compensator
SWH	solar water heater
TES	thermal energy storage
UCT	University of Cape Town
WASA	Wind Atlas for South Africa
WaSP	Wind Atlas Analysis and Application Programme
WM	weather mast

1 Description of the objective of the thesis

The objective of the thesis was to develop a plausible supply scenario for every submitted, commercial, grid-connected and approved renewable energy generation project in South Africa until 9 May 2013, once the financial closure of the Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) had taken place. This closure constitutes a proper public landmark for a national implementation of renewable sources, and should result in the grid commissioning of all participants by the end of 2014.

In terms of the above, a time series simulation was developed containing a consolidation of accurate simulated weather data, a localisation of all related projects, and the technical correlations among them, to compute an estimated annual power output for the subsequent year, 2015.

The result delivers insight into the entire annual countrywide share of renewable energies for 2015, represented by weather data of 2010, as well as by the load behaviour, in certain load cases. The study will make it possible to do more accurate forecasting as soon as all the necessary suppliers are commissioned, and will allow a further road map development to advise policymakers and other representatives, mostly at the national level, to consider decisions regarding the future energy mix. Based on the fact that a variety of renewable energy projects in South Africa are planned, and that some of them are currently in progress, it has become necessary to reflect the prospective situation in detail.

The research question is as follows:

> What will be the supposed annual trend and the summarised amount of renewable energies in South Africa that are fed into the electricity grid by 2015, since policies encourage increased implementation? How will power loads such as PV, CSP, wind power and small scale hydro power contribute to supply stability during full-load demand cases, and what are the characteristics likely to be in terms of generation volatility based on an hourly time series simulation?

2 Relevance of results

South Africa seems to possess an extraordinary amount of energy resources. The primary energy carrier, coal, which is the major fossil resource, is mainly used for national electricity production, for liquefaction and for exportation. Despite the fact that the majority of produced electricity is generated by fossil fuels, the country’s potential of renewable energy sources is vast, whereas solar irradiance and wind offer considerable commercial potential.

Within the last decade, the national approach to renewable energies issues has changed according to rising prices for fossil fuels and the increasing awareness of the their countrywide potential. As a consequence, increasingly more international lenders, funds and other sponsoring bodies have been lured to invest in alternative energy projects (Record Conference 2013). For the purposes of this study, national policy guidelines such as the Integrated Resource Plan 2010 (IRP 2010) were assembled, and incorporated with different lobbies to determine a legal framework and a specific road map for South Africa.

Currently, South Africa sets a high standard with specialised engineering departments such as the Centre for Renewable and Sustainable Energy Studies (CRSES); the Solar Thermal Energy Research Group (STERG); GeoSUN; that of the University of Cape Town (UCT); and Eskom. Despite said departments being focused on conducting scientific research in the fields of concentrated solar power (CSP), deterministic model mapping, and sustainable development, among others, a backlog exists in satisfying the demand for reliable forecasting of the total renewable energy contribution that is to be made within the next decade. Although previously released forecasts and guidelines take capacities into account, they do not take into consideration the temporal and technology-dependent energy distribution of renewable generation.

The purpose of the current thesis is to address this problem, and to overcome the present backlog.

Hence, the CRSES and UCT will cooperate in developing a proper, more explicit study, which will be based on the results of this thesis, which, in addition, specifies the prospective renewable energy contribution to be made in South Africa.

3 Methodology

The methodology of this study entailed the adoption of a comprehensive and wide-ranging approach. The present chapter describes the scientific character of the thesis, which required specific methods of research and legal proceedings. The approach was based on the bottom-up principle of obtaining results from a large quantity of information. The research was undertaken in chronological order to enable entire conformability with the set requirements.

This chapter outlines the objectives, the data assessments, the quality assurance concerns, and the model development in this study.

3.1 Definition of the objective of the project

The objective of the project was predefined by the CRSES Department, and it was derived according to the present institutional requirements. The structure of the project was discussed at the initial meeting. The objective of said Department was to advise the policymakers concerned through providing them with reliable information on which to base their decisions. The intended purpose of the thesis was established and well-defined, with the evolution of the framework being considered an integral part of the consistent progress made in terms of the project, which strongly depended on the availability of the appropriate data.

3.2 Information procurement

The first step in the procedure comprised data mining with regard to the surrounding conditions to substantiate the present need for the analysis. The main sources of required information were scientific papers, the publications of linked and relevant departments, , and the contents of scientific databases.

The following scientific databases were considered to obtain some of the required information:

- The Library and Information Service of Stellenbosch University
- The Community Research and Development Information Service (CORDIS)
- The Austrian Library Composite of the Österreichischer Bibliothekenverbund GmbH
- The library of the FH Technikum Wien/ the University of Applied Science Vienna
- The library of the TU Vienna
- The library of Science Direct

With regard to expenditure on the project, the layout was mainly on desk and literature research, with some hard copy literature but mostly online media being utilised. For further information, interviews, phone calls, electronic mail, and attendance at lectures and scientific congresses, which allowed for networking with fellow professionals, were used.

3.3 Quality assurance

The approach that was adopted to ensure the quality of work is stated as follows:

- Mutual control existed between the author, his supervisors, and the project team, with the conclusions, calculations, assumptions, and adoptions being validated.
- The reliability of the data that were obtained was compared with that of data that were obtained from other sources.
- In order to ensure the reliability of the data source, information was obtained only from government, institutional and scientific sources.

3.4 Implementation of present resources

This section deals with the utilisation of available auxiliary means, such as simulation tools and information-providing applications, which contributed to the completion of the analysis.

Simulation programmes

Beside the development of a particular model, several tools were used for simulation and verification purposes. The tools reflect the connection between the raw weather data and the corresponding power loads. The following applications were used:

- The basic PV model by P. Gauché (2011), which is a time series simulation for solar PV issues
- The System Advisor Model (SAM), by the National Renewable Energy Laboratory (NREL 2005), for CSP and solar PV applications

Data procurement

The following sources were applied to access the necessary records of data for simulation and/or validation purposes:

- The Wind Atlas of South Africa (WASA), for the weather mast (WM) measurements
- The GeoModel Solar Ltd (SolarGIS)
- The South African Department of Water Affairs (DWA 2013)

All utilised data were validated in terms of the origin, the reliability, the error margin, and the existing evaluations of the data provided by the other scientists. Cases of irregularity were considered and clearly identified, so as to be able to evaluate the probability of recurrence of an error.

3.5 Development of the model

The quasistatic nature of the model was obtained by using basic physical correlations and external time series simulated data records from specific project sites.

The model's methodology was composed of different approaches for each modelling technology used, depending on the availability of existing simulation programmes. If an already developed tool was consulted, it was necessarily validated. Such validation contains analogies to other simulation approaches, a comparison to the expectations of the project developers, and a plausibility check by project members. For a single developed method, such as the wind power analysis, a validation, as described above, had to be achieved.

For simulation concerns, certain boundary conditions and assumptions had to be met. Each assumption was clearly specified and technically justified to ensure transparency and clarity. Furthermore, every uncertainty and possibility of error was stated.

The simulation approach for every technology (whether wind, solar photovoltaic (PV), CSP, or hydropower) is described in detail in each corresponding chapter.

4 Introduction to issues relating to electricity supply and demand

The South African economy strongly depends on the consumption of fossil fuels such as coal as the primary energy source countrywide. Although other renewable potential, such as that which is possessed by hydropower and solar irradiance, as well as by wind power, is vast, it is, as yet, almost untapped.

The present and prospective countrywide power supply is subject to the following three main constraints:

- **Lack of reliability**: One of the key roles of a reliable power supply is to ensure the maintenance of a reserve margin that allows for periods of both planned and unplanned unavailability, such as for maintenance and for outages. The reserve margin in South Africa declined from 25% in 2002 to 10% in 2008, as a result of the robust economic growth experienced, as well as a coincidental missed strategy to align the demand, thus drastically limiting the scope of action (RSA Government 2008, p. 4).
- **Lack of sustainability**: In 2007, 92% of the electricity generation made use of coal, which led to extraordinary CO_2 equivalent (eqt.) emissions. In 2012, Eskom was the second highest CO_2-emitting power utility company worldwide. The average CO_2 eqt of South Africa is 1.015tCO_2 – eqt/MWh_{el} (Letete, M. Guma, 2009), whereas the mean European CO_2 eqt is 0.578tCO_2 – eqt/MWh_{el}, which is almost 45% less than the former (SEAP 2006, p. 2). The following table compares the four highest CO_2-/MWh_{el}-emitting power companies for 2009.

Table 1: The premier CO_2-emitting power utilities worldwide (Gross, 2012, p. 5)

World's biggest electricity utilities	Annual CO_2 emissions [Mt]	Energy [TWh]	CO_2 emissions [Mt/TWh]
Huaneng Power Intl (CN)	285	260	1.1
Eskom (SA)	**210 (211[1])**	**208**	**1.01**
China Huadian Group (CN)	207	195	1.06
Southern Company (USA)	206	279	0.74

The *Southern Co.* share between CO_2 emissions and cumulated energy is almost 27% less than is Eskom's ratio, which implies an inferior efficiency of resource management, causing higher emissions.

- **Power losses via transmission**: Due to the fact that the major coal deposits are located in the north of South Africa (in Mpumalanga province), the power

[1] (Letete, M. Guma 2009)

generation is situated in this region. A transmission grid connects the north of the country to the south. The vast distances involved resulted in losses of 9.5% in 2010 (World Bank 2013). Scientists such as Prof. Ernst Uken (2013) estimate the actual amount of loss to be as much as 15%.

The probability of a feasible prospective scenario, with a high integrity of renewable sources, requires an increase in supply capacity, and a concurrent specific decrease in demand through improvements in efficiency, and other methods.

Notice should be taken that the current thesis refers to the commitment of a renewable supply only.

4.1 Local renewable energy resource analysis

Establishing the potential of renewable sources in South Africa is focused on wind energy and solar irradiance. Whereas the highest measured values for solar irradiation are in the north-western part of the country, the wind potential mainly exists on the coastline, which stretches from the Atlantic to the Indian Ocean.

Other renewable resources, such as biomass and ocean energy, do not play a decisive role. Until 2006, 10 river power stations were built up with an annual yield of 1.3% to the gross sent out electricity and an installed capacity of 668MW (Nersa 2006).

4.1.1 Solar irradiance

The solar irradiance is mostly represented by the global horizontal irradiance (GHI) and/or the direct normal irradiance (DNI).

- The **GHI** ($kWh/m^2/a$ or W/m^2) is the total amount of irradiation, consisting of a direct (beam) and a diffuse (scattered) proportion that is relayed onto a particular horizontal area. The inclined GHI (global tilted irradiance – GTI) is primarily used for power estimation purposes related to a solar PV or a solar water heater (SWH) with a fixed inclined angle.
- The **DNI** value ($kWh/m^2/a$ or W/m^2) represents the direct, perpendicular on a predefined surface, beaming component of the sun only and is measured by tracking the measuring instrument. Diffuse irradiation is totally excluded from such a calculation. The DNI is utilised for CSP and concentrated photovoltaic (CPV) purposes.

In South Africa, the ceiling value for GHI can be as high as 2 300 $kWh/m^2/a$, whereas the DNI value attains a maximum of 2 900 $kWh/m^2/a$, which is significantly higher than it is in other regions worldwide. The solar GHI and the DNI data for the country, which are well documented, are available from GeoSUN Africa, SolarGIS. Figure 2 on p. 11 depicts the national differences between DNI and GHI.

4.1.2 Wind power

The South African wind potential is situated along the coastline that is stretched along the southern and north-east regions. A partnership between, inter alia, the South African National Energy Development Institute (SANEDI), the South African Weather Services (SAWS), UCT and the Risø Danish Research Institute (DTU), which was financially supported by a consortium, led by the Department of Energy (DoE), developed a numerical wind atlas to enable the planning of large-scale exploitation of wind power in South Africa. The result is an extensive Wind Atlas of South Africa (WASA), which offers specified wind data for all regions in the country. The wind model is based on a measured time series of wind speeds, direction and terrain topography (in terms of elevation, roughness and obstacles), and which illustrates the countrywide wind speeds.

Figure 1 below consists of a map of generalised annual mean wind speeds (over a period of 30 years) in an area that is 100m above ground level, with flat terrain and a 3cm roughness class. The series of numbers (1–10) featured represents the installed WMs.

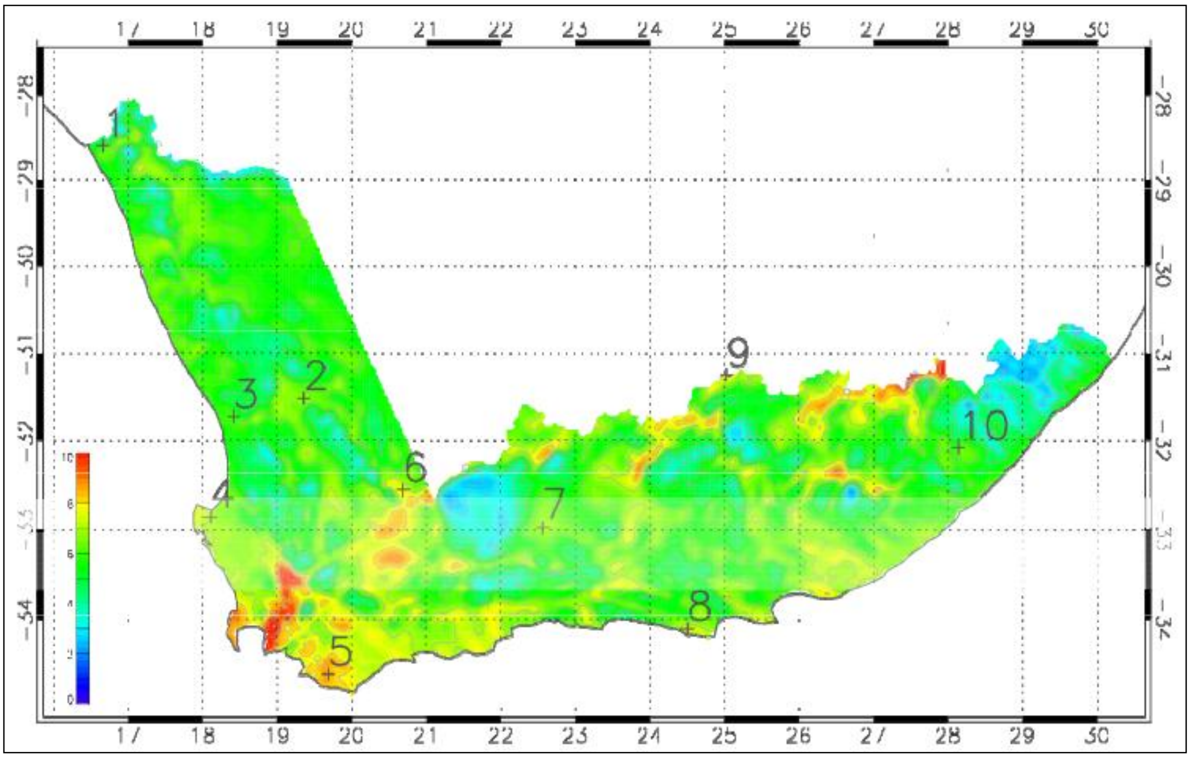


Figure 1: Wind Atlas of South Africa (WASA 2012, p. 4)

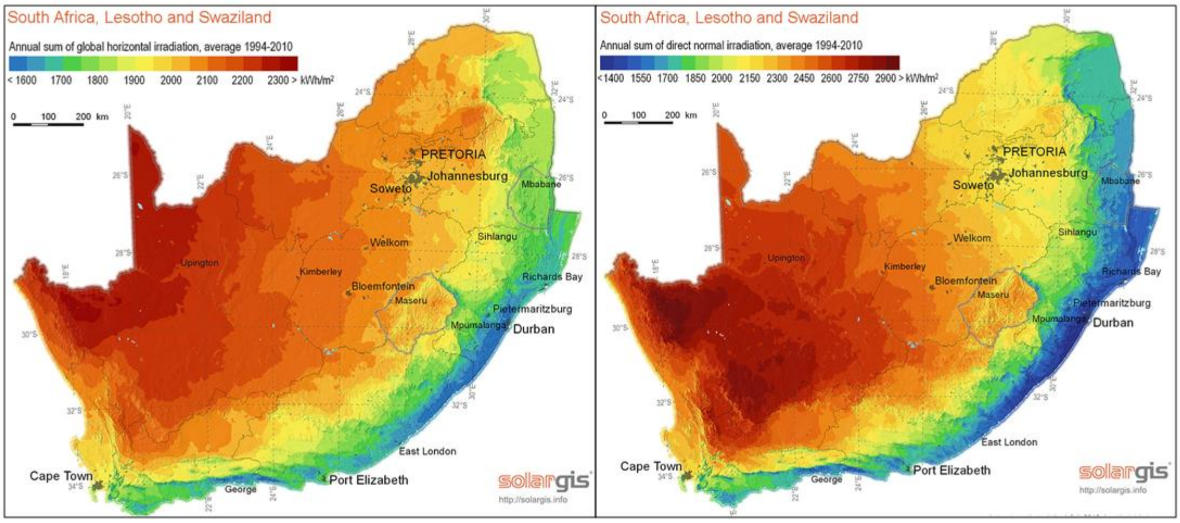


Figure 2: South African map for GHI, left and DNI, right (GeoSun Africa 2008)

4.2 National energy consumption and allocation

Most of the nationwide primary energy consumption-related publications by governmental sources are both inconsistent and no longer up to date.

The total determined primary energy supply in 2006 by the Energy Department of South Africa was 5 644 436TJ (DoE 2009, p. 4 sqq.), whereas 65.9% of such supply was provided by the use of coal, followed by crude oil (21.5%), and such renewable sources as biomass and natural processes (7.6%). In contrast to the Energy Department of South Africa, Statistics South Africa (SSA 2012) estimates a total, since 2002, decreasing primary energy supply for 2006 of 7 742 673 TJ, excluding the accumulation of imported energy. Hence, energy is a substantial key driver of the South African economy.

The three major final energy consumers in the country are the industry, which consumes about 40%, followed by the transportation sector, and the residential sector, as is illustrated in Annexure I, Part A, Figure 22, p. 72. Further information, such as a digest of the national coal and petrol allocation, is specified in Annexure I, Part.

4.3 Electricity supply and demand

An overview of the present lack of electricity supply in South Africa is supplied below, followed by a description of the prospective development of such a supply in the country. The following additional information is elaborated on in Annexure I, Part B:

- The history of supply and demand
- The key drivers of electricity growth rates
- The development of electricity intensity

4.3.1 National electricity supply

Electricity generation in South Africa is restrained by the supply of coal-fired power stations. While 4.2% of the annual supply is generated by nuclear power, and 1.3% is generated from hydropower applications, 93.2% was generated through coal in 2006, compared to the 40% share contributed by coal worldwide (Nersa 2006, p. 11).

The electricity supply is dominated by the governmental electricity utility, Eskom, a limited range of municipal power purchasers, and some IPPs. The Electricity Supply Statistics for 2006 that were released by the National Energy Regulator of South Africa (NERSA) exhibit the results that are shown in Table 2 below.

Table 2: List of power capacities (Nersa 2006, p. 42)

		Total	Eskom	Municipalitie s	IPP
Operational power stations [-]		**49**	24	16	9
Operational (net) capacity [GW]		**43.8 (39.3)**	40.5 (37.7)	1.85 (0.5)	1.45 (1)
Thereof	Coal-fired	**39.0**	36.3	1.3	1.3
	Nuclear	**1.8**	1.8		
	Hydro/Pump storage	**2.25**	2.06	0.19	0.003
	Gas turbines	**0.67**	0.34	0.33	
Stations under construction [GW]		**11.9**	11.9		0.005

The location of installed capacities correlates with the resource's occurrence and with the supplying of security interests. The strong relation that exists between the coal resources and the coal power plants in the north is apparent. Several open-cycle gas turbines (OCGTs), which form the peak load purchasers, and the Koeberg nuclear power plant, which provides the base load, are situated in the south, so as to ensure the maintenance of a reliable supply of energy during transmission grid shortages. Some existing hydropower plants are based in the Eastern Cape province.

The publicly available electricity supply data are, at present, inconsistent and differ among sources. Electricity supply statistics were last released by NERSA in 2006. The most continuous and comprehensive supply of data is provided by SSA, which publishes a monthly preliminary report on the amount of generated electricity, as well as on the amount that is available for distribution. The total amount of distributed energy in 2012, according to SSA, was 234TWh. The period between 2007 and 2009 was characterised by a significant decrease in energy supply, which can primarily be blamed on the worldwide economic crisis that was experienced at the time. The electricity trend since 2001, as reported on by SSA, NERSA and the World Bank is illustrated in Annexure I, Part B, Figure 25, p. 78.

The power supply system load factor determines the share between the average load over the set period of time (i.e. a year) and the maximum load during the specified time period as being 68.9%. The load factor ought to be as high as possible to achieve a worthwhile degree of capacity utilisation for the base-load plants. The average load factor for coal (in terms of Eskom power generation) is 73.3%, with a variation of +15% and −57%, which implies a high fault rate, which was caused by maintenance, defects, and other related factors (Nersa 2006, p. 45).

4.3.2 Sector-specific electricity demand

In 2006, the entire South African demand was 205TWh, with a strong emphasis on the primary and secondary sector (of which 60% was industry), including manufacturing, mining and agriculture. The gap between the amount of electricity available for the distribution of 233TWh, and the amount of energy sold, with an end use of 205TWh, constituted the distribution losses that are outlined in Chapter 4.4.
Although approximately 94% of the customers were situated in the domestic sector, their accurate consumption was only 19%. The mean specific retail price for electricity acquisition in 2006 was 37.5R/kWh for domestic consumers, while the average price for the mining industry was only 16.9R/kWh (Nersa 2006, p. 60). The sector-specific electricity demand is described in detail in Annexure I, Part B, Figure 26, p. 78.

4.3.3 Present lack of supply

In South Africa, since the reserve margin steadily decreases at a significant rate, the stability of the power system is exposed to a relatively high risk of outages. The demand for power has increased by 230% since 1987, while the power supply has increased by only190%. During the last decade, the reserve margin has steadily declined. As a result, the number of low-frequency incidents that have occurred during a period of under supply has increased from twice in 2002 to 15 times in 2006, and the transmission system interruption time over a minute has significantly amplified as well (Nersa 2006, p. 37).

Between 2006 and 2009, the outage duration curve of Eskom steadily increased, entailing a decreasing energy availability factor (EAF). More than 8000MW of capacity was unavailable for about 700 h per year. The related trigger was the bad coal quality, which resulted in a need for high rates of maintenance (MTRM 2010, p. 4).

The various causes of the incipient energy crisis are characterised in Annexure 1, Part B.

The DoE launched an initiative named the Medium Term Risk Mitigation Project (MTRM) in the context of the IRP 2010 (see section 5.1), when South Africa was seen to be facing electricity constraints in terms of the security of supply. While the IRP addresses the long-term outlook for the generation mix in South Africa, the MTRM's focus is on identifying supply and demand options for addressing the short-term risk for outages from 2011 to 2016 (IRP 2011, p. 60). The report forecasts a high likelihood of occurring energy shortfalls until 2015, as long as the new coal power plants, Medupi and Kusile (with a gradual commissioning of 9.5GW from 2015 to 2018), are not yet on stream. The balance between supply and demand was bound to be tight between 2011 and 2012, with a gap for the mitigation of 15TWh. The MTRM involves all stakeholders, such as the government, business, labour, civil society, Eskom, and others, and proposes options for closing the gap, as shown in Annexure 1, Part B.

4.3.4 Prospective development

A prospective South African electricity supply scenario was calculated in 2010, in line with the assessment procedure of the IRP 2010 that entailed the setting of major boundary conditions for the taking of further steps (DoE 2010). In terms of accuracy, two independent forecasts were developed, which are outlined in Annexure 1, Part B.

The forecast's trends drift apart until 2034 is caused by many uncertain assumptions that still essentially had to be set at the time of publication. The simulation was done between 2008 and 2010, following on shortly from the economic crisis, and the coincidental decrease in demand (according to Figure 25, p. 78). At the time, the deviation concerned was not conceivable, accounting for the observed gap between recent demand and forecast that was reflected from 2010 to 2012.

In terms of the current thesis, the total accurate energy demand for 2015 is expected to be between 275TWh and 315TWh, as depicted in Annexure 1, Part B, Figure 28, p. 81. Pursuant to Eskom's contribution, the power demand for 2015 should be approximately 47GW (Eskom 2013).

4.4 Power distribution

The power grid is subdivided into transmission and distribution applications. The urban areas are well tapped, whereas the rural regions are commonly used for power transmission applications, as is illustrated in Annexure I, Part C, Figure 29, p. 82. The image illustrates the South African high-voltage power grid integration stretching from the north to the south.

In 2006, the amount of electricity generated was 233TWh, whereas the end usage was 205TWh. Taking both imports and exports into account, a system loss of 10.9% was found to have occurred. Figure 3 below is a Sankey diagram that depicts the energy flow from generation to consumption in TWh, rounded.

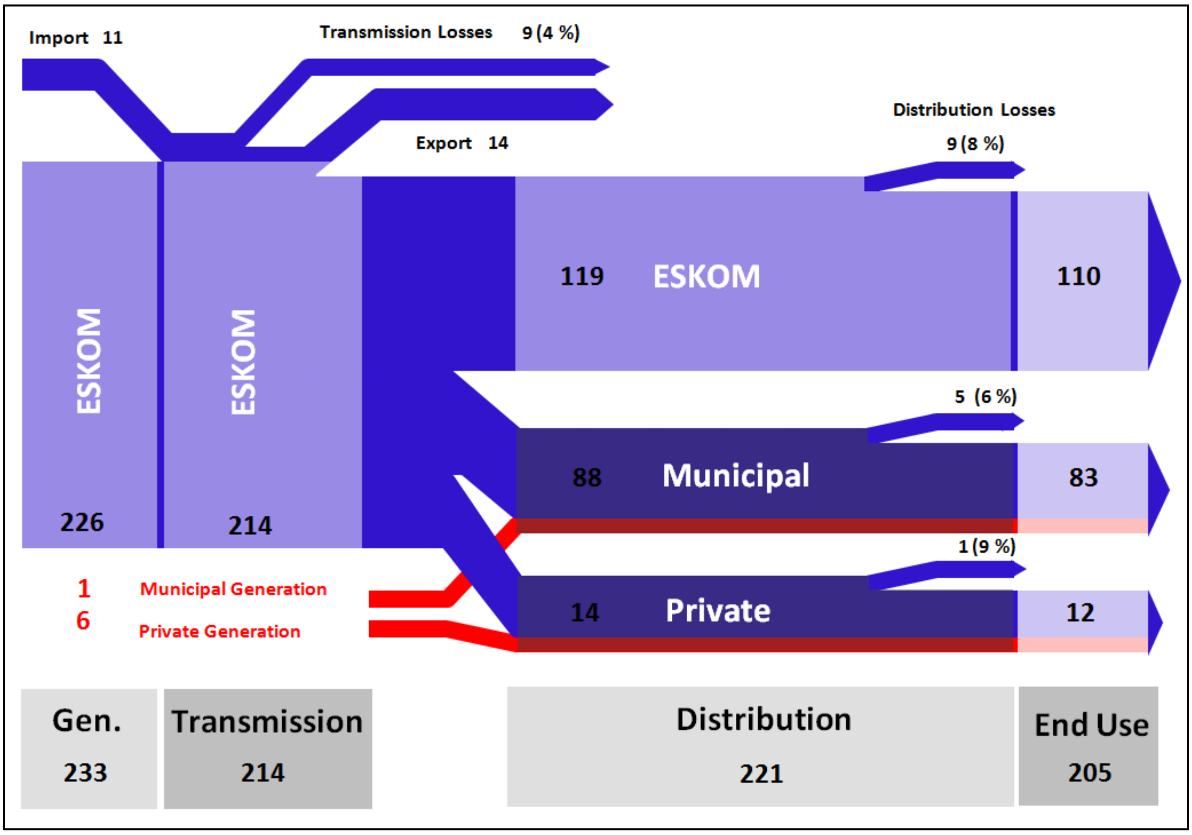


Figure 3: Transmission and distribution network; units in TWh (Nersa 2006, p. 54)

Almost 97% of generation and 100% of electricity transmission were achieved by Eskom, with the distribution being partly managed by the municipalities and the private distributors.

