Comparing concentrating solar and nuclear power as baseload providers using the example of South Africa

Stefan Pfenninger[a,b,*], James Keirstead[a]

[a] Department of Civil and Environmental Engineering, Imperial College London
[b] Grantham Institute - Climate Change and the Environment, Imperial College London

Despite the increasing importance of variable renewable power generation, baseload, that is stable and predictable power generators, remain the backbone of many countries' power systems. We here compare CSP (concentrating solar power) and nuclear power as baseload electricity providers for the case of South Africa, which is adding significant new generation capacity, has an abundant solar resource, but also one existing and additional planned nuclear power plants. Both of these technologies are considered baseload-capable with sufficient available fuel (sunlight or fissible material) to provide large amounts of nearly emissions-free electricity. We find that under a range of technological learning assumptions, CSP compares favorably against nuclear on costs in the period to 2030, and has lower investment and environmental risks. The results suggest that while nuclear power may be an important low-emissions power technology in regions with little sun, in the case of South Africa, CSP could be capable of providing a stable baseload supply at lower cost than nuclear power, and may have other non-cost benefits.

Keywords: Nuclear power; Solar power; Baseload; Low-emissions electricity

Notice: This is the author's accepted version (27 April 2015) of a paper published in *Energy*, 87, pp. 303-314, doi: 10.1016/j.energy.2015.04.077

1. Introduction

The energy sector is undergoing significant change, driven in particular by the need for a cleaner energy supply to help mitigate climate change. For example, many countries have put in place ambitious targets to increase their share of renewable energy (Martinot et al., 2007). Traditionally, the backbone of power systems has consisted of baseload providers:

*Corresponding author: s.pfenninger12@imperial.ac.uk. Address: Department of Civil and Environmental Engineering, South Kensington Campus, Imperial College London, SW7 2AZ, London, UK.

power plants able to provide a constant and predictable supply of electricity. However, power systems relying on a combination of baseload (i.e., coal or nuclear) and variable (i.e., wind or solar photovoltaics/PV) generation are considered difficult to operate (Mez, 2012). For the grid integration of variable renewables, flexible load-following rather than baseload capabilities are required. Mai et al. (2014b) show for the U.S. case that integrating up to about 50% or even up to 80% (Mai et al., 2014a) of variable wind and solar PV generation is possible with a combination of measures such as more flexible generation capacity, grid-scale storage, more transmission, more flexible loads, and changed systems operations. In power systems with ever increasing shares of renewable generation, baseload power may no longer even be a relevant concept. Budischak et al. (2013) demonstrate feasible systems relying entirely on wind and solar power for up to 99% of the time (but these results rely on the availability of affordable large-scale storage). Nevertheless, and despite the fact that wind and PV generation costs are falling, traditional baseload generation can be expected to remain relevant for some decades while the transition of power systems worldwide is underway. In particular in emerging economies, where substantial demand increases are taking place and large parts of a generation fleet relying on substantial baseload capacities still have decades of operational life ahead of them, investment decisions taken between now and 2030 will still take baseload generation into account.

The availability of low-emissions baseload generators is therefore still an immediate concern. Two main options are usually considered: carbon capture and storage (CCS) and nuclear power. As yet, however, CCS remains unproven at a commercial scale, and the future availability and costs of CCS-enabled power plants thus remain uncertain (Haszeldine, 2009). In contrast, nuclear power is a mature technology with decades of experience, and in 2011, delivered about 12% of total global electricity supply (IEA, 2013). It is advocated by many as a low-emission power generation technology with sufficient fuel availability for large-scale deployment, and thus potentially crucial to achieve deep reductions in greenhouse gas emissions (e.g., Brook, 2012; Lovelock, 2007). However, nuclear is also a technology with uniquely low public acceptance, especially in the wake of the Fukushima disaster (Rudolf et al., 2014). There is uncertainty about its future status: some countries (e.g. the UK) are moving forward with new nuclear plans despite some public opposition, while others (e.g. Germany) have announced their intention to phase out nuclear power entirely (Wittneben, 2012). In addition to the CCS and nuclear options, one additional technology has recently seen a surge of interest: concentrating solar power (CSP). There are currently 83 plants operating and 26 planned or under construction worldwide (NREL, 2013). Previous work has shown that in principle, a fleet of CSP plants is able to provide baseload electricity, and could do so at economically viable costs under some circumstances (Pfenninger et al., 2014). This leads to the question whether CSP could therefore compete against nuclear as a supplier of clean baseload power.