The South African electricity grid faces a particular challenge in having to ensure a reliable prospective supply. As long as the power consumption in the southern regions increases, and the supply is still centrally provided, the distribution distances and the imbalance in power supply will increase, which might result in power failures. Further details about the future expectations of transmission, respectively via distribution lines and the power grid, are noted in Annexure I, Part C.

4.5 Chapter summary

This introduction to issues relating to electricity supply and demand has elaborated on the essential background information to justify an increased implementation of renewable energy sources. This chapter summarises and highlights the significant impacts that were described in the previous sections:

- Although the potential for sustainable energy generation countrywide is vast, it is almost unexploited.

- South Africa's electricity generation strongly depends on the supply of such fossil fuels as coal. Even though the resource is depleted nationally, and is competitively available on the international market, its cost has substantially increased over the last decade.
- The specific CO_2 emissions for electricity generation in South Africa are of the highest worldwide, which implies a lack of efficiency and the likelihood of much environmental pollution.
- The electricity distribution is accomplished centrally. The power is transmitted from the north to the south of the country, over a long distance, which results in substantial transmission/distribution losses, and a high vulnerability to failure.
- The electricity demand has increased faster than the generation availability has done in the past. As a consequence, new capacities have become indispensable for meeting the demand, and for increasing the reserve margin. Eskom, the only national electricity utility, will be incapable of achieving the requirements on its own.
- Within the last few years, the occurrence of outages in South Africa has increased. Scientists further expect capacity shortages for the next decade. Therefore, preventive measures to provide further capacity are required.

Based on the mentioned difficulties, policy frameworks were set up in line with the intention to solve the existing problems. The most influential frameworks are discussed in the following chapter in terms of renewable generation.

5 Policy guidelines and legal framework

Within the last decade, the South African government has pursued a policy that provides legal frameworks to regulate a cumulative implementation of large-scale (>5MW$_{el}$), grid-connected renewable energy sources, due to the fact that the electricity demand of the country is increasing beyond its generation capacity (see subsection 4.3.3). The government has realised that the private sector should be given the opportunity to take part in the process of ensuring energy security. The government has announced its plans to procure renewable energy from the private sector, in order to relieve the current energy limitations that it is experiencing. The road map is divided into such long-term guidelines as the IRP 2010 until 2030, and such short-term policies as the REIPPPP, to achieve objectives in the short term. The leading stakeholders are the DoE, the National Energy Regulator (NERSA), Eskom and all involved project developers (IPP).

The policy guidelines require a quantity of installed capacity to be generated by means of renewable resources. The current thesis explores a forecast demonstrating the results of decisions that are taken on occasion, by displaying the ensuing amount of energy there from.

5.1 IRP for electricity – IRP 2010

The IRP 2010, initiated by the DoE, lays out the proposed generation new-build fleet for South Africa between 2010 and 2030. Said IRP lays out a strategy for determining how the future demand can be met to ensure sustainable development, considering the given technical, economic and social constraints. It constitutes a preliminary framework for promotional programmes supporting IPPs, which are part works simulation. The objective of the IRP 2010 is to develop a sustainable electricity investment strategy for the generation of capacity and for the transmission of infrastructure for South Africa for the future (DoE 2009a). The IRP content covers demand-side management (DSM) and pricing concerns, and proposes further capacities, such as those which are available from sustainable sources. The process takes into consideration political interests, technical expertise, and public participation rounds to ensure a high level of agreement is obtained among all the participants.

The content of the IRP is based on a number of legal references, such as on White Papers, strategy plans, Acts, and other sources that are elaborated on in Annexure II.

Final processing

To ensure the involvement of all stakeholders, two public hearings were held to modify the draft versions. The developer and lobbyists in all sectors participated to represent their interests. Related to the purposes of renewable energy, the South African Wind Energy

Association (SAWEA), the Sustainable Energy Society of Southern Africa (SESSA), the South African Photovoltaic Industry Association (SAPVIA), and other concerned bodies took an active part in the hearings.

The resulting Policy-Adjusted IRP was recommended for adoption by the Cabinet, and for subsequent promulgation as the final IRP 2010 (IRP 2011, p. 6). Table 3 below reflects the formation of the paper.

Table 3: Final development of the IRP 2010 (IRP 2011, p. 6 sqq.)

Timeline	Version	Content
Sept. 2009	IRP 2009	Preliminary Report
June 2010	IRP 2010	Adapted – draft version
–	First round of participation	Public hearings held countrywide, with all parties focused on input parameter
Oct. 2010	RBS – Revised Balanced Scenario	Scenario based on a cost-optimal solution for new build options, in accordance with qualitative measures (job creation, etc.)
Nov./Dec.2010	Second round of participation	Public hearings for interested parties and individuals to submit written comments
Mar. 2011	Policy-Adjusted IRP (final IRP 2010)	Disaggregation of renewable energy technologies (PV, CSP, wind); inclusion of learning rates; adjustment of investment costs for nuclear units

5.1.1 IRP 2010 – content

The IRP 2010 is a living plan that has to be revised and updated at least biennially, in line with changing circumstances, by the DoE. The input yield resulting from public participation was embedded in the multi-criteria decision-making process that took place in the form of the government’s represented working groups to ensure the representation of all relevant interests. The first iteration, which resulted in the Revised Balanced Scenario (RBS), implied a backlog for short-time capacities until 2013. A second round of public participation emphasised the need to reduce carbon emissions by increasing the use of renewable energy sources, and the implementation of efficiency measures.

The final IRP 2010 adjustment considered the re-evaluation of renewable sources, learning rates and a disaggregation of previous renewable grouping into constituent technologies, such as wind, CSP and solar PV, were included to allow for the establishment of specific subsidy mechanisms. Particularly the inclusion of learning rates (implicating a rising competitiveness) caused an increase in the number of regenerative sources considered during the re-evaluation. In addition, the nuclear costs were increased by 40%, which constituted a correlative and considerable disadvantage.

The resolved new capacities were recommended for firm commitment for a certain length of time (in the case of wind and PV until 2015, and in the case of CSP 2016) to quell concerns regarding security of supply, which further indicated the need for the Renewable Energy Bid (REBID) Programme. The REBID succeeded from the Renewable Energy Feed-In Tariff (REFIT), as is specified in section 5.2.

In addition, firm commitments were made regarding the installation of coal fluidised-bed combustion, nuclear power, OCGT / closed-cycle gas turbine (CCGT) plants, and others were decided upon. The IRP 2010 tentatively anticipates final commitments for prospective IRP iteration processes for unit 2030 as well.

The formal results of the policy-adjusted IRP imply a total energy consumption of 454TWh by the end of 2030, which correlates with the system operator (SO) modified scenario (see the trend in Figure 28, p. 81). The prospective share of the annual amount of generated electricity in 2030 is expected to be as follows:

- 9% of renewable energies (excluding large-scale hydropower)
- 65% generation through coal (90% in 2010)
- 20% of nuclear power
- 5% large-scale hydropower and 1% CCGT

The capacity contribution is split up in an entirely different way. Besides the existing fleet and the already committed power plants, the IRP 2010 anticipates the following new build capacity options:

Table 4: Policy-adjusted IRP – intended capacities (IRP 2011, p. 7)

		New capacity [GW]	Committed capacity [GW]
Renewable resources		17.8 (42%)	1
Thereof	**Wind power**	8.4	0.8
	Solar PV	8.4	–
	CSP	1	0.2
Nuclear		9.6 (23%)	
Coal		6.3 (15%)	10
Others (CCGT/OCGT, imported hydropower)		8.9 (20%)	1
Total		**42.6**	**13**

The final IRP suggests a replacement of nuclear generation by means of renewable capacities if the nuclear scheme cannot be met. As a consequence, an extensive range of prospective capacities (9.6 GW) might be disengaged (IRP 2011, p. 10).

In addition, the IRP 2010 estimates that the committed supply capacities until 2020 will be as follows:

- A ‘return to service capacity’ for Eskom: ~1 500MW coal-fired
- The DoE’s OCGT programme: 1 020MW
- The new coal plants Medupi and Kusile: ~8 700MW
- Cogeneration and own build, announced in terms of Eskom’s medium-term power purchase programme (MTPPP): ~390MW
- Assumed renewable generation, facilitated by REFIT: 1 025MW
- Pump storage: ~1 300MW and Eskom’s Sere wind farm: 100MW

The IRP forecasts a decrease in specific CO_2 emissions from 912g/kWh to 600g/kWh, which implies a reduction of 34%. In terms of the IRP, nuclear energy is considered emission-free. The share of renewable generation, including hydropower (5%), is expected to be 14%.

5.1.2 The Medium-Term Risk Mitigation Plan

The Medium-Term Risk Mitigation (MTRM) Plan for Electricity 2010 to 2016, which was published in 2011, forms an integral part of the IRP 2010. It is a medium-term national plan that is intended to avoid urgent predicted outages until 2016, by assessing options to mitigate the risk. The MTRM developers (the government, the business partner, The National Economic Development and Labour Council, and Eskom) emphasise that rolling blackouts are anticipated unless extraordinary steps are taken to accelerate the realisation of non-Eskom generation and such energy-efficiency projects as DSM.

The key risks that might lead to a power shortage are summarised below (MTRM 2010, p. 2):

- A missed EAF of at least 85% by Eskom’s plant fleet
- Delays in the new coal power plants Medupi and Kusile
- The lack of appropriate procedures related to enabling policy, regulatory instruments, bureaucratic red tape, and other issues

The mitigation plan earmarks a legal framework for IPPs as well. Such a non-conflicting entity as the Independent System and Market Operator (ISMO) was proposed to mitigate the conflicting interests between Eskom and the IPPs. Up until the current moment, Eskom still represented the single electricity buyer, and the only contracting party.

In terms of the evaluation of the different scenarios by the MTRM, a total shortfall of 42GWh is likely to occur between 2011 and 2016. To alleviate the short-term constraints, an additional implemented risk mitigation scheme, allowing for a further 3 500MW, has been scheduled, even though a supply gap will remain from 2012 to 2013.

The risk mitigation scheme includes such enterprises as:

- Demand market participation (DMP)
- DSM
- IPP
- Increasing Eskom's existing generator fleet performance
- The Energy Conservation Scheme (ECS) – see subsection 4.3.3

The remaining gap will be addressed through a mandatory ECS that limits the amount of energy that a consumer uses in a month before a penalty rate is charged. This method is only required as a last step prior to load-shedding.

The MTRM suggested that the contribution of IPPs, with a renewable capacity of 1 025MW, be brought into operation from 2012 onwards. Therefore, the Multi-Year Price Determination (MYPD Application No. 2) might approve funds for tendering the capacity at REFIT tariffs (MTRM 2010, p. 11 sqq.).

5.2 The Renewable Energy Feed-In Tariffs (REFIT) programme

Based on the Electricity Regulation Act 4 of 2006, which is hereinafter referred to as the 'Electricity Regulation Act' (DoE 2011), the White Paper on Renewable Energies (2003a), and the above-mentioned sources, the National Energy Regulator (NERSA) has a mandate to set electricity tariffs (in accordance with section 15, ERA, 2006).

Accordingly, NERSA developed such an appropriate market mechanism as the REFIT to stimulate the implementation of renewable generation, in order to achieve the aspiration set out in the White Paper on Renewable Energies 2003 of the supply of 10 000GWh by 2013 which has not been achieved by now. The tariffs guarantee certain prices for electricity that cover the cost of generation, and that should attract developers to invest in the scheme. The tariffs and some qualifying technologies were coincidentally adapted year by year alongside the development of the IRP 2010 to attain 1 025MW in the first step.

The subsequent low demand made by IPPs to utilise feed-in tariffs in 2008 initiated a large increase in the amount of appropriation, and an extension of the contract period from 15 to 20 years. Table 5 below gives insight into the tariff structure (in R/kWh) decided upon.

While the first REFIT draft of 2008 did not specify CSP and excluded solar PV, the 2009 wind power tariff was doubled, and the CSP tariff was tripled. The REFIT 2009 and 2011 included the biomass solid and the biogas funding as well.

Table 5: Trend in REFIT tariffs (Nersa 2008, 2011)

Prices in R/kWh	REFIT 2008	REFIT 2009 – 1	REFIT 2009 – 2	Revised REFIT 2011
Wind	0.65	1.25	1.25	0.94
CSP – not specified	0.60	–	–	–
CSP – trough with storage (6h)	–	2.10	2.10	1.84
CSP – trough without storage	–	–	3.14	1.94
CSP – tower with storage (6h)	–	–	2.31	1.40
Large-scale PV ≥ 1 MW	–	–	3.94	2.31
Small hydropower < 10 MW	0.74	0.94	0.94	0.67
Landfill gas	0.43	0.90	0.90	0.54

Until 2011, two years after the first announcement, no power purchase agreement (PPA) had been made, although the precise enhancement of tariffs implied a high level of interest from investors. Some participants designated the period as being that of a 'false start' (Kernan A. 2013), whereas blamed the failing on the undue amount of bureaucracy and red tape involved (Fritz W. 2012). As a result of the failure to meet expectations, the conveying system was changed to that of an allocation-based bidding process in 2011 since the current Act did not provide the necessary requirements for implementing a REFIT. A media release made on 31 August 2011 by the DoE announced the change from a REFIT to a REBID as follows: "The current legal framework governing the electricity sector in South Africa does not allow REFIT in the guise that had been anticipated; hence a revised procurement process in line with the existing regime had to be developed" (DoE 2011a).

5.3 The REIPPPP

The REBID is a part of the REIPPPP. The procurement documents, which were proclaimed by the DoE, were released on 3 August 2011, with an adjacent bidder's conference being held in September 2011. The DoE determined that the approach did not amount to a replacement of REFIT, but rather to its extension. Still, a REFIT process is aimed at procuring small IPPs to give the local communities an opportunity to initiate their own generation.

The government then admitted that the 10 000GWh target could not be met by 2013, but by 2015. Therefore, the target was expanded. Instead of advertising a certain amount of energy, a capacity of 3 725MW has been announced. As the government expected that it had surpassed the intended 10 000GWh, the allocation was capped to keep up demand during the bidding process. The determination provides a capacity for large-scale renewable projects of 3 625MW, and of 100MW for small-scale projects with a capacity range between 1 and 5MW (DoE 2011g). The total capacity was then used in calling for tenders in certain bidding rounds.

Table 6 below shows all large-scale technology involved, the allocated total capacities, the maximum permitted capacity for each project, and the past bidding window allocations in Megawatts.

Table 6: Overview of the REIPPPP (DoE 2011b, p. 2)

Qualifying technologies	REIPPPP capacities	Max. permitted capacity	Preferred bidder: Window 1	Preferred bidder: Window 2	Allocation still available
Onshore wind	**1 850**	140	634	562	654
CSP	**200**	75	150	50	0
Solar PV	**1 450**	100	631	417	402
Biomass	**12.5**	10	0	0	12.5
Biogas	**12.5**	10	0	0	12.5
Landfill gas	**25**	10	0	0	25
Hydropower	**75**	10	0	14	61
Total	**3 625**	–	**1 415**	**1 043**	**1 167**

Wind and solar PV power dominated the bidding process, since the reclaimable potential of such resources is the greatest. Both technologies take up around 90% of the available capacity. The procurement process additionally offers 200MW for CSP, which constitutes the latest solar technology. Other technologies, such as biomass, biogas, landfill gas and small hydropower applications, suggest insignificant capacities.

The bidding process approach attempts to establish a ceiling price for each technology (R/kWh). Subject to the condition that an IPP submits a bid, it cannot exceed the ceiling price. The first step of the bidding procedure is to submit all necessary requirements by the set submission date. An internal evaluation, with an announcement of preferred bidders, follows, as well as the financial close, with the successive signature of the PPAs involved.

Table 7 below depicts the bidding approach for bidding rounds (R) 1 to 3. R1 and R2 are already closed administratively. The procedure period between the preferred bidder's announcement and the financial close decreased from 12 (during the first round) to 9 months (during R3), since, by that stage, the related legal participating departments were already familiar with the procedure.

Table 7: Bidding approach of the REIPPPP (DoE 2013a)

	R1	R2	R3
Bid submission date	4 Nov. 2011	5 Mar. 2012	19 Aug. 2013
Announcement of preferred bidders	7 Dec. 2011	21 May 2012	29 Oct. 2013
Financial close – signature of PPA	5 Nov. 2012	**9 May 2013**	30 Jul. 2014

The thesis accruement period lasted from the financial close of bidding for R2 to the submission date for R3 (which is marked in bold in Table 7 above). Therefore, 9 May 2013 (the date of financial closure of R2) is the appointed day for the assessment of the renewable energy forecast, as referred to in Chapter 0 of the current thesis. The third bidding round will not be included, since only the residual power of 1 176MW is known, and too many assumptions would otherwise have to be set.

Primarily up to five bidding windows were estimated to award the specified capacity (DoE 2011c, p. 43). The trend distinctly shows, in spite of a decrease from bidding R1 to R2, that R3, with an available capacity of 1 167MW, is likely almost to achieve the total desired amount of 3 625MW. The DoE determined, in consultation with NERSA, by December 2012 (DoE 2012) to amplify the generation capacity from 2017 to 2020. Acting under the ERA 2006, a supplementary renewable capacity of 3 200MW has been stated in order for one or more tendering procedures to contribute towards energy security achievements, and to facilitate the IRP 2010 targets, whereas 100MW have once more been dedicated for small projects. The portions between the particular technologies remain similar, in keeping with the previous determination, except for CSP, where the share rises from 5.5% to 12.5%, with a total amount of 400MW.

The first bidding round cumulated the greatest amount of capacity and subsidy tariffs. This phenomenon was based on the fact that the IPPs had been aware of reduced competition for the first bidding window, thus the number of submitted projects (with their respective capacities) was less than the government had previously announced. The additional present urgency of new capacities related to the MTRM prospects led to an average resulted sales price that was close to the ceiling price. Such progress depicted the crude market launch, and led to a distortion. A further reduction rate of 21.5% for wind and of 40% for solar PV from bidding in R1 to R2 underlined an overestimation of subsidy tariffs (Siepelmeyer T. 2013). Table 8 below allows for insight to be gained into the tariff caps and into the fully indexed actual subsidy tariffs in R/kWh.

Table 8: Tariff cap and recent subsidy tariffs (DoE 2012a; Greyling A. 2012, p. 14)

Qualifying technologies	Tariff cap for R1	Avg. tariff – R1	Deviation	Avg. tariff – R2	Reduction R1 to R2
Wind	**1.15**	**1.143**	99%	**0.897**	21.5%
CSP	**2.85**	**2.686**	94%	**2.512**	6.4%
Solar PV	**2.85**	**2.758**	96%	**1.645**	40%
Hydropower	**1.03**	**–**	–	**1.03**	–

Table 8 above determines the technology-dependent tariff development, in terms of which specific prices for wind power and solar PV show an obvious decrease. In contrast, the average electricity production price of Eskom increases every year, as is described in the following paragraph.

Eskom's ceiling price growth rate is regulated by the National Energy Regulator (NERSA), in terms of the Electricity Regulation Act, and specified in the MYPD. This mechanism is necessary for representing the public interest, as long as Eskom dominates the electricity generation as a monopolist (Siepelmeyer T. 2013). The MYPD No. 1 was implemented in 2006 for a period of three years to ensure reasonable tariff stability and smoothed changes over time, as well as to ensure Eskom's sustainability as a business in order to limit the risk of excess or inadequate returns (Nersa 2011a, p. 7). Since the increasing shortages that were experienced from 2008 onwards showed the urgency of the need for new capacities, Eskom legitimated the double-digit increase (up to 31% per year), which was approved by NERSA between 2009 and 2010. The main drivers of such an increase were the depreciation and return on the asset components of the application, in the context of the historical under-recovery (Nersa 2013, p. 7). Between 2013 and 2018 (MYPD No. 3), NERSA confirmed an annual price increase of 8%, whereas Eskom applied for an increase of 13% for its own needs, and a further 3% for accessory costs related to further expenditures for the implementation of IPPs. Figure 4 below illustrates the annual price increase for the generation of electricity by Eskom, as regulated by NERSA, and the IPP feed-in tariffs for wind and solar PV. CSP is excluded, since the price of more than 2.5 R/kWh cannot compete with Eskom's standard price.

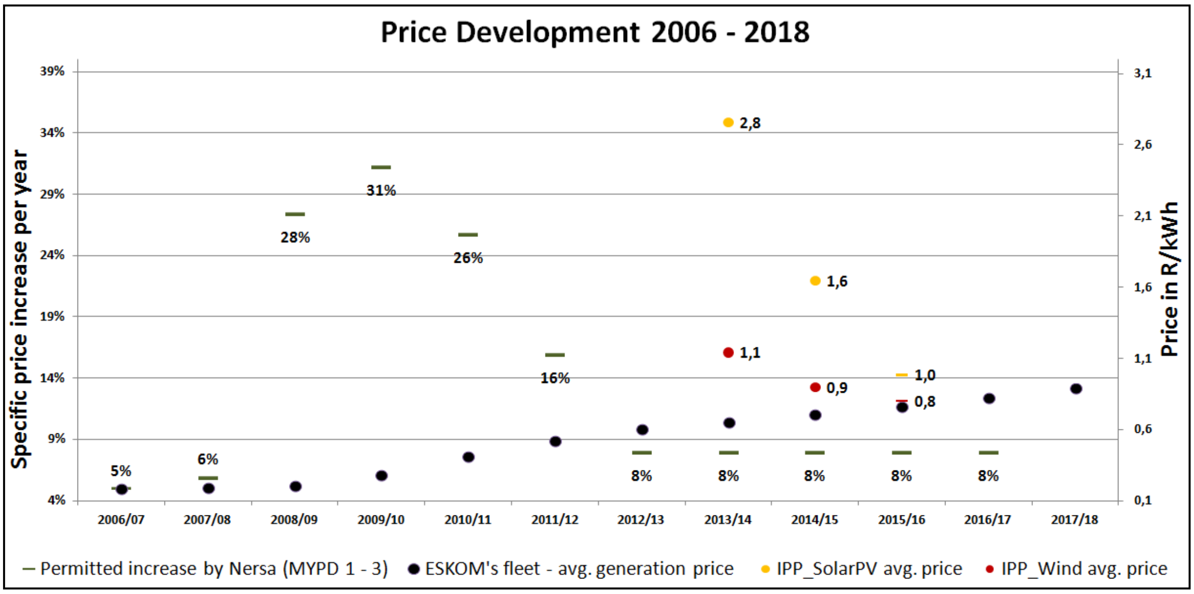


Figure 4: Eskom and IPP price adjustment/forecast 2006–2018 (Nersa 2013, 2013a)

According to NERSA, the generation price of Eskom for 2015/16 will be 0.76 R/kWh, increasing up to 0.89 R/kWh in 2017/18. As long as Eskom's price rises and the wind power and solar PV price decreases, contemplated renewable energy facilities will be able to compete over the next 5 to 10 years. They might not depend on subsidies as a consequence, regardless of the volatile power production not being of great significance, since it is not able to contribute fully to basic or peak load power generation.

The first two price levels of wind and solar PV are average values that resulted after the financial close of bidding R1 and R2, assuming that the plants will be on grid by 2013/14 and 2014/15. The average wind price for 2015/16 was estimated by N. Siepelmeyer (2013), the CEO of IPD Power Ltd, whereas the solar PV value was derived from the same decrease rate as that of the preceding year.

The REIPP Procedure Programme assumes a standardised approach for all submitted renewable energy projects. Every developer has to follow this procedure to be admitted to any bidding process.

The procedure is subdivided into three major, hierarchically ordered categories that are described in detail in Annexure II, in terms of Request for Qualification and Proposal (RFP), the bidding process, and financial closure.

Figure 5 below depicts a simplified approach to the REIPPPP and the contractual expiration of the cash and electricity flow.

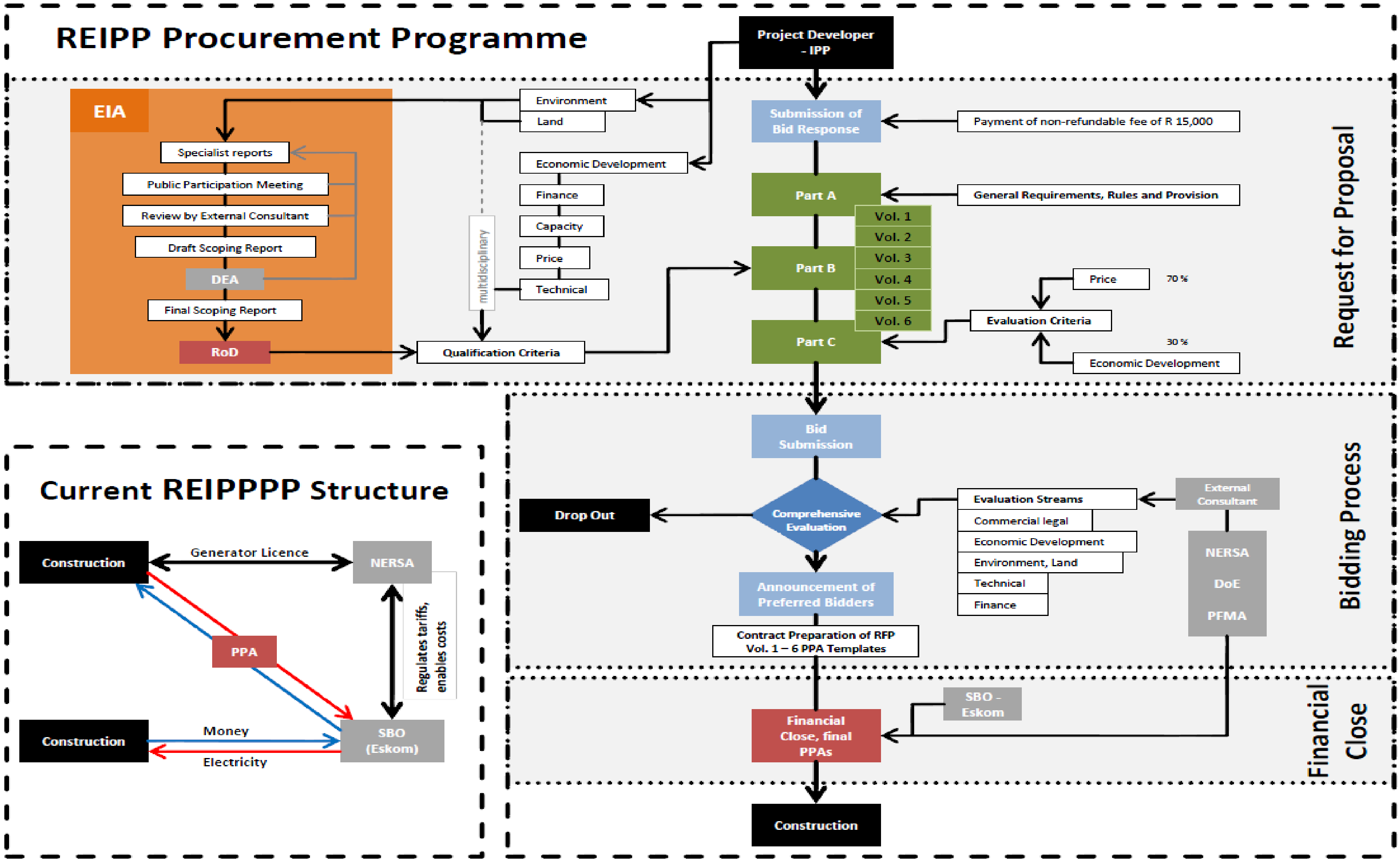


Figure 5: REIPPPP approach for an Independent Power Producer (Siepelmeyer N. 2013)

6 Involved renewable energy projects

This chapter reviews all renewable energy projects that were announced in REIPPPP bidding R1 and R2, and provides a brief overview of the already installed renewable capacities, besides the large-scale hydropower stations and the off-grid applications, which are not part of the works content. Based on the objectives of the current thesis in regard to the assessment of a time series simulation for all relevant, confirmed on-grid renewable energies, certain information, such as specific project positions, capacities, deployed technologies, and other details have to be known.