A suitable location to assess this question is South Africa, which currently operates the only nuclear power plant on the African continent. It also has one of the world's foremost solar resource potentials, with several CSP plants under construction and additional plants in the planning stage. Furthermore, it is an example of an emerging economy with substantial projected growth in power demand as well as insufficient current generation capacity. South African industry and government are making the argument that nuclear energy is the only viable baseload alternative to coal, and therefore essential for both long-term energy security and climate change mitigation (Campbell, 2014a; Paton, 2014). The question investigated here is therefore, how do nuclear and CSP as two possible low-emissions sources of baseload power compare, for the example of South Africa? In addition to their cost, we compare the two options on criteria including technology and fuel availability, their ability to contribute to climate change mitigation and environmental protection, and the technical and financial risks they may entail.

The paper proceeds as follow. The background section introduces the two technologies and their role in South African energy policy in more detail, as well as the rationale behind their comparison and other work addressing this issue. The methods section discusses the data sources used, as well as the modeling and analytical approach taken to support the comparison. Results are then presented from both the modeling work undertaken and from a review of data drawn from the literature. The concluding discussion section examines the implications for South African energy policy and its relevance for other world regions.

2. Background

Nuclear power generation uses heat released from a nuclear fission reaction to generate steam that drives a turbine. Of importance for both costs and environmental impacts is the complexity of the nuclear fuel cycle. On the so-called "front end" this includes mining, milling, conversion, enrichment and fuel fabrication, and on the "back end", temporary and long-term storage, reprocessing, and transportation of spent fuel and waste, as well as the decommissioning and remediation of reactors, processing facilities and mining sites. As of 2014, 388 nuclear reactors are operating worldwide, which is 50 less than the peak in 2002 (Schneider et al., 2014). 67 reactors are under construction, mostly in Asia, although some of these have been listed as under construction for more than 20 years (Schneider et al., 2014). The majority of currently operating reactors are generation II, i.e. the first commercial reactor types built from the 1960s onward, while those under construction mostly represent generation III/III+ plants which represent incremental improvements on generation II from the 1990s onward (Grimes and Nuttall, 2010). Next generation (IV) reactors are at various stages of development, but none are commercially available yet. These designs promise better safety, the reduction or elimination of proliferation concerns, and fuel-cycle benefits such as the ability to re-use existing depleted fuel (Abram and Ion, 2008). For example, proposed thorium reactors have received attention because of thorium's abundance as well as features such as minimal waste generation and safer operation (Schaffer, 2013). However, while the cost of generation IV technologies is difficult to assess, there is no indication that it will be lower than that of current-generation plants (Neij, 2008). Experiences such as the failed Pebble Bed Modular Reactor show the pitfalls of developing next-generation nuclear technology (Thomas, 2011).

CSP, like nuclear, uses heat to generate steam that drives a turbine. The heat source however is solar radiation. There are two different CSP technologies. The older and more established technology concentrates sunlight onto pipes directly above rows of mirrors (parabolic trough plants). The newer solar tower technology concentrates sunlight on a tower-mounted receiver using mirrors called heliostats arranged around the tower. This is the technology considered for comparison here. The thermal components of the plant have inherent thermal inertia, which means that CSP plants can provide grid-stabilizing services similar to conventional thermal plants (in contrast to PV, where power output can drop rapidly as passing clouds shade the panels). This makes CSP easier to integrate in existing grids (Denholm and Mehos, 2011). In addition to their inherent thermal inertia, CSP plants can also integrate heat storage, allowing them to further decouple the time of power production from sunny periods. Various storage technologies exist and are under continued development, with molten salt tanks the most popular current choice. While typical recent plants do not necessarily include a storage system, or have at best enough storage to run the plant for a few hours after sunset, it has been demonstrated that 24-hour operation with larger storage systems is indeed possible in the Gemasolar plant in Spain. This capability makes CSP uniquely different from both solar PV and wind power. Recent work has shown how in South Africa specifically, CSP plants could cover the evening demand peak by making use of short-term heat storage (Auret and Gauché, 2014; Silinga and Gauché, 2014). These studies found that CSP can reduce the need for both variable output from baseload plants such as coal, and for expensive and emissions-intensive gas or oil fired peaking plants.

South African electricity policy is driven by the Integrated Resources Plan (IRP) 2010-2030, which details the government's demand projections and plans for new and changed capacity up to 2030 (South Africa Department of Energy, 2011). Its stated objectives are to balance policy criteria including emissions mitigation, water use, local economic development and security of supply. After the IRP's promulgation in 2011, the intention is to update it every two years. The first such update took place in 2013 (South Africa Department of Energy, 2013), and the next one is expected in 2015. The original IRP foresaw deployment of 9600 MW of nuclear capacity by 2030, but the 2013 update has reduced this by almost half, to 4860 MW additional capacity, and recommends delaying any new build decision for at least another decade. No decision on reactor technology has been made, but a generation III/III+ technology is the likely choice. The existing Koeberg nuclear plant (1800 MW, commissioned 1984) is assumed to remain online with an extended 40-year lifetime. The reduction of nuclear capacity in the IRP coincides with rising costs for plants currently under construction outside of Asia (see cost discussion and Table 1). Despite the cautionary advice in the IRP, the government has announced that it is firmly committed to nuclear expansion within this decade (Campbell, 2014a). In contrast to the decreased role for nuclear generation, the 2013 IRP update increases the base case projected installation of CSP from 1200 MW to 3300 MW in 2030 (this is still dwarfed by the planned PV capacity of 9770 MW). This reflects two things: the rising attractiveness of renewables relative to nuclear, but also, the higher perceived attractiveness of PV relative to CSP, primarily due to the rapid PV cost reductions in recent years.

The South African government's "peak, plateau and decline" (PPD) climate change mitigation objective foresees emissions peaking in the mid 2020s and declining from the mid 2030s onward (Government of South Africa, 2011). The 2013 IRP update assumes that the electricity sector contributes about 45% to total emissions. Depending on the extent and speed of decarbonization, different scenarios give a smaller role to coal power in 2050 (summing existing and new coal, from 40.9 GW in the constant emissions case to 21.3 GW in the advanced decline case), and correspondingly, increase nuclear capacity (from 12.8 GW to 28.8 GW in the respective cases). CSP capacity remains similar in both cases, i.e. its role does not significantly grow in the advanced decline case. This suggests that CSP is considered a variable solar generation option with higher cost than PV, while nuclear power is considered a potential replacement for coal as the backbone of a reliable power system. Generally, grids relying heavily on both nuclear and renewables are considered impractical because nuclear power plants have limits to their ramping and output range preventing them from balancing variable renewable output (Mez, 2012). Furthermore, due to the substantial capital cost, nuclear power plant operators must aim at as high a capacity factor as possible (Koomey and Hultman, 2007). Recent work has attempted to solve this issue by proposing hybrid systems with geothermal heat or hydrogen storage (Forsberg, 2013), or with heat storage between reactor and generators similar to how CSP plants operate (Denholm et al., 2012). This would allow nuclear reactors to operate close to their optimal design point while giving the flexibility necessary to integrate them with variable renewable generation.

Instead of trying to adapt nuclear power to fit into this new role, an alternative approach is to replace it with a more suitable technology. While most CSP plants currently operating or under construction are designed with relatively little storage (instead intended to serve daytime or early evening demand), prior work has demonstrated the general feasibility of CSP plants with storage providing baseload power (Pfenninger et al., 2014). Yet that study did not address the possible future costs and the competitiveness of a CSP baseload solution against other technologies. Furthermore, the comparison between nuclear power and a potential CSP baseload solution also warrants an examination of additional criteria. There thus are two immediate questions. First, could CSP compete against nuclear as a largely emissions-free and reliable baseload provider? Second, how do the two technologies compare on other important aspects such as their environmental impact and the operational risks associated with them?

3. Methods and data

The analysis is based on data gathered from the literature and outlined in detail below. Levelized power costs for nuclear power are computed by assuming appropriate values for plant capacity factors. Investment costs and levelized power costs of baseload-capable CSP plants are determined with the Calliope energy systems optimization modeling framework (Pfenninger, 2014). Calliope constructs a cost-minimizing linear optimization problem, in order to design an optimal configuration of power plants for the given constraints. It is used here to simulate only CSP plants given a flat (baseload) demand, and not the rest of the electricity system.