6.1 Approved facilities prior to 2011

The number of already installed or approved on-grid renewable energy power plants before 2011 was rare, since there were no legal policy guidelines to stimulate demand, such as the REBID has constituted from 2011 onwards. Although some mid-range solar PV plants, such as the 542kWp Vodacom rooftop application (Cloete K. 2013), were built up, they were intended to be off-grid, based on the lack of technical, legal and financial constraints available. Further programmes (e.g. Eskom’s small-scale Renewable Energy Programme 2012) that support the integration of small-scale, grid-integrated plants that are less than 1 MW were excluded from the analysis.

6.1.1 Existing wind resources

Up until the current moment, the following three on-grid wind farms have come into being, but, so far, no solar PV, hydropower, biomass, biogas power plant, or other plants have been built. Two out of the three above-mentioned facilities were constructed by Eskom, which facilitates the grid connection as well. Accordingly, the number of PPA participants is limited, since the transmission grid is run by Eskom, which facilitates the grid connection procedure. Darling Wind Farm has been the first confirmed on-grid wind energy facility that is developed and run by an IPP, even though no policy guideline was developed in time. The Klipheuwel Wind Energy Facility was constructed in 2003 under the pretext of it being research-related.

The following table gives an overview of the three already committed wind farms.

Table 9: Facilities committed prior to 2011

	Developer	Capacity per turbine [MW]	Nominal capacity [MW]	Commissioning date
Sere Wind Farm	Eskom	2	100	Oct. 2013
Klipheuwel Wind Energy Facility	Eskom	0.6 – 1.75 (3 units)	3.16	2003
Darling Wind Farm	IPP	1.3	5.2	2008

6.1.2 REIPPPP-approved projects

Within the REIPPPP bidding R1 and R2, 47 IPP projects were approved, as was described in section 5.3. The assumed commissioning date for the approved plants will be at the end of year 2013 for R1, and at the end of year 2014 for R2. The dates concerned correlate with the thesis objectives to simulate an annual course for 2015 by using pre-existing data for approved developers in R1 and R2. The following tables depict an overview of all the wind farms, the solar PV, the CSP and the hydropower plants assigned in R1 and R2. Some have been partly renamed by the author to provide clarity. All listed projects were submitted by an international IPP.

Table 10: Wind facilities approved for R1 and R2

Wind facilities – project designation		**Capacity per unit [MW]**	**Rated capacity [MW]**
Dassiesklip Wind Energy Facility	**R1**	3	26.2
MetroWind Van Stadens Wind Farm		3	26.2
Hopefield Wind Farm		1.8	65.4
Noblesfontein Wind Facility		n.a.	72.8
Red Cap Kouga Wind Farm		2.5	77.6
Dorper Wind Farm		2.4	97.0
Jeffreys Bay Wind Farm		2.3	133.9
Cookhouse Wind Farm		2.1	135.0
Amakhala Emoyeni (Phase 1)	**R2**	2.1	137.9
Chaba Wind Farm		3	20.6
Gouda Wind Facility		3	135.2
Grassridge Wind Farm		3	59.8
Tsitsikamma Community Wind Farm		3	94.8
Waainek Wind Farm		3	23.4
West Coast 1 Wind Farm		2	90.8

Table 11: Solar PV facilities approved for R1 and R2

Solar PV facilities – project designation		**Rated capacity [MW]**
SlimSun Swartland Solar Park	**R1**	5.0
RustMo1 Solar Farm		6.7
Mulilo Renewable Energy Solar PV De Aar		9.7
Konkoonsies Solar		9.7
Aries Solar		9.7
Greefspan PV Power Plant		10.0
Herbert PV Power Plant		19.9

Mulilo Renewable Energy Solar PV Prieska		19.9
Soutpan Solar Park		28.0
Witkop Solar Park		30.0
Touwsrivier Project (**CPV)**		36.0
De Aar Solar PV		48.3
SA Mainstream Renewable Power Droogfontein		48.3
Letsatsi Power Company		64.0
Lesedi Power Company		64.0
Kalkbult Solar PV		72.5
Kathu Solar Energy Facility		75.0
Solar Capital De Aar (Pty) Ltd		75.0
Solar Capital De Aar 3		75.0
Sishen Solar Facility		74.0
Aurora Solar Park		9.0
Vredendal Solar Park		8.8
Linde (Scatec Solar Linde)	**R2**	36.8
Dreunberg Solar PV		69.6
Jasper Power Company		75.0
Boshoff Solar Park		60.0
Upington Solar PV		8.9

Table 12: CSP and hydropower facilities approved for R1 and R2

CSP & hydropower – project designation		**Technology**	**Rated capacity [MW]**
CSP – Khi Solar One	**R1**	Central receiver – heat storage	50.0
CSP – KaXu Solar One		Parabolic trough – heat storage	100.0
CSP – Bokpoort		Parabolic trough – heat storage	50.0
Hydropower – Stortemelk Hydro	**R2**	Run-of-river power plant	4.3
Hydropower – Neusberg Hydropower		Run-of-river power plant	10.0

The cumulative capacities of all the above tables are summarised in Table 6, p. 24. The registered capacities for R1 and R2 were obtained from the DoE's 'REIPP Announcement', and from the 'Window Two Preferred Bidders' announcement (DoE 2012b, DoE 2011f).

The nominal capacities that have been published by the developers state a slightly higher value than do the registered capacities. The registered capacity for wind, CSP and hydropower facilities can be assumed to represent the total power output at the grid connection port under full load (deducting losses) and the peak power for solar PV under standard test conditions (STC).

The map in Figure 6 below pictures the spatial distribution of all approved IPP projects. It is evident that the projects are located according to the resource potentials that were reported in the local resource analysis, in section 4.1.

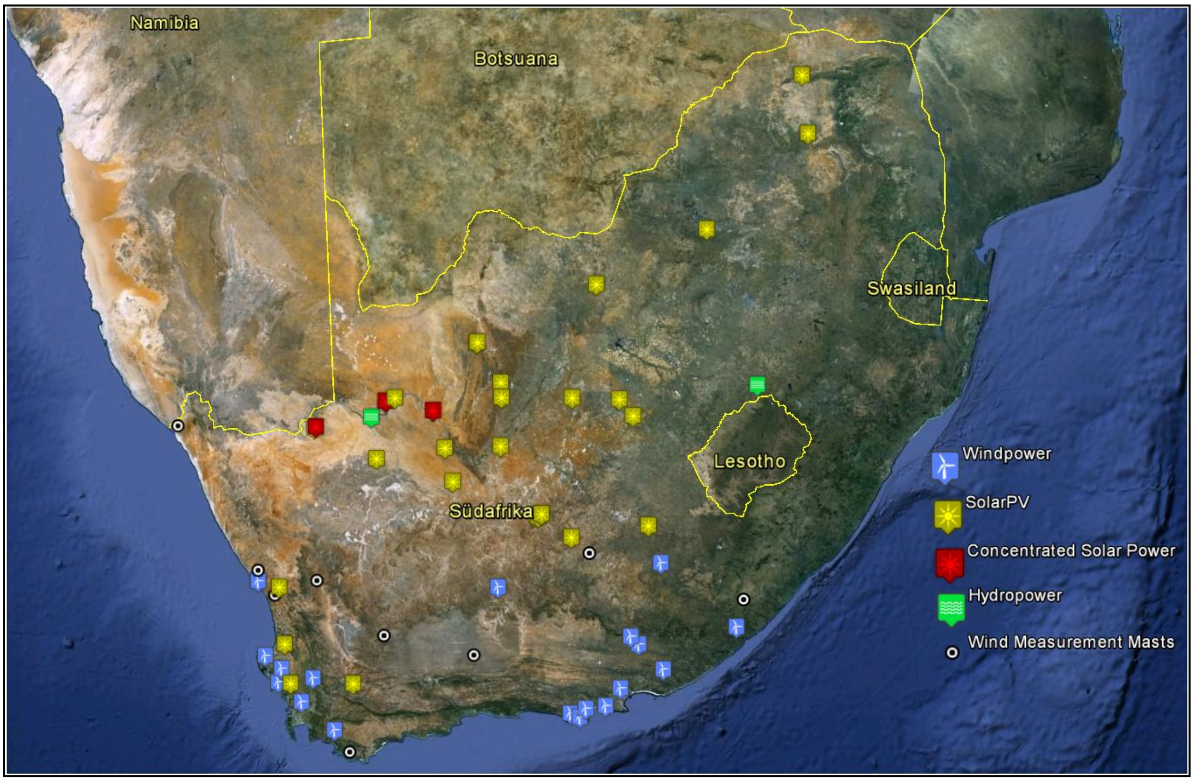


Figure 6: Location of IPP projects countrywide, featured by way of Google Maps.

7 Modelling the prospective load contribution

The model consists of four different approaches that were taken all the above-mentioned technologies used. This chapter constitutes an introduction to the model's objectives, the data assessment, the methodology, and other aspects, and describes each specific procedure in detail.

7.1 Introduction

The government's future supply ambitions are mostly linked to determined technology classifications and its single capacities. Especially renewable sources, such as wind and solar irradiation, are highly volatile. Facing the capacity for future expectations only will cause a high rate of uncertainty, which is based on the short-term fluctuation for peak load supply and the mostly unknown annual energy output of each technology. Therefore, the developed model represents a method of how to achieve load curves to be able to observe the load behaviour of all supplying, approved renewable technologies, and to enable the determination of the minimal−maximal fluctuation during different seasons. The results provide information about countrywide weather simultaneities, as well as about the fed amount of electricity by renewable energies after such stimulating measures as REIPPPP have been applied.

The model's objective is to develop a method with default input parameter thatrepresents the results in a reproducible and reliable way. Therefore, physical laws and mathematical correlations are implemented. To measure an occurring deviation, such reference values are gathered as predicted values, by independent developers, and/or calculated values, by means of using other comprehensible methods. The model uses annual input data from 2010, and approved renewable capacities from bidding R1 and R2 to process an exemplary load course for the year 2015.

For time series simulation purposes in every specific approach, various boundary conditions/ assumptions have had to be met. The assumptions will be scientifically justified and clearly specified.

The simulation requires such necessary tools as:

- Microsoft Excel by Windows Microsoft
- The solar PV model developed by the Solar Thermal Energy Research Institute
- The SAM developed by the NREL – US DoE
- The Wind Atlas Analysis and Application Programme (WAsP), developed by the Technical University of Denmark

7.2 Input parameters

The default input parameters for simulation issues were provided by GeoModel Solar Ltd and its solar GIS database. The simulated time series records were averaged on hourly based values (8 760), and represent the annual period of 2010 (1 January to 31 December 2010). The solar GIS data specification document (Solar GIS 2013) provides detailed information about the data acquisition, as well as about the related method and its occurrence.

The four data records used for research purposes are discussed below.

GHI and DNI [W/m²]

The solar radiation primary parameters, such as GHI and DNI, are derived by advanced and scientifically validated models that use satellite data and outputs from atmospheric models. The solar database input parameters are based on, inter alia, the cloud index, the water vapour database, the atmospheric optical depth, the elevation, the horizontal profile, and other factors. The spatial resolution of GHI and DNI is specified with a raster of 3 arc seconds (which corresponds to a cluster of about 90m at the Equator, and which decreases towards the Poles).

According to solar GIS, the quality assessment in South Africa shows a low bias within a range of ± 2.5% and an hourly root mean square error (RMSE) between 16 and 22%.

Ambient temperature [°C]

The spatial resolution of simulated air temperature is 1km, at an elevation of 2 meters above surface.

Wind velocity [m/s]

According to the solar GIS, the wind speeds are intended to be used as ancillary parameters only. Such meteor parameters as wind speeds, directions and humidities are derived from the numerical weather model output. In terms of said output, the spatial resolution is lower and might not represent the site-specific conditions, as does the solar resource data. Likewise, the wind's velocity data has to be verified before it can be used for further calculations to be sure about any possible deviation (see section 7.3.1). The spatial resolution of wind speeds is 900km² (30 × 30km) at a height of 10 m above surface.

7.3 Wind simulation

The purpose of the wind simulation is to calculate a power output for 18 wind farms by means of the use of individual wind conditions. Therefore, the hourly average wind speed in m/s has to be converted to an hourly average amount of energy in Wh, as generated by a certain number of wind turbines. Regarding the uncertainties of the GeoModel wind speeds, the data set values have to be analysed and verified, assumptions have to be set, and a reliable method for extrapolation has to be developed.

7.3.1 Data verification

To ensure certain accuracy of the GeoModel wind speeds at a height of 10m, GeoModel's data is compared with free available wind measurement data records. As part of the numerical Wind Atlas of South Africa (WASA), as described in subsection 4.1.2, ten WMs were sited countrywide to assist with developing, and to gauge their own model.

The WM's records are site specific for a certain spot, in comparison to the GeoModel simulation, which represents an average spatial resolution of 900km². The GeoModel data is expected to be more damped, which might imply higher maximum amplitudes of wind speeds. Nonetheless, juxtaposing both sets of data is necessary for verification purposes, as well as for subsequent adjustments.

The WM sites were not placed in areas that were expected to be windy. The placement was done in line with the following criteria (Otto. A 2013):

- Spaced out evenly across the project area (respecting the numerical wind atlas)
- At a distance from complex terrain
- In areas uniform in terms of roughness and topography
- Within such different climatological regions as coastal and inland low-/high-lying

The WMs provide 10 minutes mean, maximum and minimum wind speed values at an elevation of 10m, 20m, 40m, 60m and 62m; accurate wind directions; temperatures; barometric pressures; and relative humidity. WASA initiated the recording of data from August 2010 onwards, which limited the comparison period to 5 months. As a result, seasonal deviations cannot be taken into account. Since the wind potential in W/m² depends on the velocity power of three, cubed average hourly values for all WASA records are calculated to be able to compare both data sets.

Individual record assessment

An evaluation with regard to the standard deviation (SD) of each record at five relevant chosen sites confirmed the above-mentioned expectations. The WM's average SD was found to be 24% higher than the GeoModel deviation (2.1 to 2.8m/s).

Assessment of the analogy

To compare both data records, different methods were used. The utilisation of such formulas as the mean error (ME), the root mean squared error (RMSE), the mean absolute error (MAE), and others which are described in Annexure III.

A comparison of mean wind speed values and a relative influence of the wind power potential ($(\Sigma v_i^{3)}/1000$) are depicted in the table below. WM 09 and 10 measurements were excluded, since the deviation was implausible.

Table 13: Comparison of GeoModel data at WM sites and WM measurements

Site	V_{mean} GM [m/s]	V_{mean} WM [m/s]	Deviation [%]	GM $(\Sigma v_i^3)/1000$	WM $(\Sigma v_i^3)/1000$	Deviation [%]
WM01	3.9	5	**130**	372	987	**265**
WM02	3.1	5	**159**	238	679	**285**
WM03	3.4	5.7	**169**	225	1069	**475**
WM04	4.2	4.8	**116**	484	718	**148**
WM05	5.3	7.3	**138**	855	2251	**263**
WM06	3.7	5.6	**151**	298	773	**259**
WM07	3.6	5.8	**161**	341	1064	**312**
WM08	4.7	5.8	**123**	709	1345	**190**

The WM measurements were higher than the GeoModel values throughout. The aberration between the WM and the GeoModel mean wind speeds was between 116 and 169%, while the deviation of the summarised, single-cubed values (representing theoretical wind energy potential) extended from 148 to 475%. For the error examination, only proper geographical WM sites were evaluated.

The following five WMs were the nearest to the related 17 wind farms.

Table 14: Error evaluation between GeoModel data and WM measurements

Site	ME [m/s]	RMSE [m/s]	MAE [m/s]	MAPE [%]
WM01	1.1	2.9	2.1	**49**
WM03	2.3	3.4	2.7	**46**
WM04	0.7	2.5	2.0	**50**
WM05	2.0	2.9	2.3	**34**
WM08	1.1	2.4	1.9	**39**

The error evaluation shows that the deviation was substantial. The mean absolute percentage error (MAPE) exhibited a significant gap. An analysis of the monthly mean absolute percentage error (MMAPE) resulted in slight monthly differences, but since only five months of comparable data were available at the time of the study, further examination was not possible.

Figure 7 below represents the averaged distribution curve of the sites mentioned above. Although the distribution of the lower GeoModel simulation was higher in the ranges between 0.5 and 6m/s, the higher wind speeds above 7m/s influenced the apparent gap.

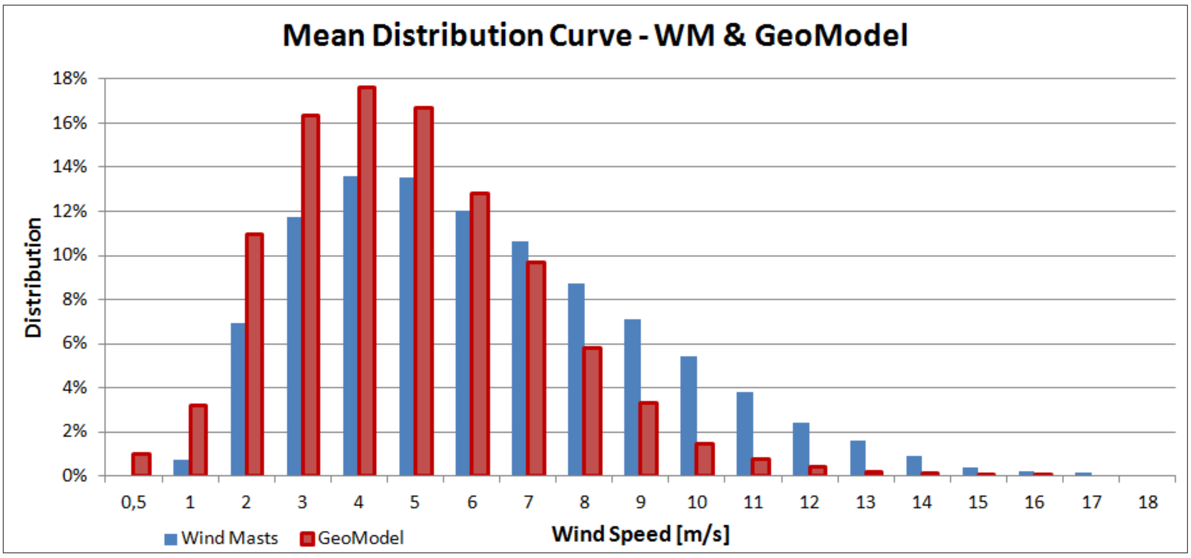


Figure 7: Mean wind distribution curve – wind mast measurement and GeoModel simulation

Visual assessment

The trend of both data records was found to be similar and consistent, even though the absolute values differed, as is described above. The relative values, such as tendency, could be used for further computing, although a difference existed in the SD, indicating the mean relative error.

A further use of GeoModel data records is not recommended without a projection being related to the results above. An approximation should be comprehensible, single-value based, and evenly distributed to adhere to the trend in the records. A multiplication of each value using the factor 1.4 as representing the v_{mean} average deviation might prove to be the probable method.

7.3.2 Height-related extrapolation

The GeoModel data at a height of 10m above ground had to be extrapolated to an accurate operation elevation. A commercial wind turbine typically operates at an appropriate height, since the wind speeds are more consistent and increase, depending on the height above surface. The wind's potential depends on the third power of the velocity, as the following derived formula describes:

$$P_{wind} = \frac{1}{8} * \pi * \rho_{air} * d_{rotor}{}^{2} * v_{wind}{}^{3} \qquad (1)$$

The most influential parameters are the velocity (corresponding to the height) and the diameter of the wind stream. The hub height of a wind turbine usually depends on the surface roughness, and on the vertical wind distribution. For simplified simulation purposes, a standard wind turbine hub height of 100m was assumed.

The Hellmann exponential law and the logarithmic wind profile law are empirical determined relations between the wind's velocity and the hub height. Both laws were simplified and empirically verified. Another method, such as the more precise Monin-Obukov relation, could not be taken into account, based on a lack of further input parameters, such as temperature differences, friction lengths, and others (Banuelos, Camacho 2011).

The following formulas represent the Hellmann exponential law (2) and the logarithmic wind profile law (3).

$$\frac{v}{v_0} = \left(\frac{H}{H_0}\right)^{\propto} \qquad (2)$$

$$\frac{v}{v_0} = \left(\frac{\ln\left(\frac{H}{z_0}\right)}{\ln\left(\frac{H_0}{z_0}\right)}\right) \qquad (3)$$

In terms of the above, v is the velocity to the height H, and v_0 is the velocity to H_0. The Hellmann exponent, or friction coefficient, is α, and z_0 represents the roughness length in m. The values of both parameters corresponded to a certain terrain class, as the following table shows.

Table 15: Friction coefficient and roughness lengths (Tong 2010; Patel 2006)

Landscape type	Friction coefficient α	Roughness length [m]
Offshore, hard ground	0.10	0.0002
Grassland, open areas	0.15	0.03
Tall crops, hedges, farmland	0.20	0.1
Urban districts, small town	0.30	0.4
City areas, forest areas	0.40	1.6

In this case, both laws were validated by existing, randomly chosen data samples from the WASA WMs, taken at a height of 10 and 60m. Therefore, α and z_0 were calculated by means of the transformed equations above ((2),(3)) for each dataset, and averaged by means of the use of the mean and median value. The two homogenised coefficients for each data set were utilised to extrapolate new sample wind speeds for a height of 60m, to be able to compare them with the according true wind speeds.

The following graphs were drawn using the determined mean/median coefficients α and z_0 at a sample wind speed of 8m/s. The comparison showed similar results as long as the aberration of the single calculated coefficients was not too high.

As a result, the Hellman exponential law was chosen for extrapolation purposes.

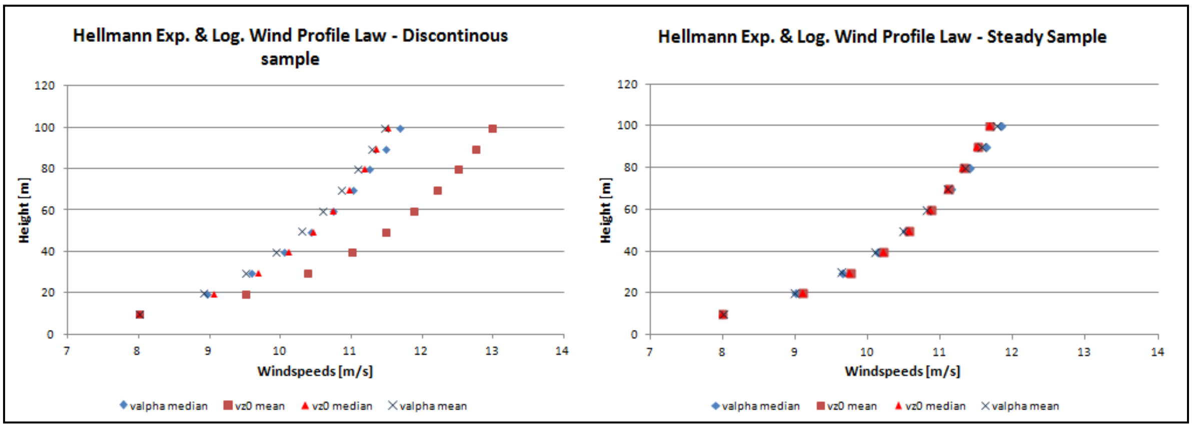


Figure 8: Comparison of the data according to the Hellmann exponential law and the logarithmic wind profile law

To be able to extrapolate each wind record at all project site using a single method, a homogenised α coefficient was calculated by using all WM data, following the same method described above.

The calculated α coefficient was 0.126, which corresponded to the sites ranging from hard ground to grassland/ open areas (see Table 15, p. 39). The less the exponential coefficient was, the smaller was the relative increase of the extrapolated value. Such an approach is based on the assumption that wind farms tend to be located on a similarly flat terrain as the wind measurement stations are, to avoid having to have excessively tall wind turbine masts.

The projection was made up to a generalised hub height of 100m, although the coefficient was calculated between 10 and 60m. The increase was expected to match an approximately realistic result.

7.3.3 Power conversion

The power conversion from an accurate extrapolated wind speed at a height of 100 m to a power output was approximated by the specific power curves of certain wind turbines. Two turbines of different performance categories were chosen to cover the bandwidth of utilised turbines at all the approved wind farms (see Table 11: Solar PV facilities approved for R1 and R2

The load behaviour of different turbines at the same performance category was found to be similar, which could lead back to such physical limits as Betz' law, component efficiencies, and others.

The approximation was based on a logarithmic conversion between 6 and 10m/s, and on linear relationships above/below that. It was made in terms of two developed wind turbines, with a capacity of 2.35 and 3MW, as manufactured by Enercon Ltd. The minimum operation wind speed was 2m/s. Above 13m/s the power output was limited due to a stall in the wings.

The graph in Figure 9 below illustrates the mathematical approximation to the real power curves involved.

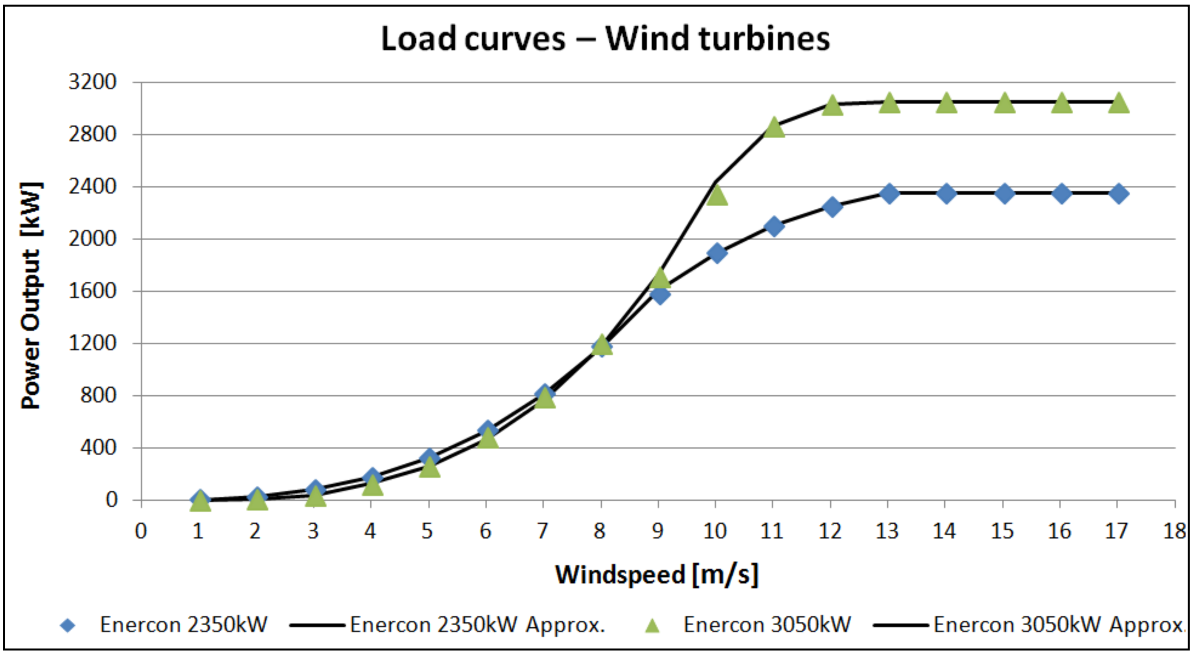


Figure 9: Approximation of the wind power curve

The course of both power curves was almost equal, up to a wind speed of 9m/s. Assuming a wind farm with a capacity of 50MW at a site with a mean wind speed of less than 9m/s, the technically exploitable energy output of a wind farm with smaller turbines at a certain constant hub height would be greater than if bigger windmills were to be used, since the number of turbines would be higher. Although the technical potential can be higher with the installation of smaller turbines, the decision criterion in terms of which turbines are chosen is based on an economic viability (e.g. on the specific cost of each wind turbine). The turbine size in the case of individual projects assumes the selection of the approximated load curve.

7.3.4 Method 1 – assorted approach

The approach adopted in the simulation can be summarised as follows:

- GeoModel 10m data projection to compensate for WM 10m deviation
- Height extrapolation – 10 to 100m
- Power conversion

The assessed simulation approach was performed for the following five wind farms, in terms of which the developers published an annual expected energy output to verify the developed methodology. The results in GWh below show an explicit overvaluation of four out of five projects with the developed methodology.
An extrapolation without a GM 10m data projection surprisingly meets the expected output.

Table 16: Wind speed extrapolation – verification. Units in GWh.

Wind farms	Expected energy output	Including GM 10 m alignment	Excluding GM 10 m alignment
MetroWind Van Stadens Wind Farm	80	126	74
Hopefield Wind Farm	**190**	**198**	**101**
Red Cap Kouga Wind Farm	290	426	283
Jeffreys Bay Wind Farm	362	627	380
West Coast 1 Wind Farm	290	440	273

This fundamental finding, and a further verification of the capacity factors (CF) of all the projects as a comparative analysis tool, led to the conclusion that the developed method was not reliable enough for a further straight forward proceeding. The CF differed greatly from the realistic bandwidth. The CF is defined as follows:

$$CF = \frac{E_{wind,annual}}{P_{el,net} * 8760\ \frac{h}{a}} \qquad (4)$$

A further step was contained an assorted approach for different groups of projects regarding to available IPP information. The proceeding is described below:

- The calculation without a 'GM to WM – 10m projection' led to an approximate result compared to the IPPs' expectations, or fell within a plausible CF bandwidth (in the case of seven projects).

- An IPP expectation in GWh or an estimated CF was available (in the case of five projects):
  - Iterative adjustment of the ‘GM to WM – 10m projection’ factor was done to achieve the expected results.
- No specific project information was available (in the case of six projects):
  - The resulting CF fell below the expectancy range after calculation without a ‘GM to WM – 10m projection’.
  - Relative adjustment into a plausible CF range resulted in a subsequent energy output.
  - Iterative adjustment of the ‘GM to WM – 10m projection’ factor achieved the expected output.

The plausible CF range was defined by means of the above results, and then verified by means of consulting literature references. For the purpose of the current study, the range was set between 27 and 42% (Siepelmeyer N. 2013; Soni 2012, p. 34; Stanley Cons. 2009). Although the CF bandwidth contained the highest assumption uncertainty, the fluctuation margin in the high wind records allowed for no other possibility than to implement such an approach.

7.3.5 Method 2 – single approach

In order to accomplish a single and comprehensible approach for all cases, and to simulate consistently, the following approach was derived in terms of the methodology discussed above:

1. GeoModel 10m records were used directly for height extrapolation from 10 to 100m.
2. The CF’s of the IPP projects were adjusted into the defined bandwidth.
3. The ‘GM to WM – 10m projection’ factor was iteratively adjusted to achieve the cumulated energy output (which was derived by the adjustment of the CF, in accordance with the above-mentioned step).
4. A power conversion and cumulative display was performed.

Figure 10 below demonstrates the CF adjustments in a bandwidth of 27 to 42%. The blue spots describe the origin CFs, following the simulation method. The red spots represent the CFs after the assimilation.

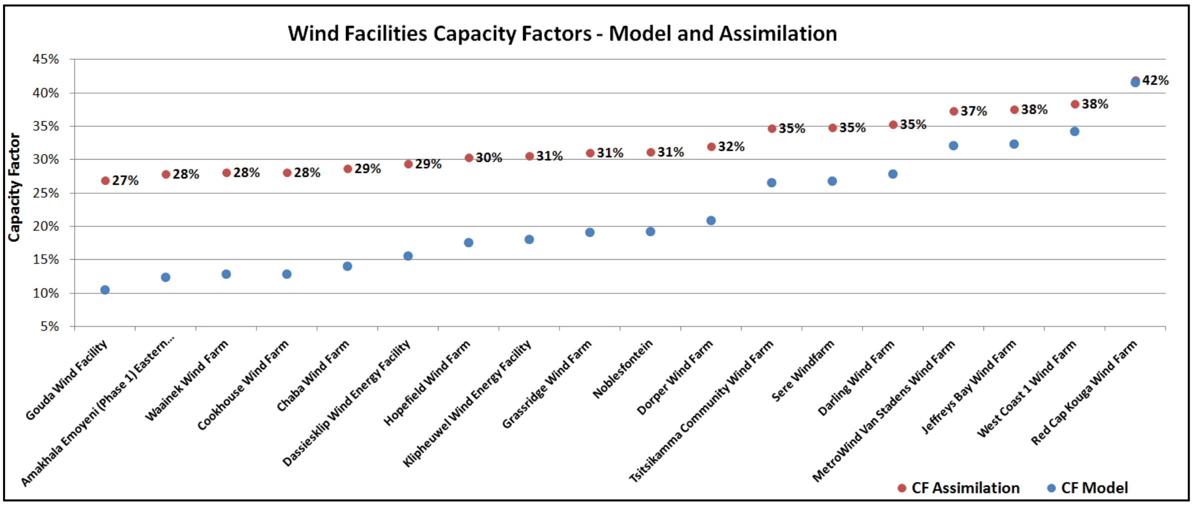


Figure 10: Capacity factors of wind facilities – model and assimilation

7.3.6 Validation – assorted and single approach

The grouped approach's output was 3 598GWh, whereas the output for the single approach was 3 685GWh. The mean deviation of 13MW corresponded to 1% of the installed capacity. The maximum deviation amounted to 60MW.

The advantage of adopting the assorted approach is that the result might be more accurate, based on the individual project information, while the single approach does not take such information into account. The disadvantage of the assorted approach lies in the lack of standardisation, which impedes replication, and also in the references not being confirmed and independent. Based on the fact that the hourly trend and the annual yield of both methodologies were very close, the single approach (Method 2) was be chosen for further study.

It must be borne in mind that the assorted approach serves as a verification model for the single approach.

7.3.7 Results

The main boundary conditions influencing the simulation must be stated to allow for evaluation of the existing uncertainties before any result can be analysed. The most important assumptions that were set are summarised below:

- A CF bandwidth of between 27 and 42%
- The usage of 10m GeoModel records, even though the deviation to measured values records was high
- A general turbine hub height of 100m
- The Hellman exponential law for 10 to 100m extrapolation

- The generalisation of the exponential coefficient α = 0.126 (determination taken from a WM 10m and 60m in height)
- Load curves approximated by Enercon Ltd

The following influences could not be fully taken into account, based on the lack of information, and, to some degree, the limited extent of the thesis:

- The seasonal evaluation of WM and GeoModel data
- The wind farm's specific simultaneities
- Probable deviation from a standard wind year
- The lack of available data in a range that was less than hourly based

Regarding the simulation, the total annual generated energy yield would be 3 685GWh. The maximum available power was 1 302MW, which almost corresponded to the total installed capacity. The least amount of available power was 8.3MW, emphasised that it represents one single value only. Such a result indicates the presence of a spatially consistent, but temporal, fluctuating wind resource. On the one hand, every wind farm will run at its ceiling capacity at certain hours, but, on the other hand, the firm capacity was found to be almost zero (~0.6%), which is a negative aspect regarding the contribution that can be made by a wind-powered base load. Whereas the annual mean was found to be 421MW, the seasonal fluctuation was considerable. Table 17 below characterises the seasonal behaviour of wind power generation.

The knowledge of the wind power contribution to satisfying the winter peak demand must be examined, since such political instruments as the IRP 2010 – MTRM require a substantial contribution from each generation unit to supply stability. About 15% of the wind distribution tends to occur between 19 and 22h, which corresponds to an appropriate time distribution of 16.7% (= 4h / 24h). The according firm capacity was 23.5MW, whereas the annual firm capacity during that period was 26MW. Further analysis of this issue demonstrated that 40.4% of the winter's distribution tends to occur between 8 and 15h, which is proportionally higher than the accurate time distribution. It can be asserted that the wind power in 2010 slightly contributes to the morning peaking hours, and nearly provides its own amount of time distribution-related energy.

Further analysis, such as an annual load duration curve, which is shown in Figure 30, and a seasonal separated duration curve, which is shown in Figure 31, are included in Annexure IV. Autumn is indicated as being a wind-rich exposed time period.

Table 17: Seasonal characteristics of wind generation

Power [MW] Energy [GWh]	Spring (21/09–20/12)	Summer (21/12–20/03)	Autumn (21/03–20/06)	Winter (21/06–20/09)
Deliv. energy	843	926	1000	916
Min. power	8.3	20.3	12.4	20
Max. power	1285	1215	1302	1284

The cumulative wind power shows concurrent increases and decreases within a few hours. As a result, the spatial distribution does not imply an upper simultaneity, as is illustrated by the exemplary wind power course that is pictured in Figure 11 below.

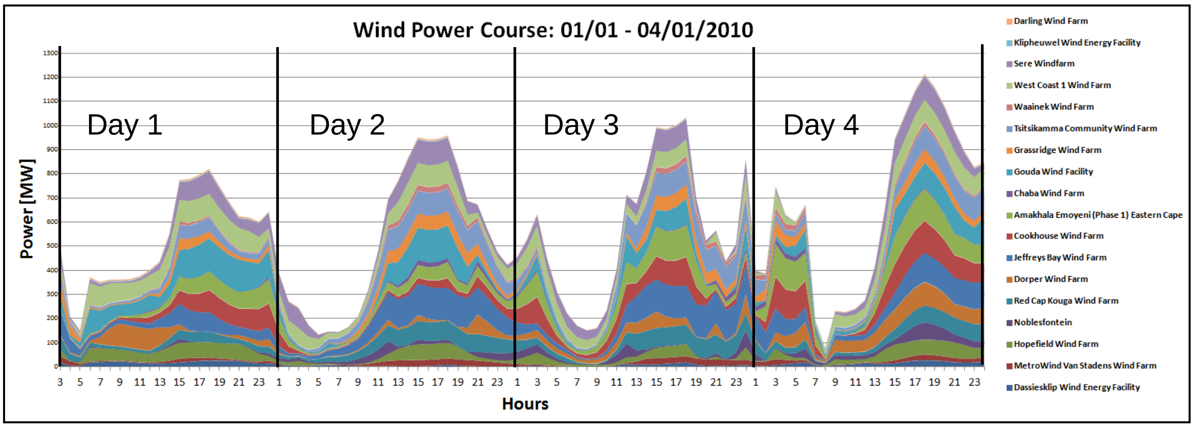


Figure 11: Exemplary wind power course in January

Figure 32 (Annexure IV) verifies the rapid wind speed changes, with locally relevant WM records taken at a height of 60m.

7.4 Solar PV simulation

The simulation covers 27 solar PV plants, which were approved in bidding R1 and R2. The purpose in doing so was to utilise a standardised approach to calculating an hourly load curve by using, inter alia, local solar irradiance data records. Therefore, an already developed method by Paul Gauché, is applied (Gauché 2011). One project, as has already been mentioned in Table 12: CSP and hydropower facilities approved for R1 and R2 is provided with CPVs, which require the adoption of such a method as is described in subsection 7.4.3.

The following sections deal with the description of the PV simulation approach.

7.4.1 Data verification

The data provided by GeoModel consists of 2010 annual GHI and DNI, ambient temperature and wind speed data for every single project site. The properties of the data records are defined in section 7.2. The temperature and the wind speeds are intended to be used as ancillary parameters. The STERG and its director, Paul Gauché, have already published papers regarding the mentioned GeoModel data. In terms of said data, the quality of the irradiance values is stated as being reliable (Gauché, Pfenninger 2012; Gauché, Heller 2012). The cooperation with GeoSun Africa©, which is a spin-off company of CRSES, and with the representatives of GeoModel in South Africa verifies the reliability of the data obtained. Based on such quality references, GeoModel data will be used for further processing.

7.4.2 Methodology

The simulation approach was conducted by means of a modified Microsoft Excel tool devised by Paul Gauché. It has been developed to simulate a central receiver (CR) CSP plant, with a solar PV model having also been derived, in addition (Gauché 2011).

The tool in question calculates the hourly position of the sun (in terms of an equation of time, altitude, azimuth, etc.), including several derived, generally valid coefficients (Stine, Geyer 2001, Chapter 5), and taking mutual module shading into account. The model can be adapted for different solar PV applications, such as for tracking types (e.g. fixed tilt, periodic adjustment, azimuth tracking, full tracking, etc.).

For solar PV purposes, the tool processes the following input parameter:

- Net aperture size — [m²]
- Length, width — [m²]
- Pitch of modules — [m]
- Site's coordinates – longitude, latitude — [deg]
- GHI, DNI, diffuse horizontal irradiance — [W/m²]
- Ambient temperature — [°C]
- Ground-level wind speeds — [m/s]
- Aperture tilt angle — [°]
- Cell efficiency — [%]
- Inverter efficiency — [%]
  - Coefficients
  - Temperature efficiency — [% per °C above 25°C]
  - Irradiance efficiency — [% per W/m² below 1000W/m²]
  - Temperature rise coefficient — [°C per W/m²]

and computes, among others, the following values:

- Maximum actual power output — [W_{max}]

- Time series load behaviour [Wh]
- Annual amount of energy [Wh]
- Maximum cell temperature [°C]

The results are validated by means of single projects that are conducted on a random basis by means of the SAM of the US NREL in efforts to confirm the model's reliability.

7.4.3 The making of assumptions

The solar PV simulation requires the following modifications/assumptions in terms of a consistent approach:

- 25 of 27 solar PV systems were mounted in a fixed position on a rack facing north.
    - A location-dependent optimum tilt (between 24 and 32°) for a maximum annual energy yield has been developed by GeoModel, and has been adopted for simulation approaches (Suri, Cebecauer 2012, p. 5).
- A conversion factor from a peak power to a certain aperture plain was implemented, since the model requires a PV size, and the developers published only the peak power of each plant. Five appropriate modules of different manufactures from 240 to 250Wp were chosen, and a mean specific peak capacity of 167Wp/m² was determined (see Annexure V).
- The module efficiency was generalised to 15.1%, corresponding to an average value for the five chosen modules described above.
- The panels did not cast shadows on each other.
- Since the required DHI was not available from GeoModel, it was derived by means of the following formula. Theta represents the zenith angle in the following equation:

$$GHI = DHI + DNI * cos(\theta) \tag{5}$$

  Some DHI values, which were negative at the beginning of the day, were replaced by 0. This incident can be blamed on DNI/GHI simulation inaccuracy. For validation purposes, solar irradiance data at the measurement station at Stellenbosch University was examined, where it was found that the same effect occurred.
- The following coefficients were derived by Gauché (2011) and received from Stine and Geyer (2001).
    - Temperature efficiency −0.5% per °C
    - Irradiance efficiency 0.0125% per W/m²
    - Temperature rise coefficient 0.03°C per W/m²
- For the 36MW CPV plant, a simplified and reproducible methodology was developed.

The concentration lenses focused only on the DNI, which was multiplied by the efficiency and the net module size, as the following formula describes:

$$P_{el,CPV} = DNI * \eta_{CPV} * A_{net,\ plant} \tag{6}$$

The efficiency was derived by means of a concentrator triple-junction solar cell, type 3C40, made by Azur Space Solar Power Ltd.

Table 18: Solar CPV properties, type 3C40, Azur Space Solar Power Ltd, under STC

Specifications	Type 3C40
Sun concentration	× 1000
η_{cell}	36.3%
W_{MPP}/m^2_{gross}	362
Temperature coefficient (25 – 80°C)	-0 035%/ΔT

Based on the lack of temperature rise coefficients that could have designated the cell temperatures, the cell efficiency was reduced by means of a mean alternation between 25 and 80°C, and yielded 35.3%.

Based on the above assumptions, the simulation was done for each project.

7.4.4 Results

The annual cumulative energy from solar PV summarised the single output rating of 25 solar PV plants with a fixed tilt, one plant with a one-axis tracker system, and one CPV plant that was fully tracked. The total amount of delivered energy was 1 906GWh. The cumulative maximum power was almost 900MW, which was 14.2% less than the registered capacity of 1 049MWp. The gap of 149MW was based on the fact that the peak power corresponded to the STC, which did not represent an appropriate irradiance and cell temperature course per day.

The CF's bandwidth for the fixed tilt plants ranged between 18 and 22%, which implied consistent specific results. The one-axis tracker CF achieved almost 25% and the CPV CF was 28.5%. Eleven determined IPP expectations (annual energy generation and/or CF) and a SAM simulation output for a 75MWp plant (Kalkbult Solar PV) confirmed the results obtained. The deviation was insignificant (see Annexure V).

The seasonal characteristics appeared as follows: The spring delivered the highest amount of energy, which was almost 26% more than the autumnal contribution. The mean delivered energy per day was 5.9GWh during spring, and 4.7GWh during autumn.

Table 19: Seasonal characteristics of solar PV generation

Power [MW] Energy [GWh]	Spring (21/09–20/12)	Summer (21/12–20/03)	Autumn (21/03–20/06)	Winter (21/06–20/09)
Max. power	900	852	830	856
Delivered energy	533	485	429	459
Min. peak power	265	291	270	257

The cumulative, delivered solar PV energy visibly runs synchronically with the solar irradiance, influenced, as it is, by local weather conditions. Solar PV without energy storage basically contributes to the higher demand during daytime, but a base-load firm capacity contribution cannot be ensured. During winter, the total output decreases, based on the limited irradiance, resulting in a further lack of contribution to evening peak loads. Figure 12 below depicts two days of an exemplary cumulative generation course during January.

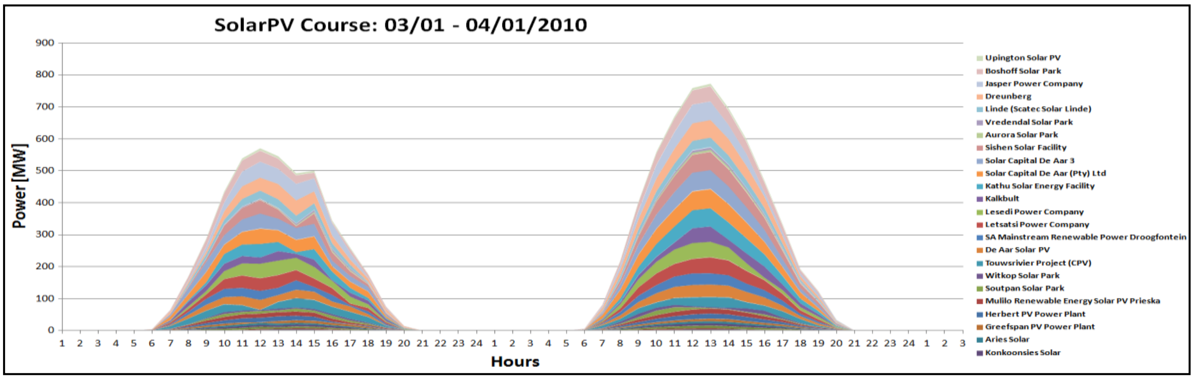


Figure 12: Exemplary cumulative solar PV generation in January

7.5 Concentrated solar power simulation

The CSP simulation contained three approved projects, with a net capacity of 200MW. They were located in the Northern Cape, where the highest solar irradiance potential occurs, especially in terms of DNI. In contrast to solar PV, which directly exhibited the PV effect, the CSP technology mirrored/concentrated the direct solar irradiance onto a small area, where the uprising thermal energy was used to run a heat engine. Two parabolic troughs and one CR plant were deployed, with energy storages ranging from 2.5 to 9h. The simulation was based on hourly specific site GeoModel weather data, such as the GHI and the DNI records, and was computed by means of SAM. The results were verified by means of expected energy outputs that had been released by the developers of the project.

7.5.1 Methodology and assumptions

The SAM offered a variety of different possible input parameters. A projects-related literature research revealed a number of specific boundary conditions that were implemented. The residual number of unknown parameters was set at default values. Business concerns were not taken into account. Besides the individual underlying weather data for each project, Table 20 below specifies some modified input parameters.

Table 20: CSP SAM – input parameters (CSP World 2013)

	KaXu Solar One	Bokpoort CSP	Khi Solar One
Technology	Parabolic trough	Parabolic trough	CR
Net capacity [MW]	100	50	50
Storage	2.5h/ molten salt	9h/ molten salt	3h/ saturated steam
Cooling	Dry	Wet	Dry
Reflecting area [m²]	800 000	588 600	580 000

Annexure VI reports the remaining boundary conditions. Some further parameters were plausibly adapted to obtain the hypothesised input values.

The thermal storage dispatch control was consistently defined as follows (Gilman 2012), with no specified approach being required by the Single Buyer Office (SBO):

- The turbine was operated at nameplate capacity, as long as sufficient energy was available from the solar field, or from thermal energy storage (TES).
- The plant-generated electricity operated at nameplate capacity, using solar field energy with TES to cover low sunlight conditions.
- If there were no sunlight, the TES would dispatch energy, as long as there was some thermal energy in storage.
- The backup boiler does not operate, except for in response to thermal oil freezing protection issues.

The model further required ambient air (T_A), dew bulb temperature (T_{db}), relative humidity (RH), and wind speeds. The provided GeoModel record contained data relating to ambient air temperatures and wind speeds only, from which no dew bulb or relative humidity information could be derived. Based on this lack of information, the closest WM data (WM02 – see subsection 7.3.1) were gathered for all three projects. Although the WM's mean ambient temperature was less than the appropriate site temperatures, the decision rested on the assumption that T_A, T_{db} and RH influenced only the re-cooling process, which changed the result in a manageable way. The dew point temperature calculation is described in Annexure VI.

After the completion of the input parameter, the output of each plant was calculated by means of SAM. The output offered a range of parameters, of which a net sent-out load was required.

7.5.2 Results

The specific annual sent-out energy matched the expectations of the developers. The relative deviation was between −0.8% and +4.1%. The CF was found to be significantly higher than was the CF of the solar PV, since storage capacities were available and the solar multiple is higher than 1. A solar multiple of 1 is the aperture area required to deliver sufficient thermal energy to the power cycle to drive it at its nameplate capacity under design conditions. Table 21 below shows the results obtained.

Table 21: Verification of CSP simulation results

Energy in GWh	KaXu Solar One	Bokpoort CSP	Khi Solar One
Annual output	325	228	197
Expected output	320	230	190
CF [%]	37.2	52.1	45.2

The cumulative annual delivered amount of energy was 752GWh, and the maximum calculated power was 217MW. The storage dispatch differed strongly, relative to the storage size and to the season-dependent irradiance densities. KaXu and Khi Solar One, with 2.5 to 3h capability of nameplate storage capacity, rarely contribute to the winter evening peak, although the generation can be shifted towards evening.

Khi Solar One's annual energy share constantly decreased from 18:00 onwards, while the number of days without any generation increased from 7% (16:00 to 17:00) to 34% (19:00 to 20:00). If the plant were to deliver energy from 19:00 to 20:00, the minimum power would be 18.5MW out of 50MW nameplate capacity. Although Khi Solar One could not provide a certain quantity of firm capacity during a period of time, contribution probabilities (see Annexure VI) distinguish the difference involved from other fluctuating technologies. Figure 13 below illustrates the seasonal energy share.

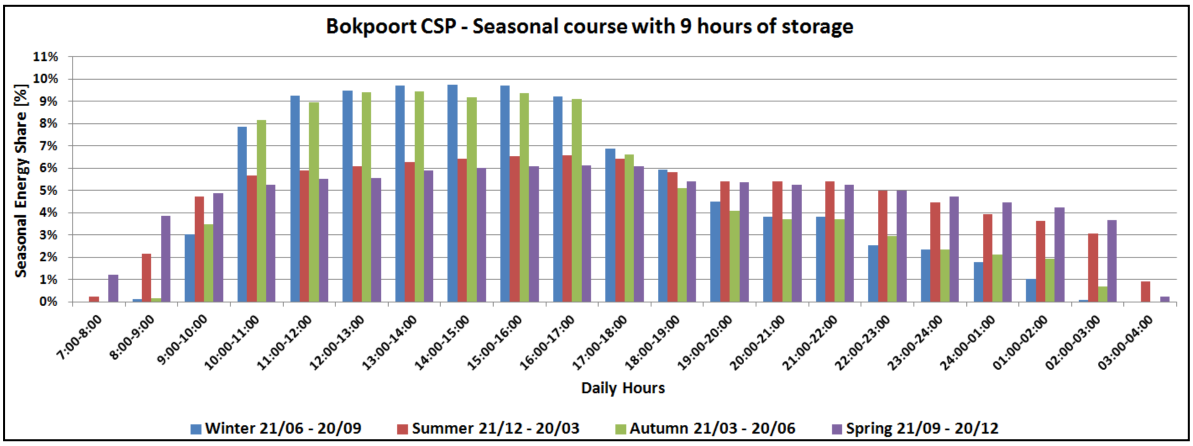


Figure 13: Khi Solar One – seasonal course with 3h storage

During summer, Bokpoort CSP plant with 9h of storage, can deliver until 16:00, with a probability of 93%. The contribution probability decreases to 82% between 19:00 and 20:00, with appropriate capacities above 45MW (see Figure 37, Annexure VI). During wintertime, the higher capability of storage capacity does not pay off, since the solar input is too little to charge the storage fully while the plant is generating at nameplate capacity.

As soon as temporal referred tariffs are implemented, the dispatchability of CSP plants with large storage facilities will have to be re-evaluated.

Figure 14 below represents the seasonal course of Bokpoort CSP. The striking high winter and autumn energy shares between 10:00 and 17:00 are caused by the fact that the storage cannot be fully charged, resulting in an increase in the single proportions.

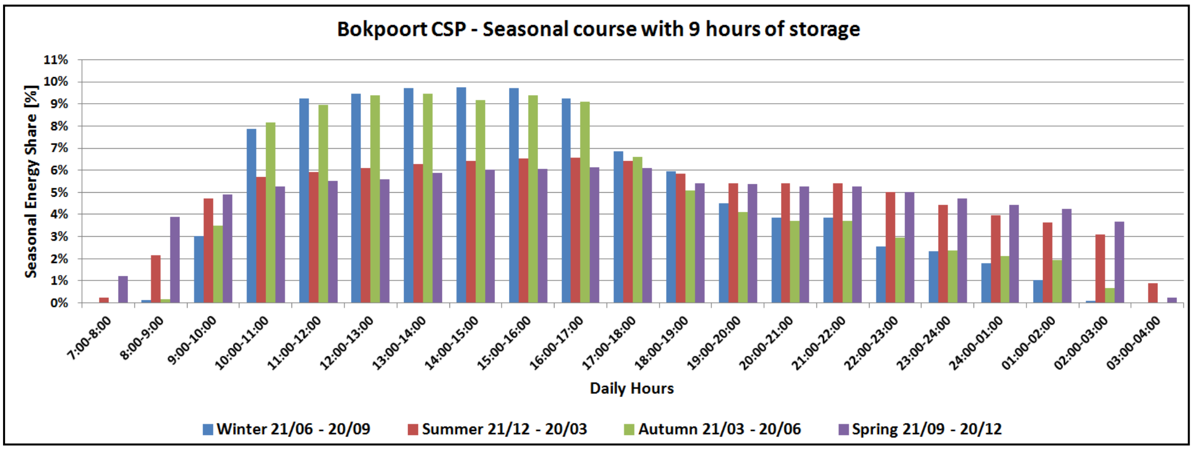


Figure 14: Bokpoort CSP – seasonal course with 3h storage

A sample power course is illustrated in Annexure VI, Figure 35.

7.6 Hydropower simulation

The hydropower simulation includes two run-of-river plants with a total capacity of 14.1MW, which are located in the Northern Cape on the Orange River (Neusberg Hydropower), and in the Free State on the As River (Stortemelk Hydropower), as is shown in Figure 6. The model is based on discretionary flow rate time series data records provided by the DWA.

7.6.1 Methodology and assumptions

The approach of both plants was equal. The power calculation was done based on specific project information and on the daily flow rate records in m³/s (at monitoring stations D7H014 and C8H036 of the DWA).