CSP power output is based on a central receiver plant model (Gauché et al., 2011) using solar irradiance data from the SolarGIS database for the years 2008, 2009 and 2010 (GeoModel Solar, 2012). The modeling approach allows planning the location and dimensioning of CSP plants as well as simulating their operation, and analyzing scenarios with different constraints and conditions. 30 possible sites are spread through those areas of South Africa identified for CSP development, using land coverage data (JRC, 2010) to ensure they are in suitable areas (see Figure 6). For all model runs, the complete three years of solar data are used. The data is resampled to 12-hourly intervals in order to improve computational tractability, but left at its original 1-hourly resolution for the "worst" week of data, with the lowest solar irradiance values across the set of chosen sites (the week of 8th June 2009). In order to size CSP plants, the Calliope model is run in planning mode to determine cost-minimal plant configurations, freely choosing the installed power block capacity, solar field size, receiver dimensions, and storage size for each possible site. The constraints are set such that the total set of CSP plants must supply a stable baseload supply in each time step.

The data presented in the IRP 2013 update reflect a range of overnight capital costs for nuclear from about 3800 to 7000 USD/kW based on various nuclear cost studies. The upper range of nuclear capacity cost is uncertain. Plants under construction for which there are recent cost estimates are Finland's Olkiluoto-3 at about 7000 USD/kW and France's Flamanville-3 at about 6750 USD/kW (Schneider et al., 2014), both using Areva's generation III+ European Pressurized Reactor (EPR) reactor designs. The Hinkley Point C deal reached in the United Kingdom in late 2013 amounts to 5000 GBP/kW or about 8300 USD/kW at 2014 exchange rates (EDF Energy, 2013). Nuclear projects have frequently experienced cost overruns. For reactors with a construction start between 1966 and 1977 in the United States, final costs were between 209% and 381% above initial overnight cost estimates (Ramana, 2009). In addition, at the aggregate U.S. level, investment costs increased over time rather than exhibiting learning effects or economies of scale (Ramana, 2009). Similarly, Grubler (2010) found that in France, the real investment cost escalated by a factor of about 3.5 between 1974 and the post-1990 period. Reasons for this include the increasingly complex reactor designs and safety requirements (MacKerron, 1992). For all these reasons, we assume a 0% learning rate for nuclear, as given in Neij (2008). Considering the historical data this assumption appears justified. Possible future generation IV plants are, at least initially, unlikely to reduce in cost savings (Hultman et al., 2007). However, instead of technological learning, we consider a range of uncertainty in overnight capital costs drawing both from plants currently being constructed and from published estimates, as shown in Table 1.

Table 1: Capacity costs for nuclear power plants. A 7-year construction time is assumed. The column including decommissioning assumes 430 USD/kW decommissioning costs (see text). OC = Overnight cost. RC = Real cost. RCwD = Real cost with decommissioning.

Source	Type	OC (2012 USD)	RC (2012 USD)	RCwD (2012 USD)	Source
Olkiluoto-3	Plant	-	7000	7430	Schneider et al. (2014)
Flamanville-3	Plant	-	6750	7180	Schneider et al. (2014)
Hinkley Point C	Contract	-	8137	8567	EDF Energy (2013) adjusted to 2012 USD
Taishan 1&2	Plant	-	2407	2837	Beaupuy and Patel (2010) adjusted to 2012 USD
IEA Africa	Literature	4000	-	5910	IEA (2014)
IEA China	Literature	2000	-	3170	IEA (2014)
IEA Europe	Literature	6600	-	9472	IEA (2014)
EIA	Literature	5530	-	8006	EIA (2013)
IRP 2013 Update	Literature	5800	-	8376	South Africa Department of Energy (2013)