The following formula was used for the power calculation, with ρ_{H2O} standing for density, g for gravity, h for height difference, and η_{system} for the total system efficiency:

$$P_{el} = \rho_{H20} * g * h * \dot{V}_{stream} * \eta_{system} \tag{7}$$

The required input parameters are shown below. The numbers given in bold were not available, but were approximated or assumed.

Table 22: Hydropower input parameters

	Neusberg Hydropower	Stortemelk Hydropower
Registered capacity [MW]	10	4.1
Max./Min. flow rate [m³/s] through turbine	**60**/5	30/**5**
System efficiency	93%	**93%**
Rated head [m]	18.7	14

The released maximum flow rate of Neusberg Hydropower was contradictory, due to it having been derived from formula (7), taking the registered capacity into account. The minimum flow rate and the system efficiency of Stortemelk Hydropower was adopted by Neusberg Hydropower.

7.6.2 Results

A validation of the expected annual output by the developer yielded reliable results. The deviation was −0.5% for Neusberg, and +8 % for Stortemelk Hydropower, with a CF of 82 and 76%, and an output of 71.5 and 27.2GWh. The annual course of Stortemelk Hydropower was consistent, since the design flow rate was mostly surpassed. The flow rate course of Neusberg (on the Orange River) showed a surplus during summer and autumn, including flooding, and an inferior discharge rate during winter and spring, as is illustrated in Figure 15 below.

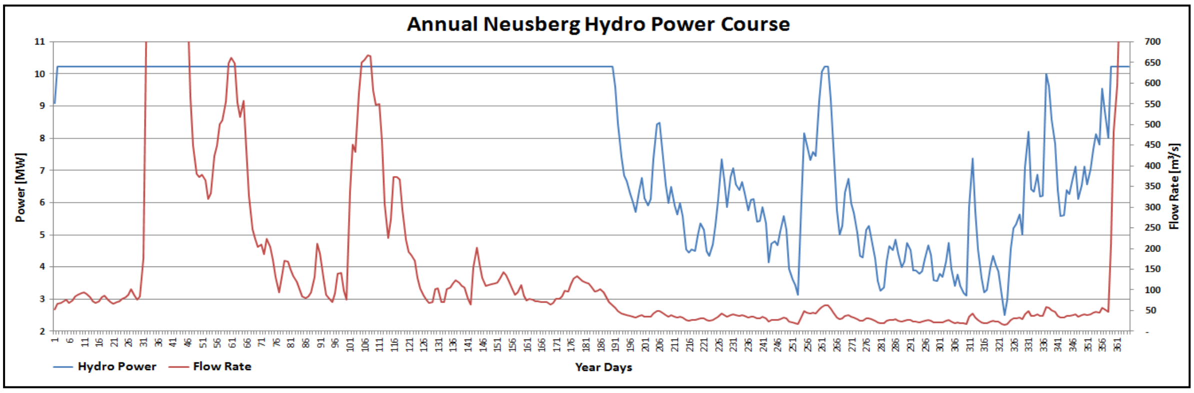


Figure 15: Neusberg hydropower – annual course

The two approved hydropower plants yielded a maximum capacity of 14.1MW and a minimum of 5.4 MW. The base-load contribution was superior, unlike with solar PV, wind, and CSP, since the CF showed the highest values by far, and the full load hours exceeded 7 000h/a.

8 Simulation results

The results include an evaluation of the cumulative output load behaviour to obtain information about the future electricity contribution for South Africa, and an assessment of the contribution made by each technology to the security of supply. The evaluation was done to identify the strengths and weaknesses of each technology utilised.

The results are based on the weather data records for 2010 only, including irregularities caused by single weather phenomenon. Hence, the simulation output does not represent standard yearly conditions over a long period of time.

8.1 Cumulated output

The cumulative energy yield consists of an hourly addition of every source to gain a mutual energy output. It generalises the individual contribution, to allow for the evaluation of the systems output. In addition to a system assessment, an individual evaluation is done as well.

8.1.1 Overview of general results

The model forecasts an annual energy yield of 6 442GWh (including 319GWh of Sere, Klipheuwel and Darling wind farms, which are not part of the REIPPPPP), with the following limit values:

- A maximum occurring power of 2 302MW (27/03, 13:00–14:00), which constitutes 95% of the maximum possible capacity of 2 433MW
- A firm capacity – representing the minimum occurring power of 27.2MW (20/10, 15:00–16:00), which is 1.1% of the maximum possible capacity. It is essential to point out that the firm capacity represents one single value only. Further analysis has to be done to assess the systems quality of minimum contribution.

Regarding to the IRP 2010 prediction analysis (see subsection 4.3.4 and Annexure 1, Part B), which forecasts a demand between 275TWh (low scenario) and 315TWh (high scenario) for 2015, the annual renewable energy distribution will range between 2.05% and 2.34%. The installed capacity will be 4.9% of 47GW of expected maximum demand load for 2015.

A breakdown of the different technologies is shown in Table 23 below.

Table 23: Technology-specific annual energy yield

	Wind power	Solar PV	CSP	Hydropower
Delivered energy [GWh]	3 685	1 906	752	99
Share of total occurring output	57%	30%	12%	1.5%
Max. occurring power [MW]	1 302	900	217	14
Share of max. possible capacity	54%	37%	9%	0.6%
Average full load h [h/a]	2 830	2 119	3 456	7 016

About 57% of the annual output is delivered by means of wind power. The share between the maximum occurring and the total installed power was found to be relatively low (54%), which corresponds to the higher wind power full load hours rather than to the system's average. Related to the dispatchability of CSP and the continuity of hydropower, the contribution that is made to the annual yield is remarkably higher than the capacity share (ranging from 133%, in the case of CSP, to 250%, in the case of hydropower).

The 2011 adjusted target stated in the White Paper on Renewable Energy 2003 of more than 10 000GWh in 2015 cannot temporarily be met. The government's estimation included the entire tendered capacity. An according linear extrapolation of the results reveals an annual yield of 9 124GWh, assuming that biomass and biogas applications operate with similar full load hours as does hydropower. The announced capacity of bidding in R3 will presumably be online by 2016.

To be able to evaluate the frequency occurrence of system loads, a duration curve was calculated. Every value was sorted according to size, and depicted over time (8 760 values). The duration curve in Figure 16 represents the total system load and the contribution that was made by each technology.

The total duration curve does not reflect the sum of the specific curves, because the time-related occurrence of the maximum values differed. The hydropower and wind power graphs are the most constant, which indicates the highest mean power contribution during the period of a year.

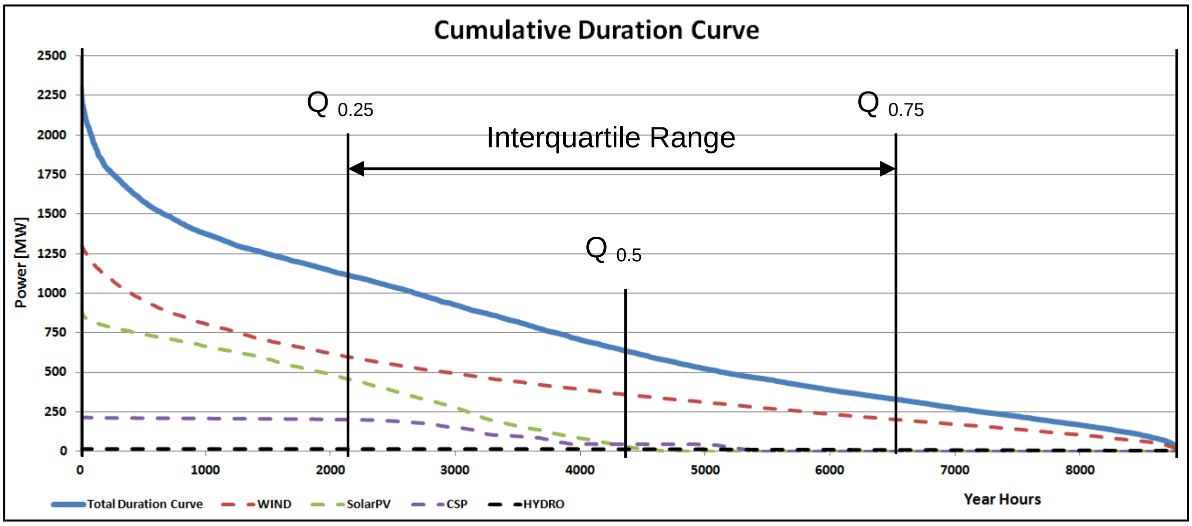


Figure 16: System duration curve

As derived from the table above, a classification into time-related quartiles (Q_i) was done. The interquartile range covered 50% of the distribution (4 380h) and was between 325 and 1 103MW. The results are illustrated below.

Table 24: System duration curve – classification into quartiles

	$Q_{0.25}$	$Q_{0.5}$	$Q_{0.75}$
No. of h [h/a]	2 190	4 380	6 570
Power < h_{XY} [MW]	1 103	632 (= median)	325
Share of maximum power	48%	27%	14%

The duration curve exhibits a high-power bandwidth regarding the fluctuation of the wind power and the solar PV. The power was less than 632MW for 6 months each year.

The seasonal distribution was almost equal, with the share during wintertime being 24%, whereas the summertime contributory share was 25.6%. The wind occurrence was focused on autumn, which supplied 27% of the annual yield, whereas the solar PV contribution that was made during spring achieved 28%.

8.1.2 Contribution to winter demand peak

The main difficulties that were encountered in terms of supply security occurred during winter at around 20:00 (see Annexure 1, Part B, Figure 27). Therefore, an availability evaluation of the results between 19:00 and 24:00 was done.
The supply system's firm capacity during the time period differed seasonally, with it being explicitly greater during summer, based on the availability of the higher wind speeds, on the hydropower contribution, and on the dispatchability of the CSP. Solar PV made no contribution, besides from 19:00 to 20:00 during summertime. Figure 17 below constitutes the firm capacities, which showed a definite trend between 19:00 and 01:00.

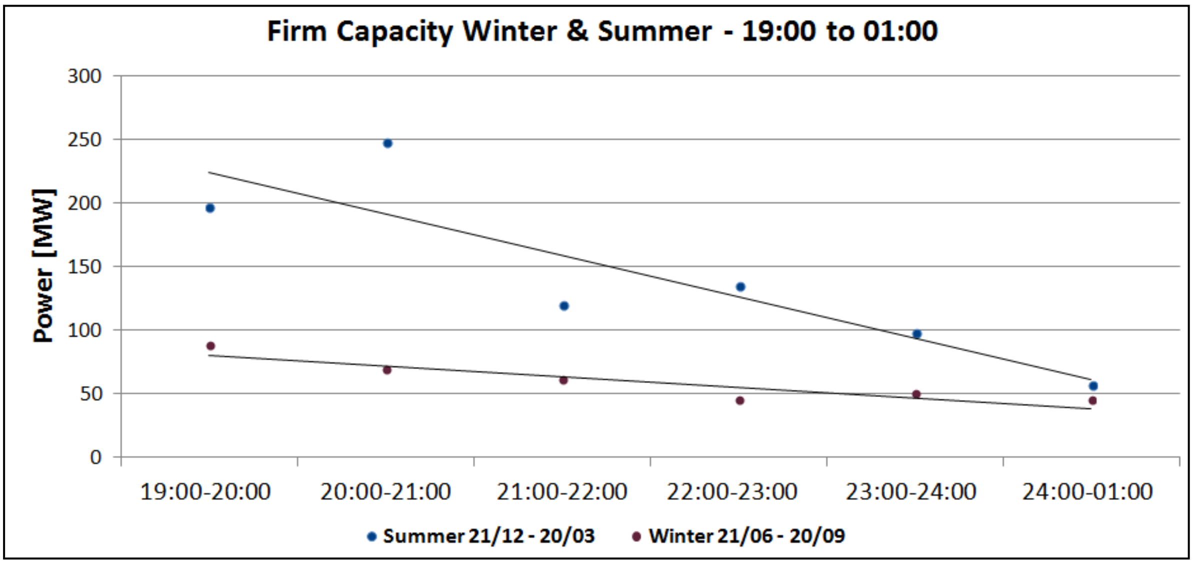


Figure 17: Winter and summer firm capacity – 19:00 to 01:00

The firm capacity represents a single value only. Although it can be used to evaluate the merest temporal contribution, it does not provide information about the probability of occurrence.

To be able to compare the results with those of other fluctuating power systems, a frequency scale for use during certain hours, such as is shown in Table 27 below, might be helpful. The frequency range between winter and summer differed. The gap obviously decreased from 19:00 to 24:00, related to a minor contribution that was made by CSP. In summertime, from 19:00 to 20:00, only 3% of the occurring power loads were less than 350MW, while almost 40% were so during wintertime. On the one hand, such an occurrence indicates the gap existing between summertime and wintertime, but, on the other hand, such an occurrence indicates a deficient wintertime contribution in terms of systems performance.

The gap between summertime and wintertime decreases temporally until both graphs are almost equal (supplementary information in Annexure VII).

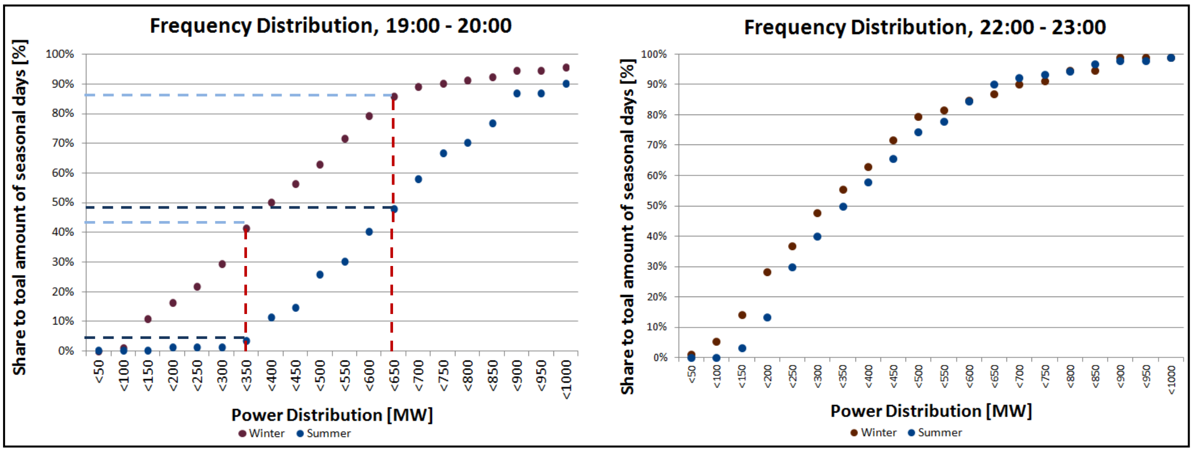
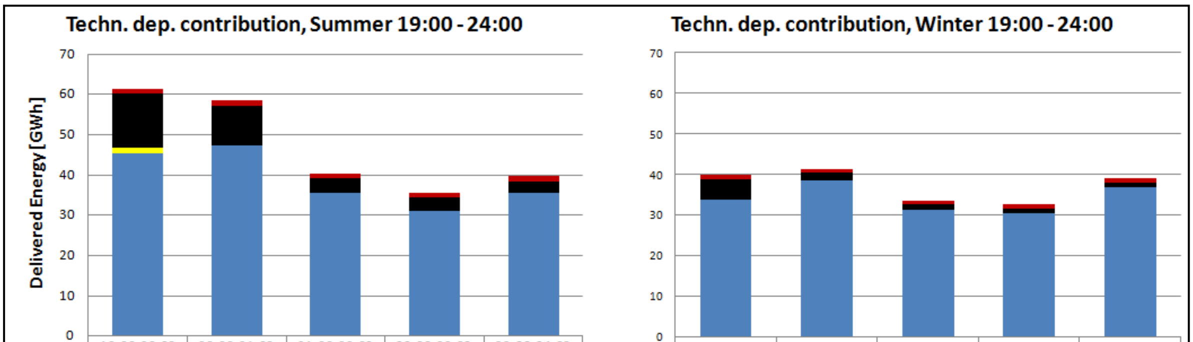


Figure 18: Frequency distribution during summer and winter (A)

To understand the technologically dependent contribution, an average seasonal share is depicted in Figure 19 below. The majority of contributed load is provided by wind power. The decrease in the amount of CSP is based on the limited storage capabilities, since only one out of the three plants was appointed with storage larger than that of 3h of nameplate capacity.



	19:00-20:00	20:00-21:00	21:00-22:00	22:00-23:00	23:00-24:00
HYDRO	1,2	1,2	1,2	1,2	1,2
CSP	13,5	9,9	3,7	3,2	2,8
PV	1,3	0,0	0,0	0,0	0,0
WIND	45,5	47,4	35,5	31,2	35,7

	19:00-20:00	20:00-21:00	21:00-22:00	22:00-23:00	23:00-24:00
HYDRO	1,0	1,0	1,0	1,0	1,0
CSP	5,0	1,7	1,3	1,1	1,0
PV	0,0	0,0	0,0	0,0	0,0
WIND	33,9	38,7	31,4	30,5	37,0

Figure 19: Mean power distribution during winter and summer – 19:00 to 24:00

The amount of energy delivered between 19:00 and 24:00 decreased from 235 during summer to 187GWh during winter. The share between wind power and CSP changed as well. The yellow band represents the limited contribution that was made by solar PV.

8.1.3 Fluctuation characteristics

Based on the high volatility of renewable energy sources, the system tends to fluctuate, with the power output changing within short periods of time. This chapter examines the hourly fluctuation susceptibility, to obtain an impression of generation volatility properties.

The fluctuation can be defined as the derivative of the power change per time. According to an annual, hourly calculated power course, 8 760 alternations occurred. The maximum number of alterations was +960MW and −1 073MW. A determination of the seasonal variation obtained by using the SD yielded a slight difference. The winter SD was 199 MW, whereas the deviation during spring was 182 MW.

A repeated classification into quartiles showed a distinct result. A number of extreme values occurred since the ratio of the lower quartile power ($Q_{0.25}$) to the maximum power was only 18% (see Table 25: Fluctuation duration curve – classification into quartiles Table 25 below). The median was proportionally low (10%) in comparison to the ceiling power change, which confirmed that the majority of the values fell within a limited bandwidth.

Figure 20 depicts the systems absolute- and a real fluctuation duration curve.

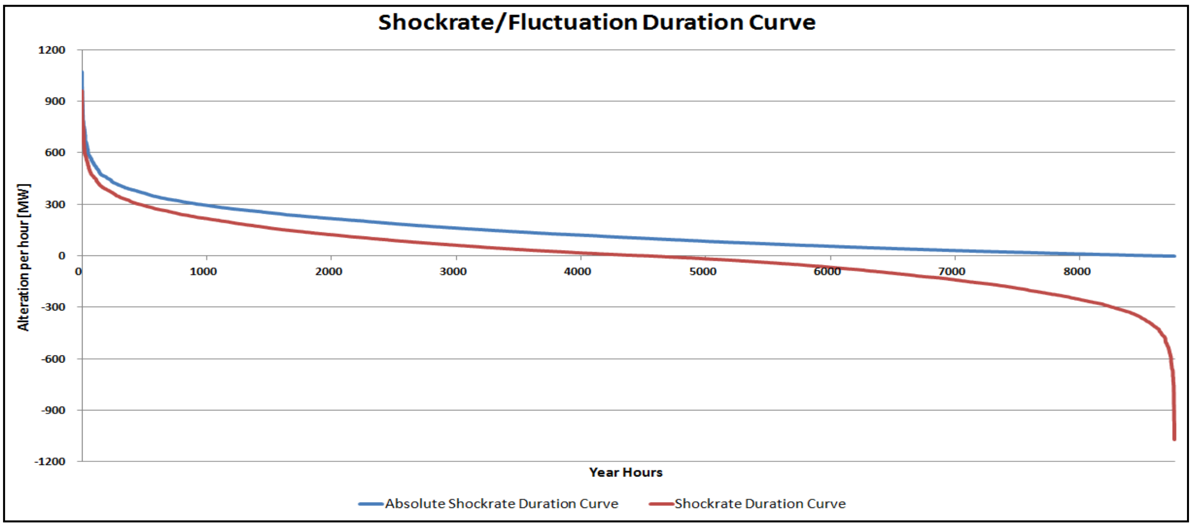


Figure 20: Fluctuation duration curve

Table 25: Fluctuation duration curve – classification into quartiles

	$Q_{0.25}$	$Q_{0.5}$	$Q_{0.75}$
No. of h [h/a]	2 190	4 380	6 570
Power < h_{XY} [MW]	208	108 (= median)	43
Share to maximum power	18%	10%	1%

An exemplary power course is illustrated in Figure 16 below.

Exemplary power course − 01/01/2010–11/01/2010 (representing 01/01/2015–11/01/2015)

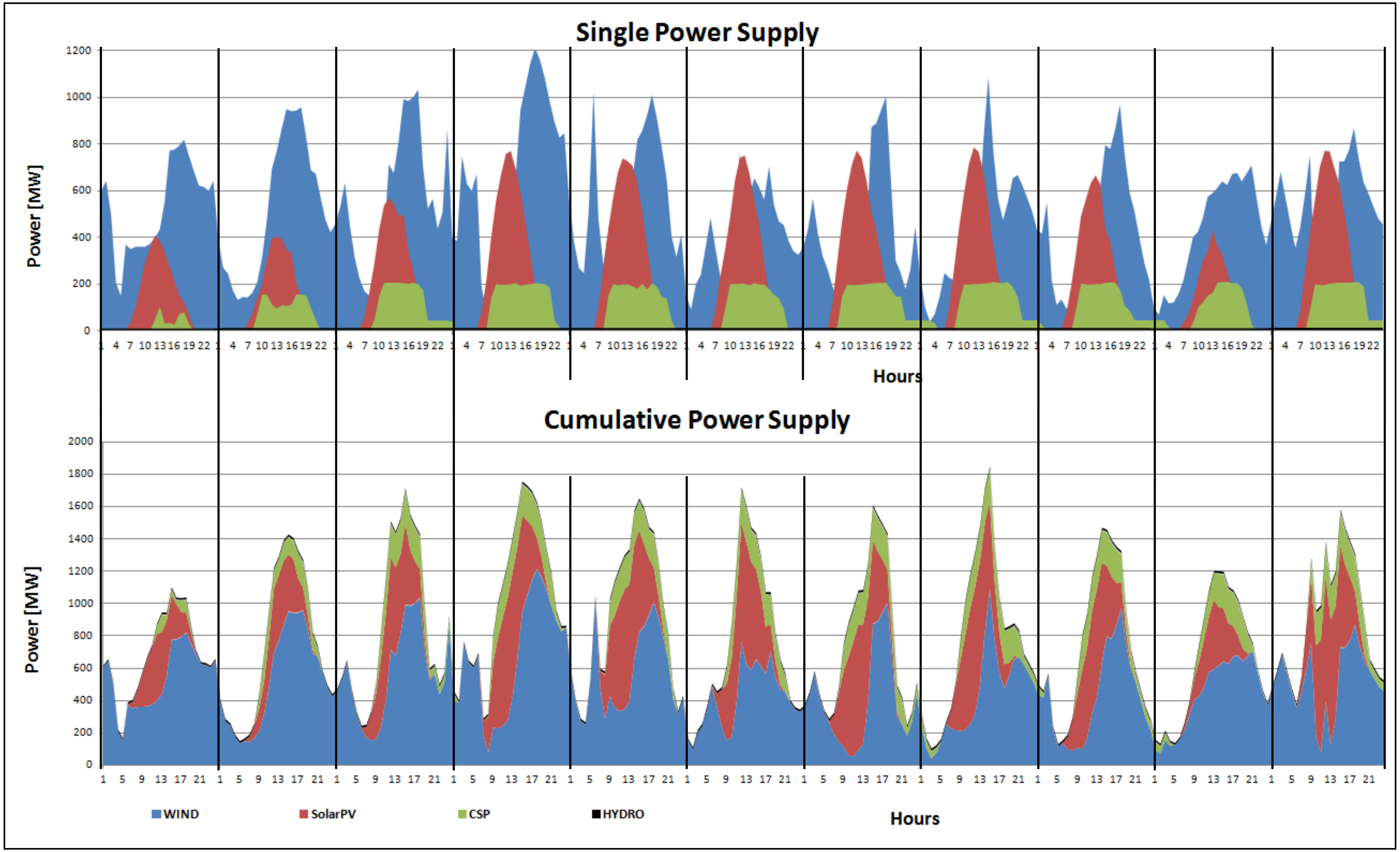


Figure 21: Exemplary single and cumulative power course – 01/01/2010–11/01/2010

8.2 Conclusion

The current thesis consists of an annual renewable energy output, a load behaviour, an evaluation of the contribution to the winter peak demand, and a fluctuation assessment. In terms of such, the scientific question asked can be answered clearly.

The work represents a variety of different, technology-dependent approaches that have been adopted to gain an entire annual load for 2015, by taking 2010 data into account. It simulates every approved IPP project until the financial close of REIPPPP bidding R2 (9 May 2013), as well as three further, already authorised renewable energy projects.

Conclusions drawn from the work

The conclusion of the thesis is split into the following aspects that summarise the most important findings of the work:

- The annual delivered energy was 6 442GWh, which corresponded to from 2.05 to 2.34% of the expected electricity demand in 2015. An inclusion of a linear extrapolation from the results of bidding R1 and R2 to bidding R3 yielded an amount of 9 124GWh. In terms of such figures, the government's ambition to surpass the 10 000GWh level cannot be met.
- Although the wind farms are spread countrywide, the wind speeds were found to be spatially consistent, but temporally fluctuating. Despite the vast variation, almost no (less than 1%) firm capacities can be guaranteed. Further analysis in that field has to be done.
- Solar PV does not make a perceptible contribution to any evening peaking demand. The actual capacity of installed solar PV is 14% less than the registered capacity, which is based on a specification of peak capacity, in accordance with STC. The retail prices per kWh for solar PV and for wind power generation are the most favourable by far, which justifies the highest economic feasibilities.
- CSP offers the greatest degrees of freedom regarding security of supply. Depending on the storage size involved, it could contribute to the evening peak demand. The CF's were almost 2.5 times higher than solar PV exhibits. The insertion of an increased amount of technical implementation into the supply mix would cause a higher individual availability of renewable generated electricity.
- The difference between the summer and winter contribution was found to deviate strongly, especially in terms of frequency distribution from 19:00 to 24:00. The contribution that was made during the winter season was found to be 20% less than in summer.
- The more volatile are the sources that feed into the public grid, the higher the power hub and the burden are. As soon as a regulatory strategic electricity plan

requires an upper share of peaking distribution, storage capabilities have to be taken into account.

- The shock rate of the system that expresses fluctuation in behaviour demonstrated high, but temporally rare, amplitudes. The median was 10 times less, which implies a smoothed course.

It is essential to mention that the entire methodology included many uncertainties and assumptions that strongly influenced the results. Every assumption for each approach has been clearly stated and scientifically justified. The focus in each approach was on developing a single applicable method, by means of using external, reliable information sources, such as the expectations of developers, for validation purposes only.

During the development process, a number of new perspectives and problems arose that could not be processed within the precisely structured framework of the thesis. To examine the open questions, further research would have to be undertaken, which has already scheduled for the next time period by the CRSES.

Contribution to knowledge

The thesis provides a first step towards an ongoing forecast prospective method. The researcher involved assembled tendered capacities into annual energies to figure out the strengths and the weaknesses of the evolving renewable energy mix. The results of the thesis might contribute to advising policymakers to take further decisions in this regard, since a detailed annual projection is now available in the public domain.

Prospect of future research

The thesis determines a first step in forecasting South Africa’s industrial renewable energy supply. It forms part of an ongoing approach to keep the results up to date, to take additional guidelines into account, and to which to append prospective projects.

Research in the following fields is required:

- A focus on the contribution that is made by each technology, to gain a more detailed forecast and to take such technologies as landfill gas, biomass, and others into account
- An improved method of evaluating the simulated results for every single approach
- The models susceptibility of aberrations depends on uncertain assumptions. An assessment of every met boundary value causes an error minimization by coeval adjustments. Each aberration could be quantified in terms of error bandwidths
- A closer collaboration than at present with the weather records, enabling GeoModel to increase the reliability of wind data sets

- An additional examination of the weather data in terms of long period records would reduce the dependency on unforeseen weather phenomenon, and provide an ordinary annual output
- A prospective, ongoing evaluation of the model’s results, according to real values from 2015 onwards

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Annexure I, Part A – Energy consumption

Primary energy consumption

Oil and gas explorations, which are rare, are mostly imported from the Middle East and from other African countries than South Africa, as well as being provided by means of the liquefaction of coal. The annual primary energy proportions differ, due to the fact that the majority of the consumed energy depends on the mining and industrial production of a few crucial players who rely on the changing worldwide economic growth.

The primary energy intensity, as a ratio between primary energy consumption and the gross domestic product (GDP), decreased from almost 7MJ/R in 2002 to 4.2MJ/R in 2009 (SSA 2012, p. 42). Such a key performance indicator has to be considered controversial, since the structure of the economy, the energy sector intensities, the technological development, the sustainability of energy use, and the social indicators strongly influence the value. The Integrated Energy Plan (IEP 2003, p. 4 sqq.) signifies that the industrial policy has shifted towards a greater focus on knowledge-intensive sectors and human resource development than in the past. Such primary production as agriculture and mining with high energy intensities currently contributes less to the economy than does the tertiary or services sector, which might have caused the significant decrease in primary energy intensities experienced.

Final energy consumption

The three major consumers are the industry, of almost 40%, and the transportation and the residential sector, as are illustrated in Figure 22 below. The category ‘Other’ represents such energy carriers as petroleum product solvents, lubricants and bitumen.

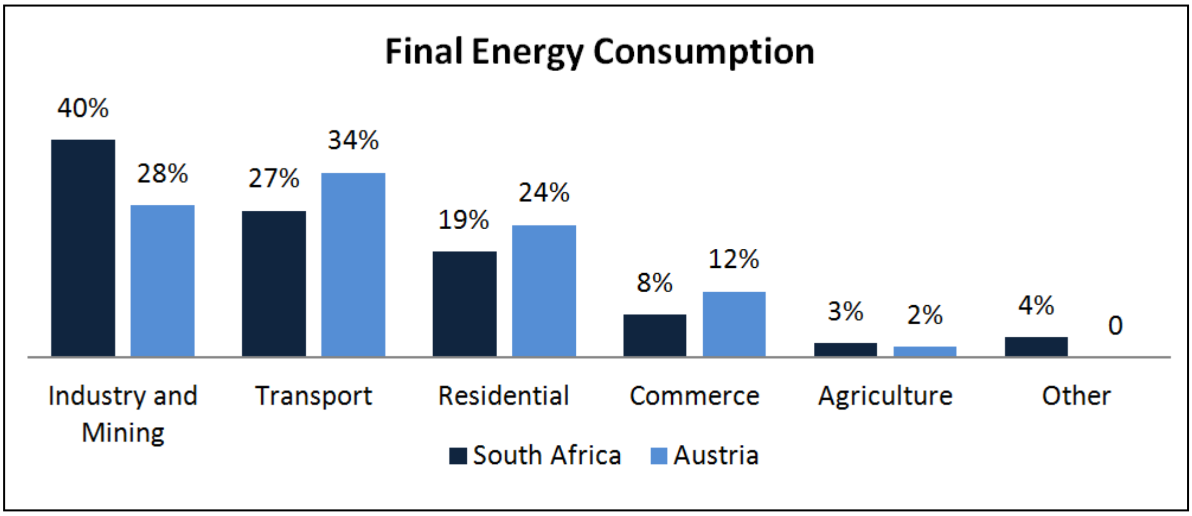


Figure 22: Final consumption, 2006 (DoE 2009, Statistics Austria 2013)

The South African mining industry is characterised by a traditional mining history that currently covers 7.5% of total consumption, while Austria's proportion is only 0.58%. Although the total energy consumption in Austria is 41% less than it is in South Africa, the ratio between GDP per capita is 712% higher, which leads to the conclusion that the economy of South Africa is not as adequately developed and per capita intensive as the Austrian economy is (DoE 2009, World Bank 2013).

Coal industry

Due to the fact that the national mining industry is well established, coal and other mining goods are traded at a more favourable price than the international standards assume. A supply of coal is usually available, with about 53% being facilitated by means of inexpensive opencast mining operations (Chamber of Mines 2007, p. 17).

The expected South African coal reserves are estimated to be about 30 000 Mio tons, which corresponds to 3.5% of the world's proven reserves. South Africa provided 3.6% of the annual worldwide produced coal in 2011, of which the country consumed 2.5%. As a result, about 30% of the country's annually produced coal was exported (BP 2012). In 2000, approximately 41% of the overall coal depletion was used for electricity generation, whereas 98% of it was utilised by Eskom (King N.A., Blignaut J.N. 2002, p. 6).

Table 26 below displays that the share between the total coal revenue and the traded mass deviates from the norm. While 31% of the exported coal earns 56% of the revenue (price to the mass share of 181%), the price that Eskom disburses is 50% lower.

Table 26:Coal sales by sector, 2000 (King N.A., Blignaut J.N., 2002, p. 6 sqq.)

Sectors	Mass rel. share [%]	Price rel. share [%]	Price to mass share [%]
Electricity (non-Eskom)	0.7	0.5	**70**
Eskom	41	20.6	**50**
Exports	31	56.1	**181**
Synthetic fuel (Sasol)	20.7	14.2	**69**
Others	6.7	8.5	**127**

The countrywide coal resources are exclusively depleted in the north-eastern part of the country, leading to disparities in the contribution that is made by power generation.

Petrol industry

According to the South African Petroleum Industry Association (SAPIA 2012), the total consumption of petroleum products in 2010 was 25 300 Mio litres. Of the liquid fuel demand in 2005, 36% was synthesised from locally depleted coal by Sasol (30%) and from natural gas by PetroS (6%), whereas the total installed refinery capacities were lower (being 27.5% in 2007). This development implied a greater degree of capacity utilisation from synthesised fuels than from refined crude oil. The remaining 64% of the liquid fuel demand was refined by means of imported crude oil (DoE 2013).

Petroleum fuels (except for the liquefied coal products) and other chemicals for industry, transport, heating, and other uses were provided by such national and international energy utilities as Caltex (Chevref – Chevron Cooperation), Sapref (which is a joint venture between Shell SA Refining and BP Southern Africa), Engen, and others.

Annexure 1, Part B – Electricity supply and demand

History

South African electricity consumption increased almost steadily, from 75TWh in 1975 to 260.5TWh in 2007. The major uncertainties in more recent years have been based on the unbanning of the African National Congress (ANC) in 1990, with a subsequent extraordinary increase of consumption, the Asian and emerging market crisis in 1997/98, and the economic crisis after 2007 (Mashao M. 2012, p. 4).

In 2010, 58% of the African continent's electricity utilisation was owned by South Africa (in comparison to 60.5% in 1975), underlining the country's primacy in Africa (World Bank 2013).

Key drivers of electricity growth

An assessment of key drivers of electricity growth was performed by Eskom (taking historical impacts into account), to figure out the most influential correlations. Various interrelations are enumerated below (Mashao M. 2012, p. 3):

- **Economic growth**
  The relationship between the GDP and the growth rate, as well as the relationship between the electricity sales and the sales growth rate has shown a correlation since 1920. The chart in Figure 18 below illustrates the fact that the electricity sales grew to a similar extent as did the GDP. While the average electricity sales growth rate dropped between 1950/75 and 1975/2007 from 7.5 to 3%, the GDP growth decreased by a similar amount (from 5 to 2%).

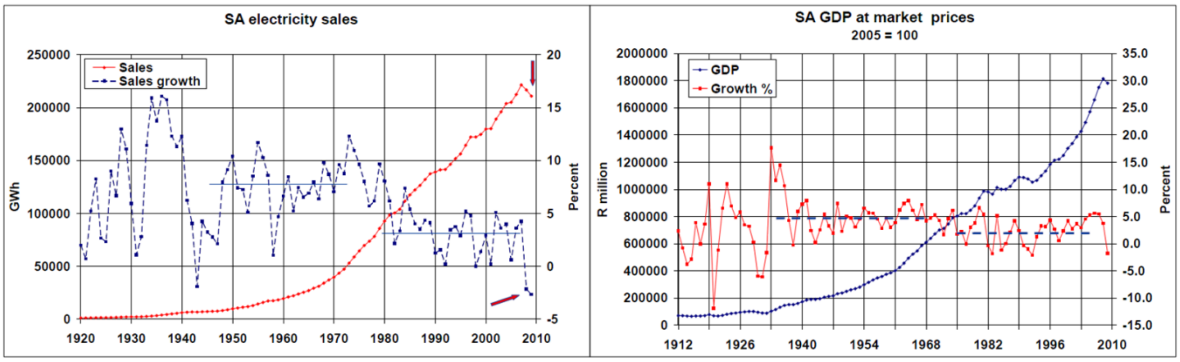


Figure 23: Correlation between the electricity- and the GDP growth rate (Mashao 2012)

- **Weather – seasonal temperatures**
  Due to the fact that the majority of the installed heating devices are driven by electricity, and due to the fact that the insulation of buildings is insufficient, heating

during wintertime influences the daily consumption load curve significantly more than does air conditioning during summer (see Figure 27, p. 79)

- **Large industrial projects**
  The larger the industrial sector is, the higher is the influence on electricity consumption. South Africa's heavy industry and mining sector exhibits vast energy expenditures (see section 4.2)

Electricity intensity development

The electricity intensity (i.e. the share of electricity sales and the GDP) steadily increased until 1997, due to the increased efficiencies of power production units, the heightened efficiency of the transmission system, and favourable resource prices. The growth of electricity demand was higher than was the GDP growth. In later years, the electricity intensity started to decline, since the South African economy had matured, and the prices of fossil fuels had increased. The future development forecast by Eskom anticipates a distinct downturn in the electricity intensity, since the electricity demand growth is expected to be less than the GDP growth (Mashao 2012, p. 19 sqq.). Figure 19 below illustrates the past course and future trend of the electricity intensity in kWh/R.

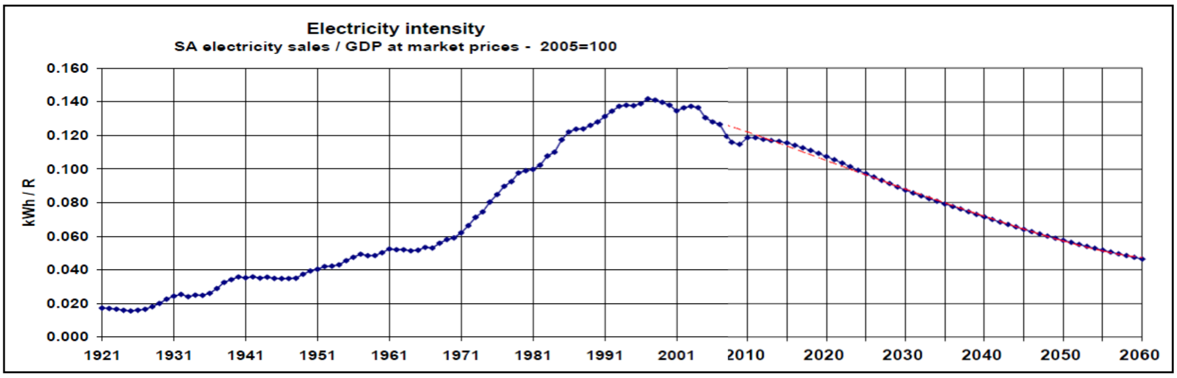


Figure 24: Electricity intensity (Mashao 2012, p. 19 sqq.)

The electricity intensity in 2009 was 0.12kWh/R, whereas the primary energy intensity in 2009 was 1.17kWh/R (= 4.2MJ/R), as was noted in Annexure I, Part A. The difference can be explained in simplified form as being due to the intermediate reduction factors that are involved in converting primary energy to electricity (such as conversion losses, power efficiency, transportation, and other related factors).

Electricity supply progression

Figure 20 below refers to the contents of subsection 4.3.1, covering the National electricity supply.

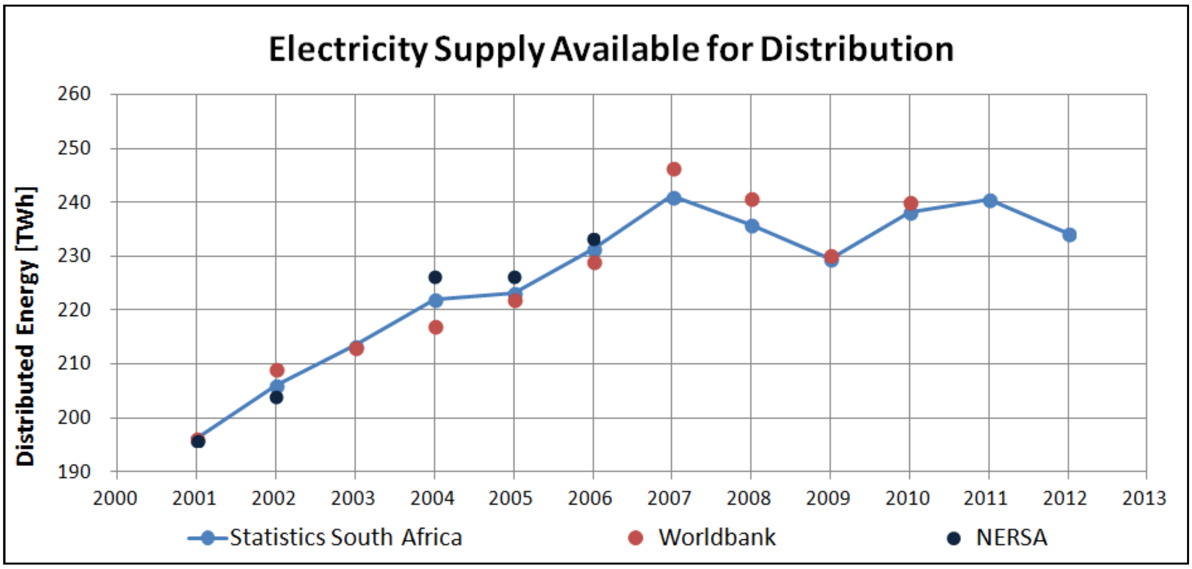


Figure 25: Electricity available for distribution (SSA 2013, World Bank 2013, Nersa 2006)

Sector-specific electricity demand

Figure 21 below illustrates the share of customer categories referred in subsection 4.3.2.

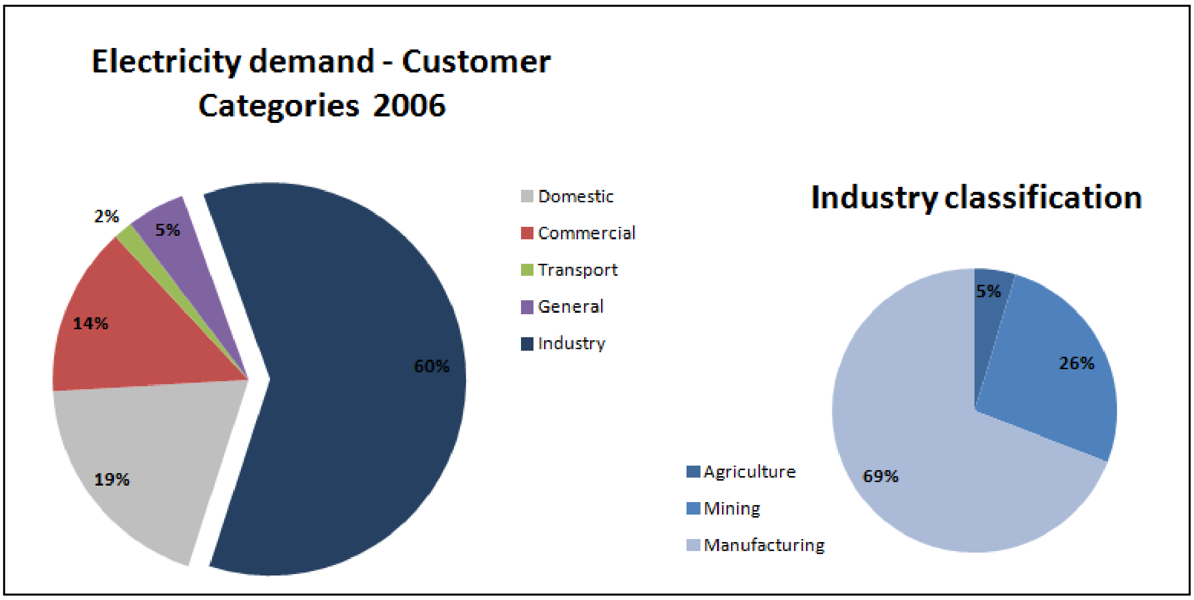


Figure 26: Electricity demand, by sector (Nersa 2006, p. 58)

Weekday electricity demand

To understand the meaningful implementation of fluctuating renewable generation in the electricity supply, the daily consumption trend has to be considered, since the demand precisely determines the supply. The generic South African weekly load curve changes, depending on the time of day, and varies markedly between the lower summer and the greater winter demand. Two major peaks typically occur during a winter's day: at 09:00, and at 19:00. The higher consumption during wintertime is caused by electrical heating devices. Figure 27 below depicts the daily demand during a week in winter and one in summer. The difference in the consumption of power between summer and winter can increase by as much as 15%.

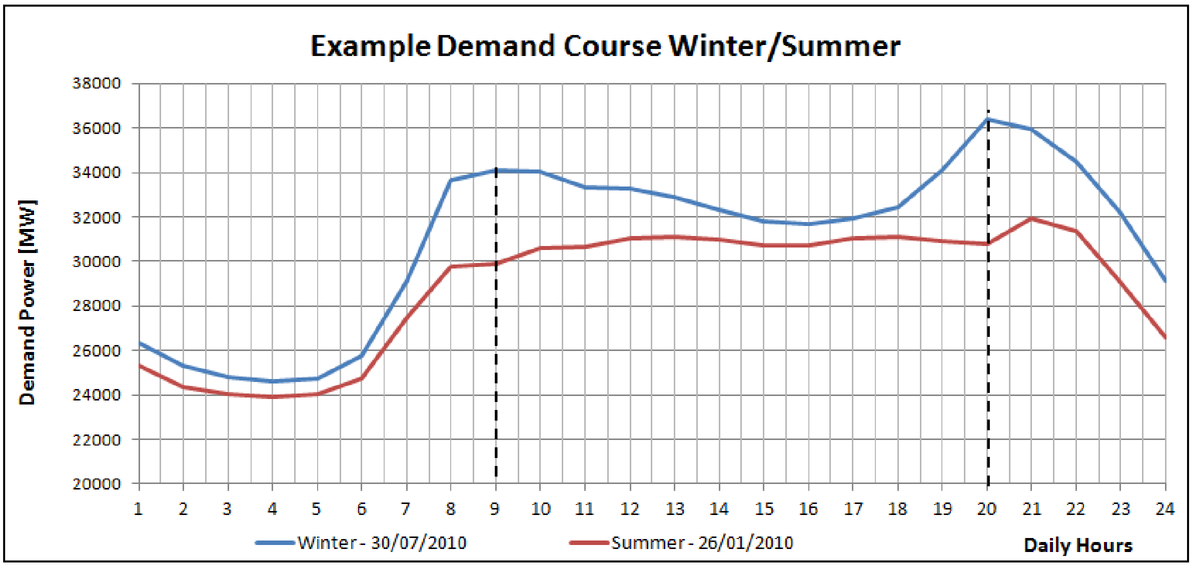


Figure 27: Exemplary weekday demand during summer and winter in 2010 (Eskom 2012)

Causes of the incipient energy crisis

This subsection refers to subsection 4.3.3 – 'Present lack of supply'. The causes of the incipient energy crisis are controversial, due to the different interests of all the stakeholders involved. Eskom blamed the energy crisis that was experienced in 2007/08, and the shortages that are anticipated until 2016, on the following contributory factors (Inglesi R., Pouris A., p. 2):

- The exceptional increase of 50% from 1994 to 2007 was based on (World Bank 2013):
  - A strong, unexpected upturn in the economy occurred after sanctions were lifted in the early 1990s.
  - The implementation of the Free Basic Electricity Policy in 2003 prescribed the allocation of an allowance of 50kWh electricity per month to poor households, executed by the individual provinces (DME 2003).

- The government's decision in 2004 to fund new capacities was delayed.
- A countrywide lack of research into energy in general (with only 0.34% of the international research publications reporting on energy-related topics, with South Africa contributing 0.5% of academic research papers in all scientific disciplines internationally).

MTRM – recommendation for closing the supply/demand gap

The recommendations discussed below are directed by the IRP 2010 (2011, p. 66).

Supply-side options

- Implementation of the REFIT programme, which was modified to form the REBID programme (see section 5.3)
- Implementation of co- and own generation
- Increased generation availability from existing fleet, by means of enhancing the outage rate (with 1% improvement by 2012 corresponding to about 2.5TWh per year)

Demand-side options

- Meeting the government's target to roll out 1 million SWHs to cut down power demand
- DSM: the addition of 25% on existing commitments, with a vast forecast reduction potential
- Supplying of demand response (DR) to small, commercial and industrial applications

The IRP 2010 (2011, p. 69) determined that a gap would still remain during 2011 and 2012, even if every identified potential could be captured. Therefore, three further options were added to avoid load-shedding in future:

- ECS: A reduction target could be established for the 500 largest power consumers during peak loads, which would include penalties if specifications are not met. The estimated saving potential is 6 TWh.
- Compulsory DR: Consumption during peak hours could be limited for certain residential users.
- Increasing OCGT load factor: By increasing the OCGT operation by 5%, about 1 TWh of supplementary energy output could be provided.

IRP demand forecast

As part of the IRP, two demand forecasts were assessed. They varied widely, since different methods were applied, although the same input parameters were utilised to keep the result comparable. Such input parameters as economic growth (in terms of the GDP), changes in energy intensity, international sales, system losses, load profiles for customer sectors, and others were utilised (IRP 2010b):

The two forecasting methods can be abstracted as follows (IRP 2010a, p. 4):

- SO forecast: "The model is a combination of statistical analysis, tracking of historical trends and applying expert knowledge."
- Council for Scientific and Industrial Research (CSIR) forecast:
  "The model is basically a multiple regression model forecasting technique used to forecast the annual consumption within the individual electricity sectors by relating various conditions (or 'drivers') to the demand in each sector."

For both methodologies, a sensitivity analysis was undertaken during the IRP process to ensure a reliable generation forecast. A high and low forecast scenario was allocated as well, with the intention that it should not be breached.

Figure 23 below illustrates the trend experienced in both methods, and the actual generation that occurred until 2012, according to the SSA, as well as a power demand forecast by Eskom.

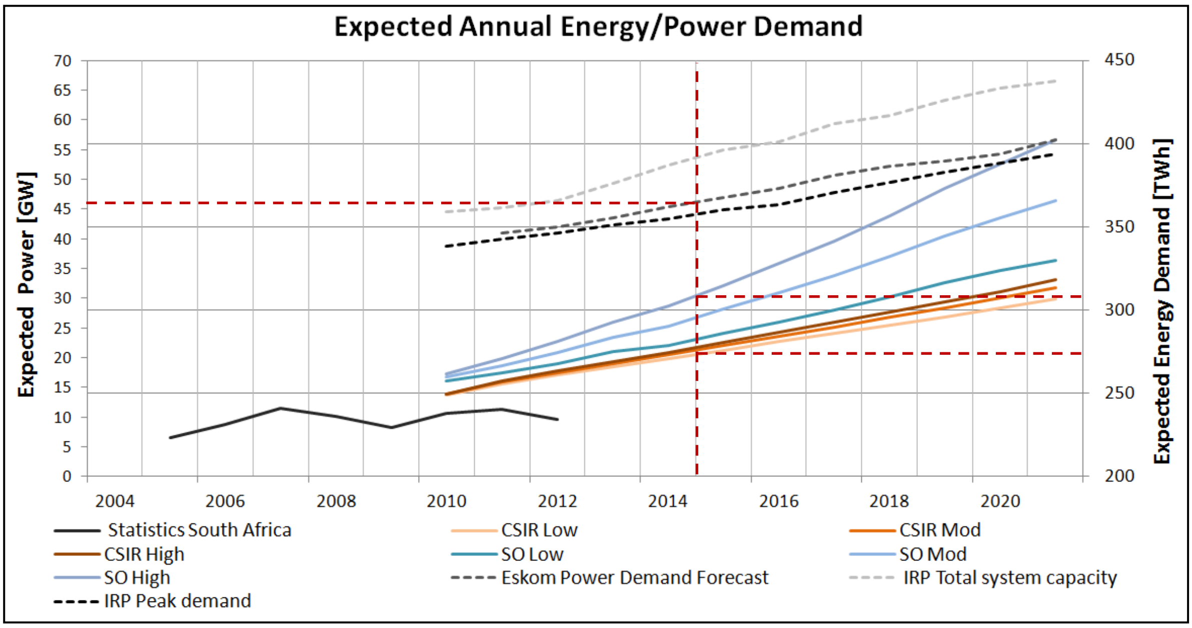


Figure 28: Expected annual energy simulation (DoE 2010, IRP 2010b)

The results of the above were discussed in subsection 4.3.4 – 'Prospective development'.

Annexure I, Part C – Electricity distribution

High-voltage grid map

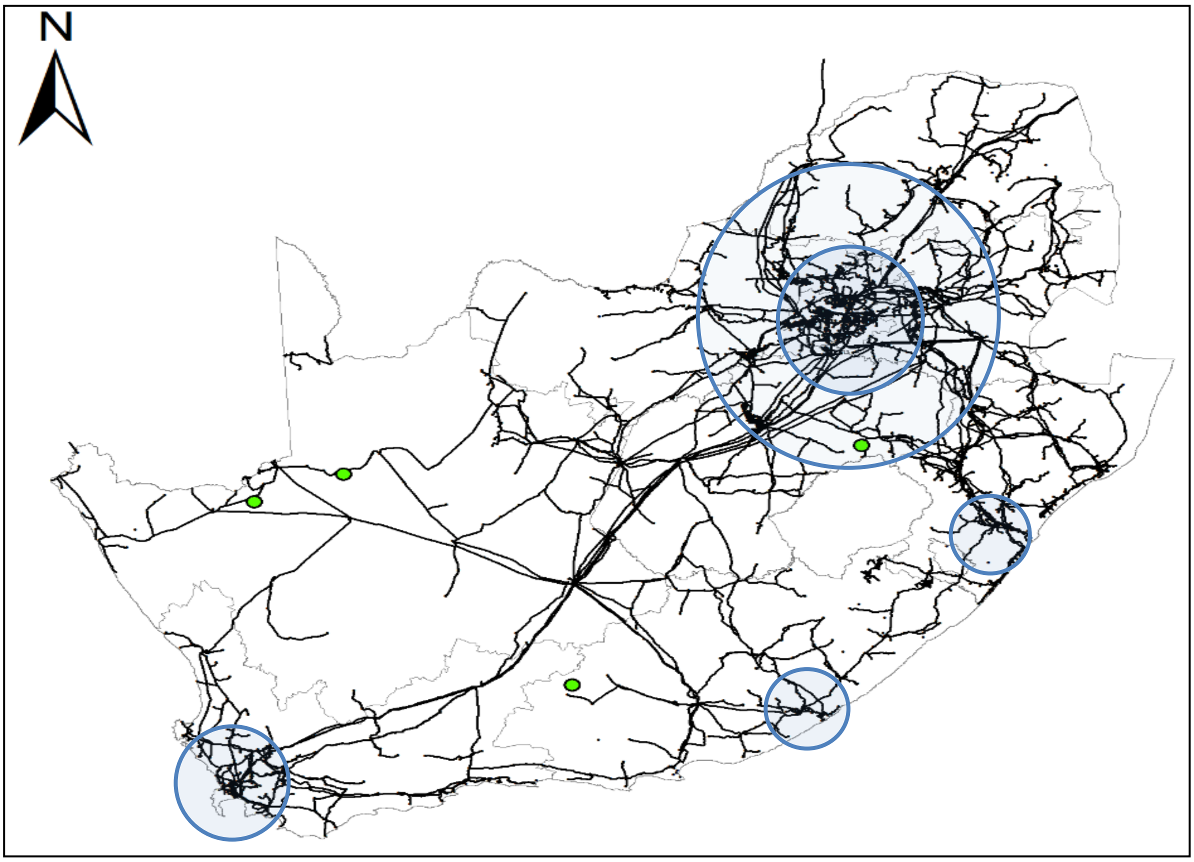


Figure 29: High-voltage grid map – South Africa (CRSES 2013)

Transmission and distribution line specifications

The last released electricity supply bulletin of the SSA (Nersa 2006) determined the total number of transmission and distribution lines for 2006.

The transmission grid, which is carried and owned by Eskom, consists of 765, 400, 275, 220 and 132kV lines, whereof 56% are 400kV lines. An additional 533kV high-voltage direct current (HVDC) line connects Johannesburg with Sonogo (Mozambique), for international power transfers. The total transmission line length is 27 770km.

The distribution network can be differentiated into lines and cables, and is subdivided into high-voltage (44 to 132kV), medium-voltage (1 to below 44kV) and low-voltage (below 1kV). While 78% of the distribution lines are carried by Eskom, the majority (96%) of the distribution cables are owned by municipalities and a private provider. The total distribution length is 608 000km, of which almost 47% consists of medium-voltage lines managed by Eskom, and 24% of low-voltage cables run by municipalities and a private provider. The total transformer capacity in 2006 was 403GVA.

Future expectations

A further, intended installation of renewable energies will cause decentralisation of the power supply, which will basically bring relief to the transmission grids, but which will strain the local grids during full-load times. A bidirectional current flow has to be technically feasible, which implies the need for further applications, such as dynamic transformers and static VAR compensators (SVCs), to reduce the reactive power that is required for voltage stability and variation.

Under the prospective ‘Transmission Ten-Year Development Plan 2013–2022’ (Eskom 2013, p. 11), the following investments are provided until 2022:

- 3 700 km of 765 kV lines and 8 631 km of 400 kV lines
- A total installed transformer capacity of about 84 000 MVA, including the transformation capacity that is required to integrate the fluctuating generation
- A capacitor power of 2 600 Mvar, which is required to support areas of the network under contingency conditions, to ensure that the required voltage levels are maintained
- A reactor power of 9 200 MVA, which is a consequence related to the extensive distance that the transmission system has to cover

Annexure II – Legal Framework

IRP Accruement

The development of such a future-orientated plan as the IRP 2010 requires extensive preliminary work. Various policy and legal guidelines, such as a legal framework and certain resolutions, have to be set before standards and other technical specifications can be implemented. The following guidelines and decrees strongly contributed to the development of the IRP 2010.

White Paper, 1998

The 'White Paper on the Energy Policy of the Republic of South Africa' was published in December 1998 by the DME. South Africa's external and internal environments, including the lifted, apartheid-induced embargos had experienced fundamental shifts, which resulted in significant changes occurring in the context of the energy policy. The White Paper's objective constitutes a major re-evaluation of the sector's policies that are aimed at providing policy stability for energy suppliers, investors and consumers.

The energy policy objectives were spelled out as follows:

- Increasing access to affordable energy services
- Improving energy governance
- Stimulating economic development
- Managing energy-related environmental impacts
- Securing supply through diversity

The White Paper further covers the major topics of the demand sector, the supply sector, and cross-cutting issues. The White Paper, which takes integrated energy planning as part of the cross-cutting issues, promotes a development of standards, guidelines and codes of practice for the correct use of renewable energy sources as part of the supply diversity that can be facilitated by the DME, but which must, in addition, include facilitation by the standard authorities and the renewable energy industry (DME 1998).

IEP, 2003

The IEP 2003 was published by the DME. The integrated energy planning process was based on the results of Energy Outlook 2002 (DME 2002), which was developed by DME, Eskom, and UCT, with its Energy Research Institute (ERI). The IEP 2003 is not a precise blueprint for the energy sector, but it is a framework within which specific energy development decisions can be made.

Amongst derived, valuable conclusions regarding the integrated planning process, the IEP accentuates that historically driven energy sector decisions were mostly made by maintaining supply security. The economic, environmental and social impacts of such alternatives as renewable energies were, by and large, not considered, which amounted to a large-scale, capital-intensive supply, instead of to a more cost-effective, long-term alternative (DME 2003a, p. 4 sqq.).

White Paper on Renewable Energy, 2003

As well as the IEP, the White Paper on Renewable Energy 2003, published by the DME, strongly facilitates the commitment of sustainable resources. It requires essential elements of renewable energy implementation, such as suggestions for financial, legal and regulatory instruments, as well as explaining policy principles. One of the White Paper's objectives was to develop an appropriate legal and regulatory framework for pricing and tariff structures to support the integration of renewable energy and to attract investment. The government's medium-term (10-year) target of 10 000GWh to be attained by 2013 was set (DME 2003b).

South Africa has two Acts that have directed the planning and development of the country's electricity sector, including a strategy for renewable energy power supply as well.

The Electricity Regulation Act, 2006

A part of the Electricity Regulation Act (ERA), No. 4 of 2006, named 'Electricity Regulation on New Generation Capacity', and gazetted by the DoE in May 2011, established rules and guidelines for the implementation of an IPP Bid Programme and for the procurement of an IPP for new generation capacity. The Act regulates simple access for the buyer, as well as for the purchaser, and all necessary requirements, into a PPA. Since the subsidy scheme for IPPs was changed from a feed-In tariff to a bidding approach in 2011, the Act has since been adapted, as was explained in section 5.2 (DoE 2011).

The National Energy Act (NEA), 2008

The NEA, assented to by the president in November 2008, has been established by the Ministry of Energy with the main intention of developing an IRP, in terms of which the IRP 2010 was developed. The Government Gazette No. 31638 of 2008 (NEA 2008) contains a variety of objectives that are more detailed than are those contained in the White Paper 2003. Some of the former are listed below:

- To ensure an uninterrupted supply of energy to the country
- To promote diversity in the supply of energy and its sources
- To promote energy research
- To promote appropriate standards and specifications for the equipment, systems and processes used for producing, supplying and consuming energy

The Act further established the SANEDI as a regulatory body for guaranteeing energy efficiency and research, as well as development matters.

Standardised approach for the Renewable Independent Power Producer Purchase Programme (REIPPPP)

This section is referred to in section 5.3, p. 23, 'The REIPPPP'.

1. Request for proposal (RFP)

The 'Request for Qualification and Proposal for New Generation Capacity' under the IPP Procurement Programme (DoE 2011c) assumes a number of requirements for developers and authorities that have to be conformed to in order to be admitted for the further steps.

The RFP's content comprises general requirements (Part A); sets qualification criteria for each bidder (Part B); and defines evaluation criteria after the submission (Part C). Six different further volumes determine the detailed legal, technical, financial and economic development requirements, as well as government policies, in terms of guidelines and templates.

The first step for an IPP to access the RFP requires a non-refundable fee of R15 000, whereupon the government provides the necessary briefing notes for the full approach. As Figure 5, p. 28 illustrates, the RFP consists of the three parts discussed below.

Part A – General requirements, rules and provisions

Part A addresses all legal requirements, rules and provisions for the bidders in order to guarantee a suitable bidding process. It states the DoE's rights, the RFP structure, and a timetable that has to be met by all involved parties. A bid response must include, inter alia, a payment confirmation of a 1% development fee of the total project expenses (to cover DoE costs incurred), as soon as the project achieves the 'Preferred Bidder' status and a bid guarantee of R100 000/MW for submission, and R200 000/MW after being selected as a 'Preferred Bidder'. The bidder has to confirm a binding offer to the DoE. The bid response must remain valid and binding for 300 days, from the submission date on.

Part B – Qualification criteria

The qualification criteria constitute the major integral part of the RFP process. They determine legal, environmental, financial, technical and economic development criteria, and prevalently refer to volumes 1 to 6. In any case, a project developer has to fulfil all consent criteria to be permitted as a preferred bidder.

During the final submission procedures, the fulfilment of environmental and financial criteria emerged as one of the main challenges for IPPs during the submission process. Especially the long duration and the high expenditure involved have been key challenges to the process (Siepelmeyer N. 2013):

The following monetary requirements imply difficulties for IPPs:

- Whereas the investors principally postulate a preferred bidder's status in relation to a submitted project before they confirm an investment, the DoE requires funds and bank guarantees as a submission condition, without any legal consent.
- An IPP is bound to allocate 40 to 45% of the project funds by a national lender, which limits broader options. The share depends on which renewable technology is acquired.

The RFP's environmental criteria consent by the DoE depends on a successfully completed environmental impact assessment (EIA), as confirmed by the Department of Environmental Affairs (DEA).

According to the RFP, Part B – 'Environmental Consent Criteria and Evaluation' (DoE 2011d, p. 18), each bidder has to fulfil the following requirement in its own bid response: "Provide evidence [...], in its sole distinction, that all the requisite Environmental Consents [...] for the relevant Technology have been obtained and identify all other Environmental Consents that are required [...] and not listed in [...] the General Overview of Environmental and Land Use Consents."

The EIA is executed by the DEA, which represents the interests of diverse public, environmental concerned authorities. It is an interdisciplinary procedure that is related to various qualification criteria in Part B of the RFP. The assessment's emphasis mainly focuses on such environmental issues as, inter alia, a geotechnical and agricultural report, and a botanical, faunal and paleontological impact assessment. It is further adapted to various power production technologies which, among others, include birds, bats, and shadowing reports, and a Civil Aviation Assessment (CAA) for wind turbine purposes. The evaluation process further considers different subjects, such as a social and a visual impact assessment. The accumulation of all related reports and assessments represents an entire EIA.

The EIA procurement, as illustrated in Figure 5, p. 28, is a public, ongoing and iterative process that includes all participating parties, including abutting neighbours, lobbyists, authorities, and others. A developer has to publish all comissioned specialist reports related to every contemplated concern. A public participation meeting follows, with comments and appeals submitted by the participants. The developer is committed to providing a timely responding statement, and is responsible for resolving all complaints until the time of that all parties concerned give their consent. It is the developer's duty to appoint an independent, accredited consultant to assess the reports before they can be approved by the DEA. Such consultancies as Terramanzi Environmental Consulting, EcoAfrica, and Aurecon Group Ltd, as well as others, commonly release their results for public perusal. Provided that all concerns are perceived and resolved in the Final Scoping Report, a Record of Decision (RoD) confirms the closure of the EIA process.

The RoD grants a projects permit to construct a full-scale power plant, which is a requirement for an REIPPPP bid response.

Part C – Evaluation criteria

The purpose of the evaluation criteria is to determine the relative rankings of all received bid responses. The project's evaluation criteria are based on the equivalent annual tariffs in R/kWh, and the coincidental economic development, with a split of 70% financial and 30% social issues. Whereas the economic development assessment includes a multipart social environment analysis, the tariff assessment is set with the following principle in mind: the lower the bid price is, the better the likelihood is of it being accepted. The economic development should guarantee a national/regional benefit, since international power producers have entered the market. The accurate evaluation methods are depicted in the RFP Volume 5 – 'Economic Development Requirements' (DoE 2011e, p.12,13).

According to the 30% contribution of economic development (social concerns), the following weightings were allocated:

- Job creation (25%)
- Local content (25%)
- Ownership (15%)
- Socio-economic development (15%)
- Preferential procurement (10%)
- Enterprise development (5%)
- Management control (5%)

2. The bidding procedure and the financial close

As soon as the bid submission is completed by the applicants at a certain appointed date (see Figure 5, p. 28), an assessment, which is based on the evaluation criteria of Part C, can be done. The evaluation team consists of international reviewers, and a legal, a technical, and a financial team, drawn up by external and governmental consultants. The different evaluation streams are shown in Figure 5. The result is a ranking of all bidders, which is published in the form of an official announcement in respect to the bid submission date. The DoE appoints as many preferred bidders as are required to provide the maximum allocation of Megawatt for a technology.
Once an IPP is declared as a preferred bidder, the final contracts of shareholders can be prepared. After an appropriate-to-every-technology announced PPA is comprehensively concluded, a Direct, Transmission, Distribution, Implementation, and Connection Direct Agreement is signed between the SBO, NERSA, and the DoE in terms of the Public Finance Management Act (PFMA), with the contract involved being valid for 20 years. So far, the SBO has been managed by Eskom.

Annexure III – Data record analysis

The following formulas were used to evaluate the wind records and their error characteristics.

Univariate key performance indicators

Univariate figures are used to evaluate a single record.
Arithmetical mean value: n = number of data points, Y_i = single data point for i = 1,2,3,...

$$\bar{Y} = \frac{1}{n}\sum_{i=0}^{n} Y_i$$

Median: separates the upper and lower half of a data sample.
Standard deviation (SD): Characterises the expected ordinary aberration of a single chosen data point in the record. The higher the deviation is, the higher is the variation. The SD's unit complies with the values unit.

$$\sigma = \sqrt{Var(Y)} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(Y_i - \bar{Y})^2}$$

Key performance indicators for model assessments

Evaluation of the error between model and measurement concerns the following indicators.
Absolute error: Constitutes the difference between measurement and simulated value.
e_i = error, y_i = measured value, y'_i = model's value.

$$e_i = y_i - \hat{y}_i$$

Root mean square error (RMSE): RMSE is a mean quadratic error. In comparison to the ME, in terms of which positive and negative errors might be complementary, the RMSE determines every error based on its square. The RMSE unit complies with the values unit.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}$$

Mean absolute error (MAE): The MAE does not take high single errors into account, since it is not squared. If the MEA is equal to the RMSE, all occurring errors are equal.

$$MAE = \frac{1}{n}\sum_{I=1}^{n}|y_i - \hat{y}_i|$$

Mean absolute percentage error (MAPE): The MAPE determines the error in relation to the measured value, and is expressed in percent.

$$MAPE = \frac{1}{n}\sum_{I=1}^{n}\frac{|y_i - \hat{y}_i|}{y_i}$$

Annexure IV – Wind analysis

The following figures contribute to a better understanding of the annual wind power production and are referred in the text.

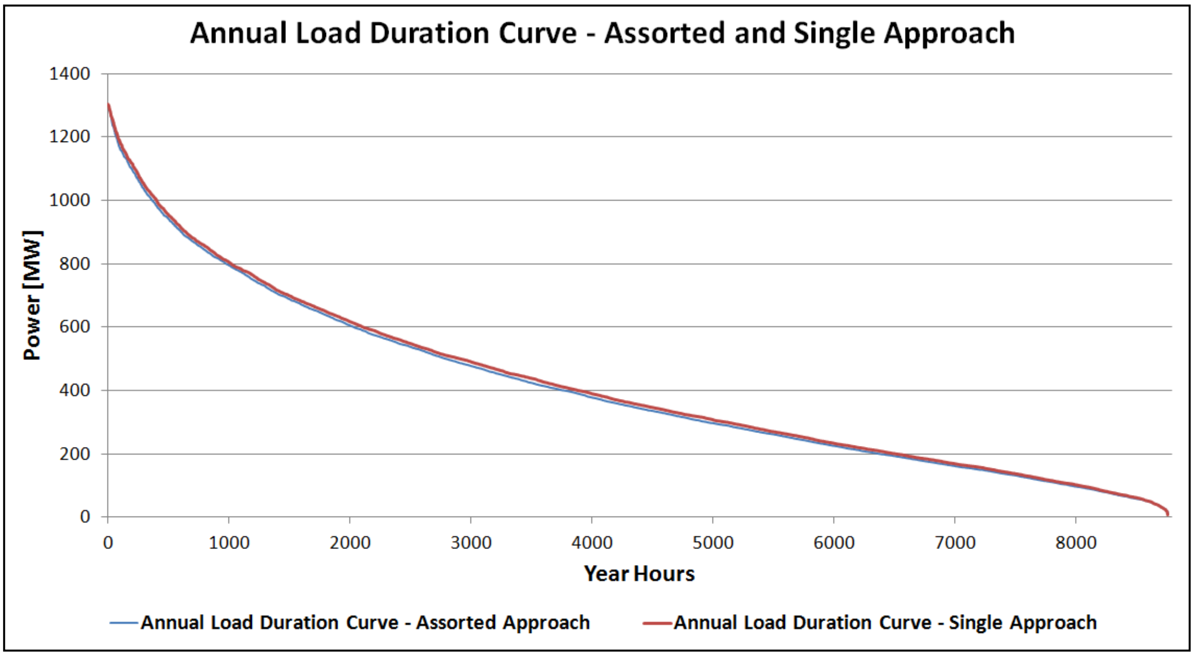


Figure 30: Wind – annual load duration curve (assorted and single approach)

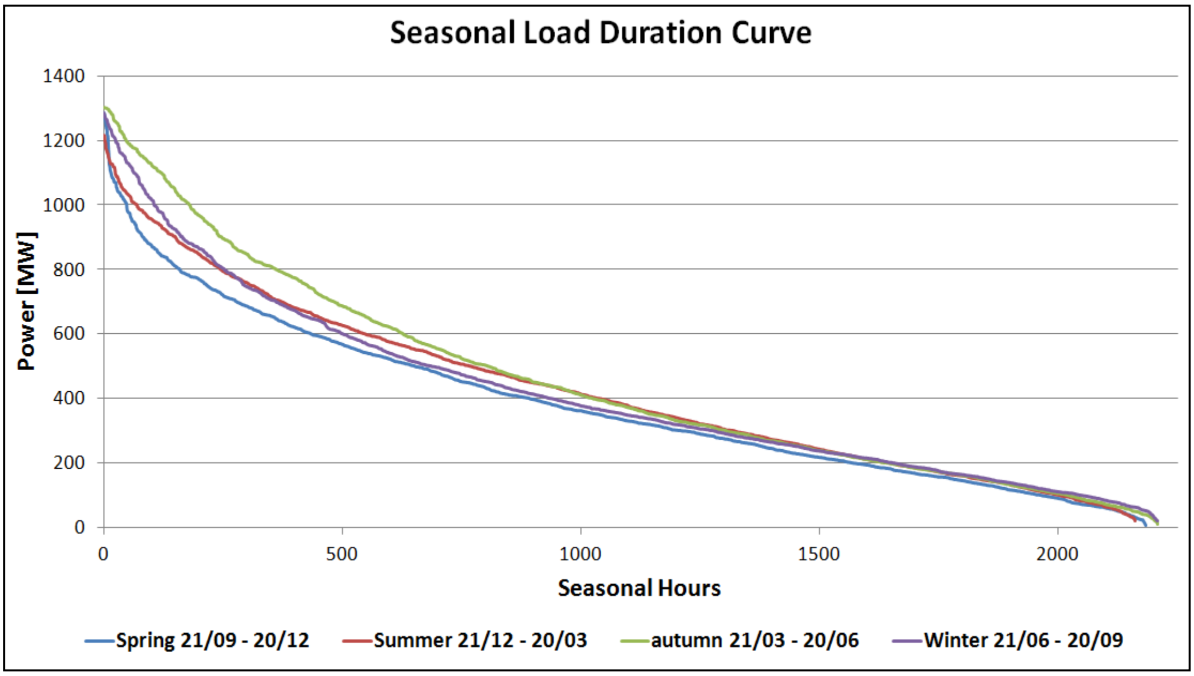


Figure 31: Wind – seasonal load duration curve

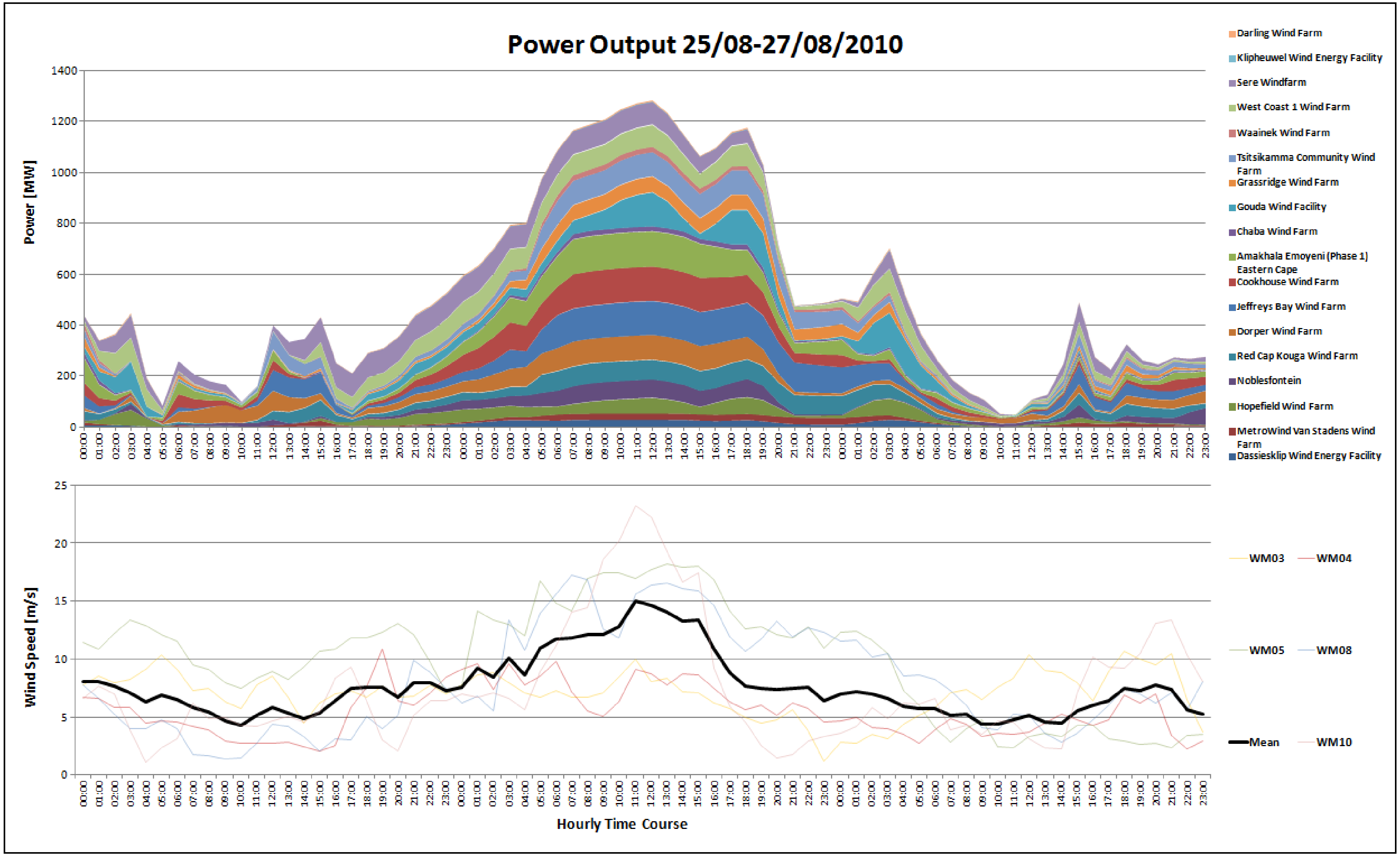


Figure 32: Validation of contemporaneous power increase and wind speeds at WMs (60m)

Annexure V – Solar PV analysis

Determination of conversion factor and cell efficiency of five panels

Table 27: Comparison of five solar PV modules

	P_{MPP} peak power [W_P]	Size net [m²]	Specific power [W_P/m²]	Cell efficiency
Schüco MPE PG04 250Wp	250	1.46	171	15.1%
BYD P6-30 250Wp	250	1.50	167	15.4%
BLD SOLAR 240-60P	240	1.51	159	14.7%
Sharp Solar NU-E245 (J5)	245	1.46	168	14.9%
TSolar TSM-250 PC/PA05	250	1.46	171	15.3%
Mean	-	1.47	167	15.1%

Optimum tilt for maximising annual energy yield of solar PV systems, mounted in a fixed position in a rack facing north

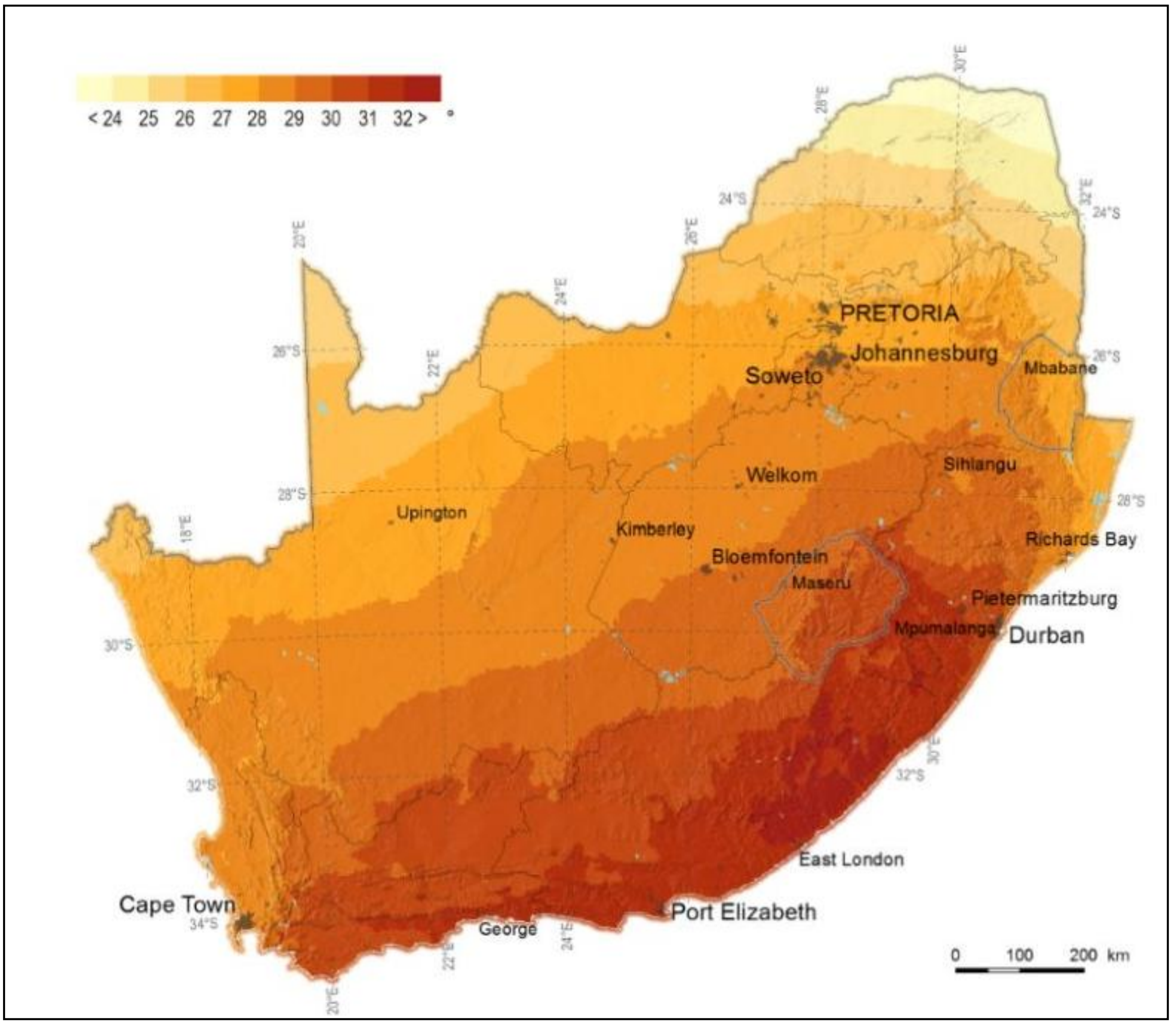


Figure 33: Optimum PV tilt for maximising annual energy yield (Suri, Cebecauer 2012, p. 5)

Verification of applied methodology by ENREL's SAM

The verification was done for a project called 'Kalkbult Solar PV', with a registered capacity of 72.5 MW_P (in bidding R1). Despite the fact that SAM offered a higher possibility of input parameter (including various default values), the boundary conditions were equally set. The difference in annual distributed energy was immaterial, and the time series course was similar.

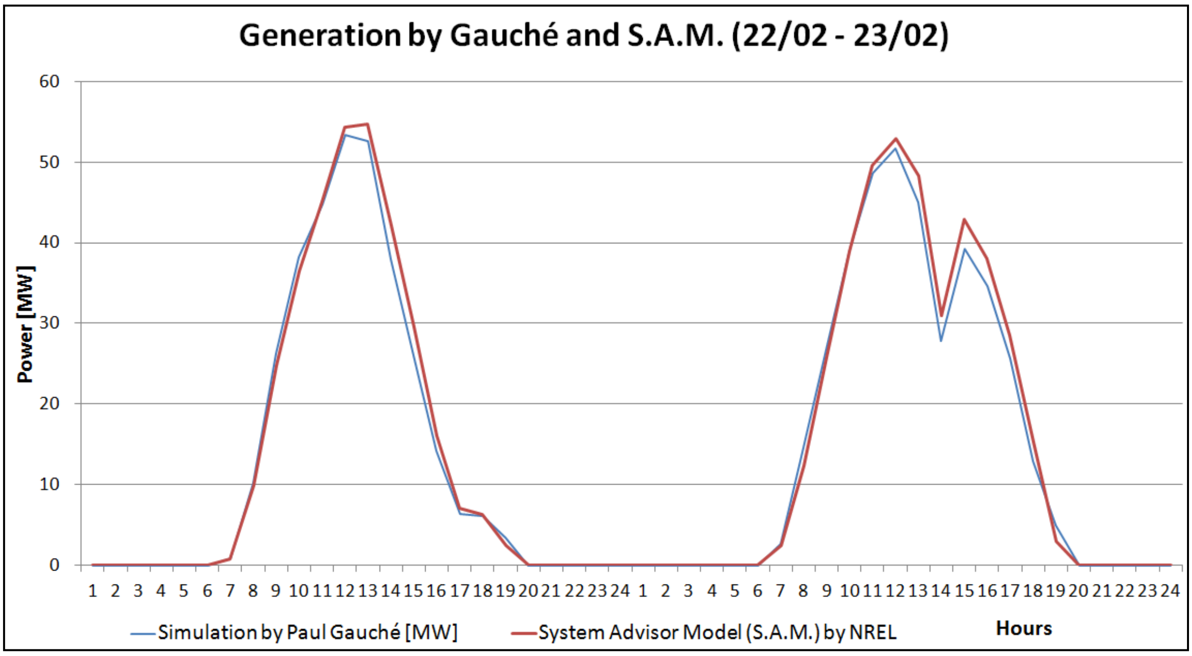


Figure 34: Solar PV model verification (Gauché 2011, NREL 2005)

Annexure VI – CSP Analysis

Simulation boundary conditions

Table 28: CSP, SAM – additional input parameters (CSP World, 2013)

	KaXu Solar One	Bokpoort CSP	Khi Solar One
Turbine steam temp. [°C]	375		
Turbine steam pres. [bar]	100		
Working fluid	VP-1	Dowtherm D	VP-1
No. of loops [–]	300	180	–
No. of collectors/loops [–]	4	5	–
Tower height [m]	–	–	200
Heliostat aperture [m²]	–	–	120 × 4 500

Dew point temperature calculation

The dew point temperature calculation is derived by means of the function of relative humidity to ambient temperature and the Magnus formula. It is valid for a temperature range between −45 and +60°C.

$$\vartheta_d(\varphi,\vartheta) = \left(\frac{241.2 * \ln\left(\frac{\varphi}{100\%}\right) + \frac{4222*\vartheta}{241.2°C+\vartheta}}{17.543 - \ln\left(\frac{\varphi}{100\%}\right) - \frac{17.5}{241.2°C+\vartheta}} \right) \qquad (8)$$

$\vartheta_d(\varphi,\vartheta)$ is the dew point temperature in the dependency of relative humidity (φ) and ambient temperature (ϑ).

Sample, cumulative CSP course in January

The relatively large storage capacity of Bokpoort CSP is apparent.

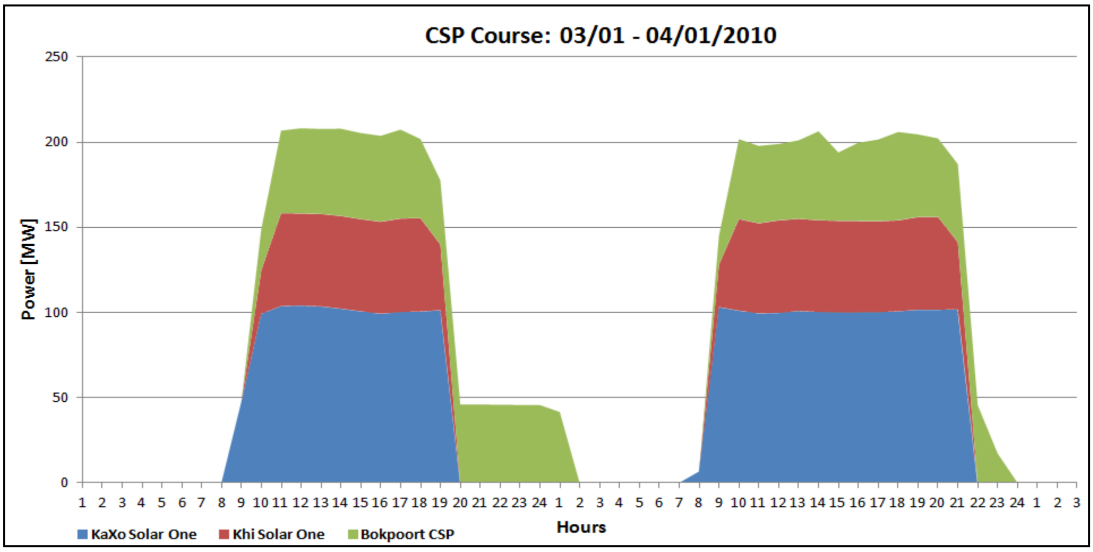


Figure 35: Cumulative CSP course in January

Khi Solar One seasonal and mean temporal distribution

The minimum power defines the firm capacity as soon as the plant generates electricity. The generation distribution in % is expressed by means of the red bar. The blue bar describes the hourly average energy share in each season.

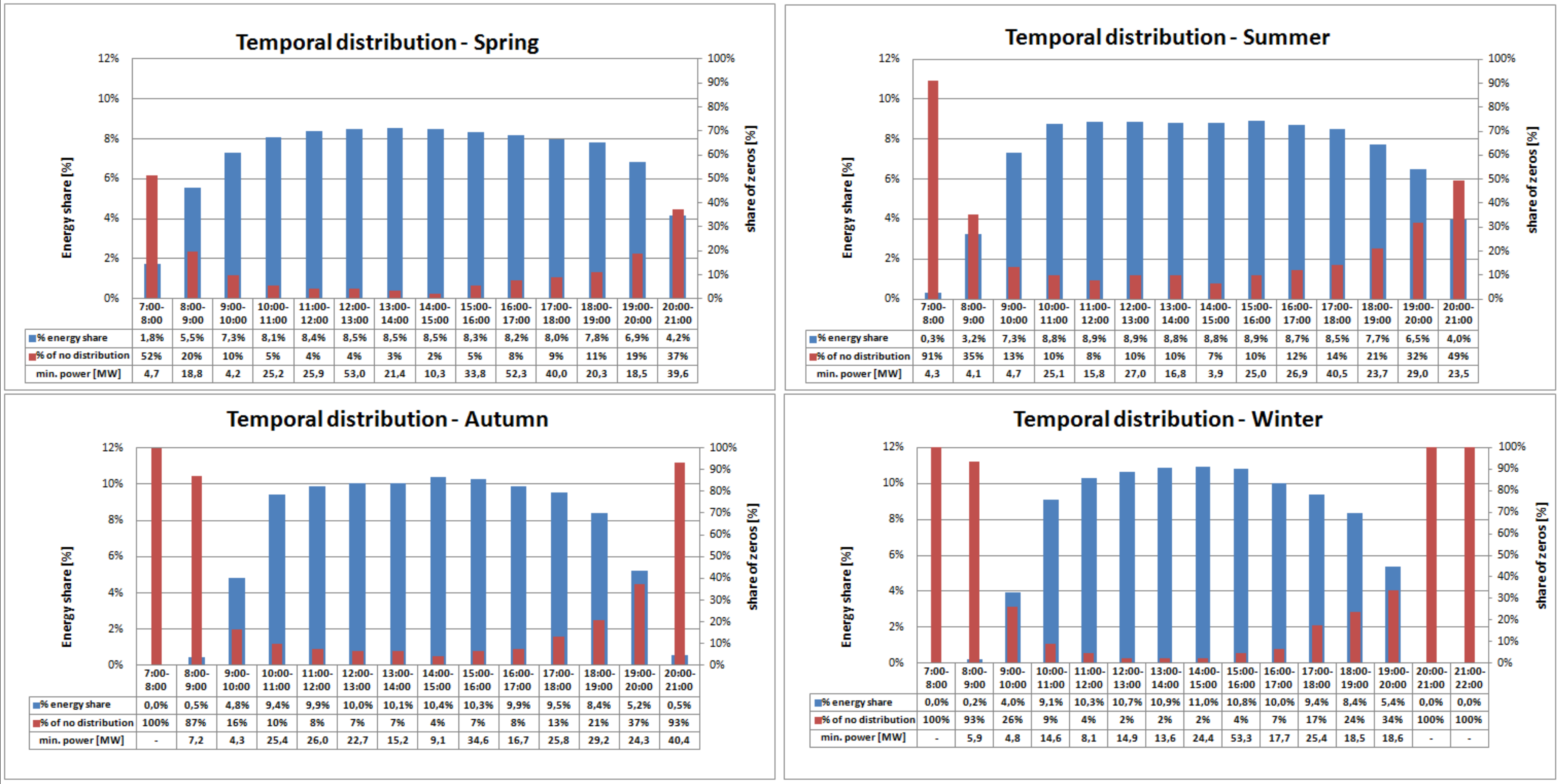
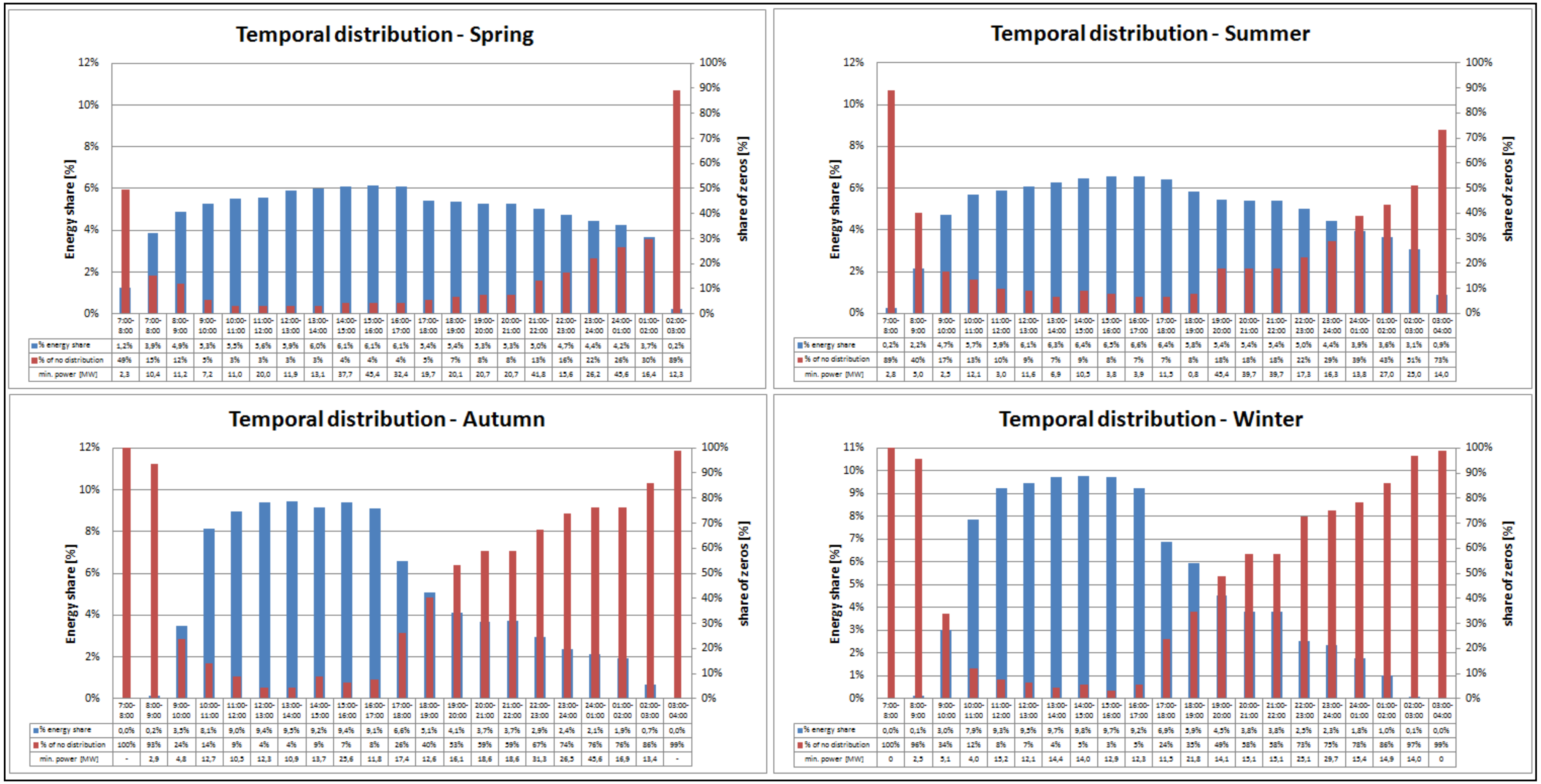


Figure 36: Khi Solar One – seasonal, temporal distribution

Bokpoort CSP – seasonal and mean temporal distribution

The minimum power defines the firm capacity as soon as the plant generates electricity. The generation distribution in percentage is expressed by means of the red bar. The blue bar describes the hourly average energy share in each season.



Spring:

	7:00-8:00	7:00-8:00	8:00-9:00	9:00-10:00	10:00-11:00	11:00-12:00	12:00-13:00	13:00-14:00	14:00-15:00	15:00-16:00	16:00-17:00	17:00-18:00	18:00-19:00	19:00-20:00	20:00-21:00	21:00-22:00	22:00-23:00	23:00-24:00	24:00-01:00	01:00-02:00	02:00-03:00
% energy share	1,2%	3,9%	4,9%	5,3%	5,5%	5,6%	5,9%	6,0%	6,1%	6,1%	6,1%	5,4%	5,4%	5,3%	5,3%	5,0%	4,7%	4,4%	4,2%	3,7%	0,2%
% of no distribution	49%	15%	12%	5%	3%	3%	3%	3%	4%	4%	4%	5%	7%	8%	8%	13%	16%	22%	26%	30%	89%
min. power [MW]	2,3	10,4	11,2	7,2	11,0	20,0	11,9	13,1	37,7	45,4	32,4	19,7	20,1	20,7	20,7	41,8	15,6	26,2	45,6	16,4	12,3

Summer:

	7:00-8:00	8:00-9:00	9:00-10:00	10:00-11:00	11:00-12:00	12:00-13:00	13:00-14:00	14:00-15:00	15:00-16:00	16:00-17:00	17:00-18:00	18:00-19:00	19:00-20:00	20:00-21:00	21:00-22:00	22:00-23:00	23:00-24:00	24:00-01:00	01:00-02:00	02:00-03:00	03:00-04:00
% energy share	0,2%	2,2%	4,7%	5,7%	5,9%	6,1%	6,3%	6,4%	6,5%	6,6%	6,4%	5,8%	5,4%	5,4%	5,4%	5,0%	4,4%	3,9%	3,6%	3,1%	0,9%
% of no distribution	89%	40%	17%	13%	10%	9%	7%	9%	8%	7%	7%	8%	18%	18%	18%	22%	29%	39%	43%	51%	73%
min. power [MW]	2,8	5,0	2,5	12,1	3,0	11,6	6,9	10,5	3,8	3,9	11,5	0,8	45,4	39,7	39,7	17,3	16,3	13,8	27,0	25,0	14,0

Autumn:

	7:00-8:00	8:00-9:00	9:00-10:00	10:00-11:00	11:00-12:00	12:00-13:00	13:00-14:00	14:00-15:00	15:00-16:00	16:00-17:00	17:00-18:00	18:00-19:00	19:00-20:00	20:00-21:00	21:00-22:00	22:00-23:00	23:00-24:00	24:00-01:00	01:00-02:00	02:00-03:00	03:00-04:00
% energy share	0,0%	0,2%	3,5%	8,1%	9,0%	9,4%	9,5%	9,2%	9,4%	9,1%	6,6%	5,1%	4,1%	3,7%	3,7%	2,9%	2,4%	2,1%	1,9%	0,7%	0,0%
% of no distribution	100%	93%	24%	14%	9%	4%	4%	9%	7%	8%	26%	40%	53%	59%	59%	67%	74%	76%	76%	86%	99%
min. power [MW]	-	2,9	4,8	12,7	10,5	12,3	10,9	13,7	25,6	11,8	17,4	12,6	16,1	18,6	18,6	31,3	26,5	45,6	16,9	13,4	-

Winter:

	7:00-8:00	8:00-9:00	9:00-10:00	10:00-11:00	11:00-12:00	12:00-13:00	13:00-14:00	14:00-15:00	15:00-16:00	16:00-17:00	17:00-18:00	18:00-19:00	19:00-20:00	20:00-21:00	21:00-22:00	22:00-23:00	23:00-24:00	24:00-01:00	01:00-02:00	02:00-03:00	03:00-04:00
% energy share	0,0%	0,1%	3,0%	7,9%	9,3%	9,5%	9,7%	9,8%	9,7%	9,2%	6,9%	5,9%	4,5%	3,8%	3,8%	2,5%	2,3%	1,8%	1,0%	0,1%	0,0%
% of no distribution	100%	96%	34%	12%	8%	7%	4%	5%	3%	5%	24%	35%	49%	58%	58%	73%	75%	78%	86%	97%	99%
min. power [MW]	0	2,5	5,1	4,0	15,2	12,1	14,4	14,0	12,9	12,3	11,5	21,8	14,1	15,1	15,1	25,1	29,7	15,4	14,9	14,0	0

Figure 37: Bokpoort CSP – seasonal, temporal distribution

Annexure VII – Results

Supplement to the frequency distribution from 20:00 to 22:00

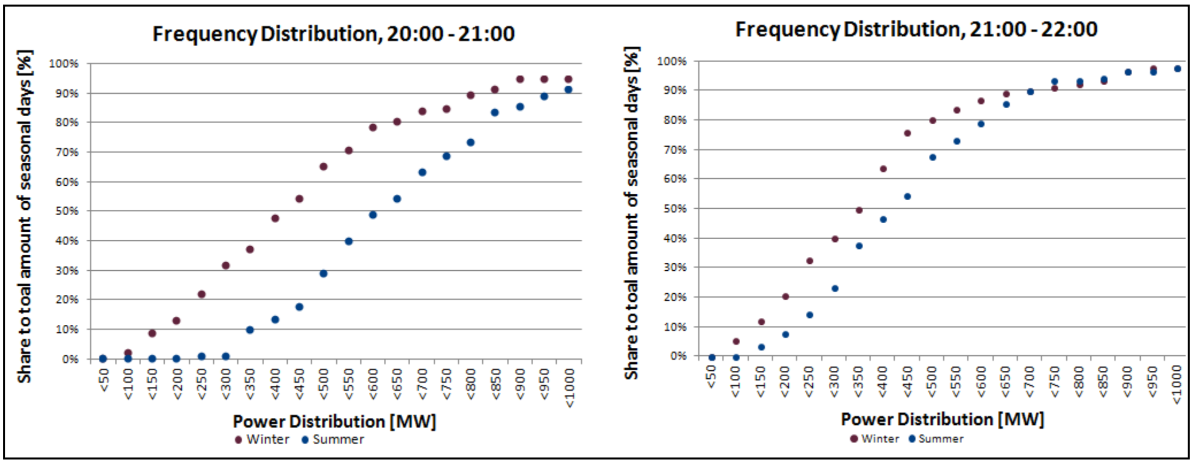


Figure 38: Frequency distribution during summer and winter (B)

Systems distribution share between 19:00 and 22:00 during winter

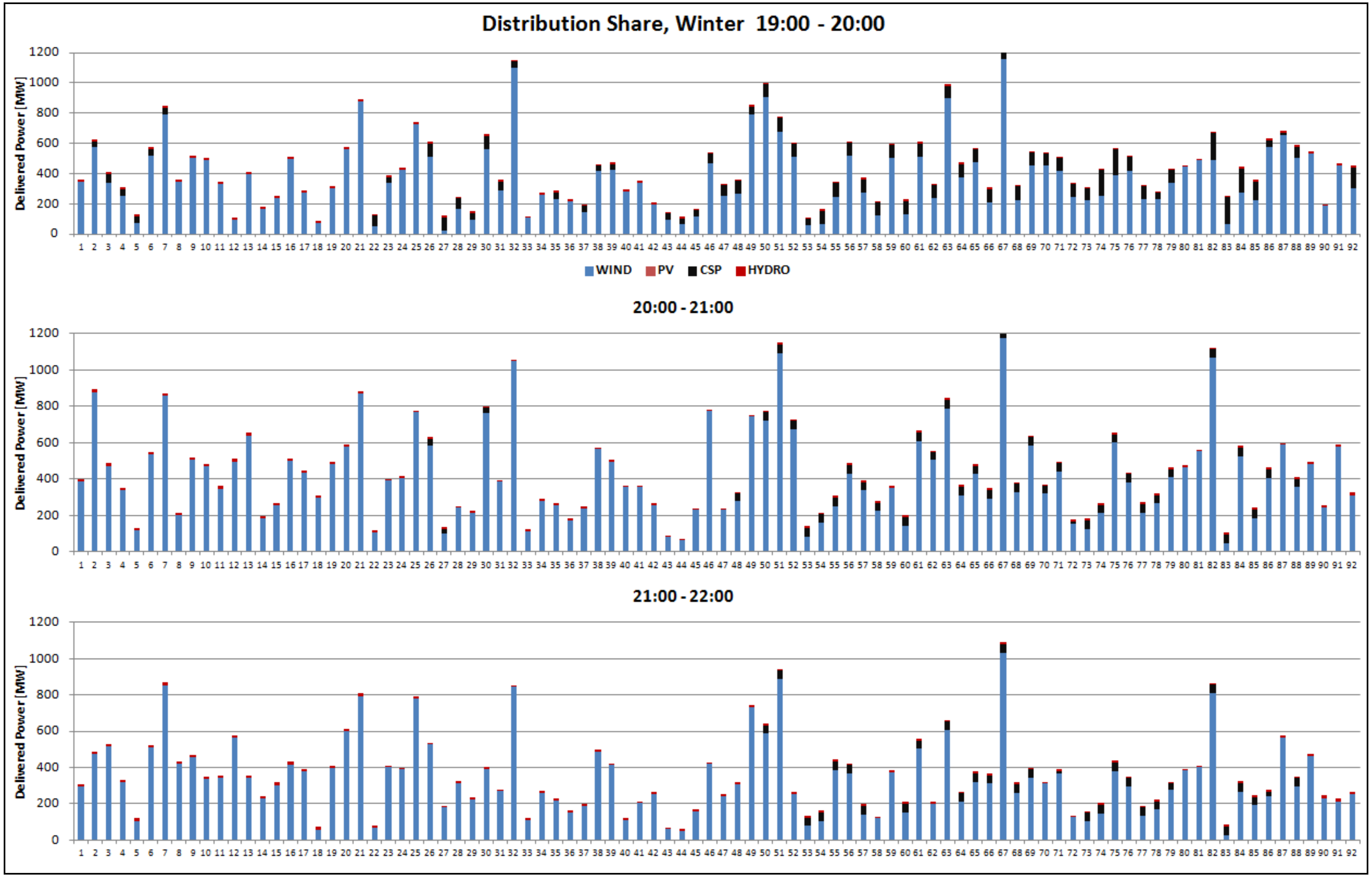


Figure 39: Distribution share, winter 19:00–22:00

Systems distribution share between 19:00 and 22:00 during summer

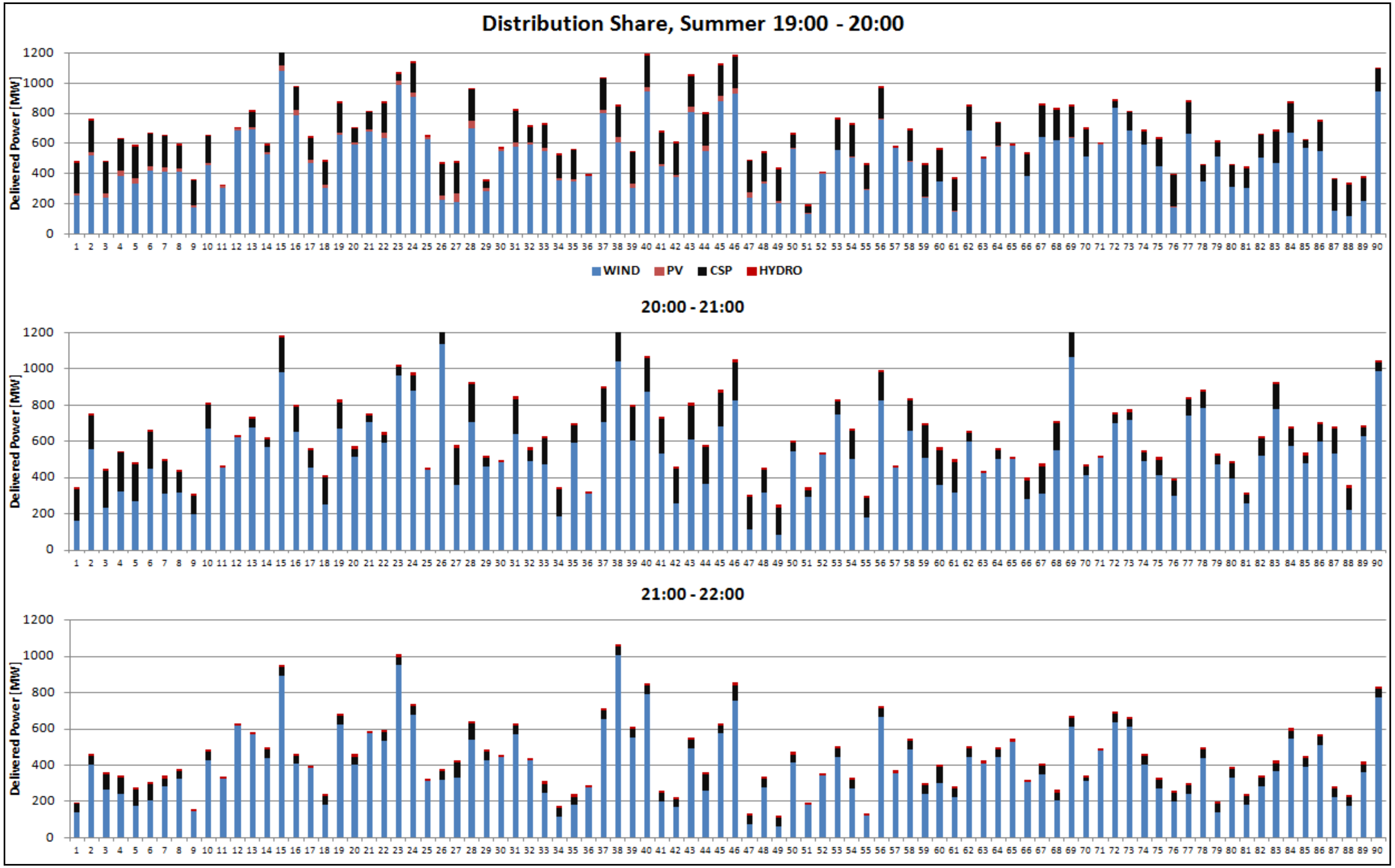


Figure 40: Distribution share, summer 19:00–22:00