To assess overnight installation costs for CSP plants, the costs of four main components are used: the power block, the solar field, the receiver, and the storage system. This allows explicit comparison of plants with substantially different configuration. We use the 2010 costs reported in Kolb et al. (2011) as basis for our estimates. Of three projects currently under construction in SA, cost information is available for two, Bokpoort at 11,300 USD/kW (ACWA Power, 2014) and !Khi Solar One at 78,000 ZAR/kW, or 9516 USD/kW at 2012 exchange rates (IDC, 2013). There is no information about cost or construction schedule overruns (scheduled construction times are 2.25 and 2 years, respectively). Bokpoort is a parabolic trough plant with 9 hours of storage, while !Khi is a central receiver plant with 2 hours of storage. As shown in Table 2, we reproduce the reported costs for !Khi by assuming that 30% of total costs come from component costs, which we assume are 10% higher than the base case costs from Kolb et al. (2011) (5% of which are due to inflation), and assuming that financing costs were between 10% and 15% for this first of a kind (in South Africa) plant. This also assumes a 2-year construction time with equal spread of costs over those two years. Using this initial component cost estimate as a starting point for technological learning, we consider several scenarios for future costs as shown in Table 3, with the resulting component costs shown in Table 4. These technological learning scenarios are based on worldwide deployment of central receiver plants with 2 hours of heat storage. An alternative version of the "optimistic" learning scenario deploys plants with 8 hours of storage to assess the effect of increased learning for storage technologies. The learning scenarios are exogenous to the model analysis considered here, where storage size is freely optimized such that plants are base-load capable, but it is assumed that for the global average fleet deployment, 2 hours of storage is a good estimate.

Table 2: Reproducing reported investment costs for the !Khi Solar One plant from component cost values modified from Kolb et al. (2011). No reported value for the receiver size is available, so it is assumed that receiver size (in kW) is 54% of the solar field size (in m^2).

Item	2010 USD (Kolb et al., 2011)	2012 USD (10% increase)	Khi dimensions	Khi costs (million 2012 USD)
Storage	30	33	333,333	11
Solar field	200	220	576,800	127
Power block	1350	1485	50,000	74
Receiver	200	220	311,472	69
Fixed costs (30%)				120
Total overnight				401
Investment (10 % interest)				445
Investment (15 % interest)				481
Investment (reported)				476

Table 3: Learning rate (LR) scenarios for CSP. The 2012 starting value of 2.5 GW was chosen for all scenarios based on 2012 capacity according to NREL (2013). Learning rates for the pessimistic scenario are adjusted downwards from what Viebahn et al. (2011) assumes. Learning rates for fixed costs own assumptions. "LR other" is the learning rate for solar field, receiver, and storage.

Scenario	2012	2020	2030	LR other	LR power-block	LR fixed	Source
Realistic	2.5 GW	29 GW	138 GW	0.12	0.05	0.05	Adjusted from Viebahn et al. (2011)
Pessimistic	2.5 GW	14 GW	47 GW	0.10	0.05	0.05	Adjusted from Viebahn et al. (2011)
Optimistic	2.5 GW	148 GW	337 GW	0.10	0.10	0.10	Adjusted from South Africa Department of Energy (2013)

Table 4: Component costs resulting from the learning rate scenarios shown in Table 3

	Storage capacity (kWh)	Receiver area (m^2)	Receiver capacity (kW)	Power block (kW)
Base case (2012)	33	220	220	1485
Pessimistic (2020)	25.4	169.3	169.3	1307.3
Pessimistic (2030)	21.1	140.8	140.8	1195.2
Realistic 2h (2020)	21.0	140.0	140.0	1238.7
Realistic 2h (2030)	15.7	105.0	105.0	1103.6
Realistic 8h (2030)	16.3	140.0	140.0	1238.7
Realistic 8h (2030)	12.2	105.0	105.0	1103.6
Optimistic (2020)	12.2	105.0	105.0	1103.6
Optimistic (2030)	15.7	104.4	104.4	704.7

For nuclear power, the IRP 2013 update gives fixed operating and maintenance (O&M) costs as 66.42 USD/kW-year, variable O&M as 0.368 cents/kWh, and fuel costs as 0.913 cents/kWh. These values are used as base case assumptions here. Some studies use significantly lower values, however. For example, Du and Parsons (2009) quote fixed O&M costs at 56 USD/kW-year, variable O&M costs at 0.042 cents/kWh, and fuel costs at 0.697 cents/kWh. To examine the sensitivity to fuel and O&M costs, we consider two additional scenarios: a fuel cost of 0.5 cents/kWh, no variable O&M costs and a fixed O&M cost of 56 USD/kW-year, and a fuel cost of 1.5 cents/kWh with otherwise default values. For nuclear decommissioning costs, an additional cost of 430 USD per kW capacity is added, based on the mean value for all water-cooled reactors from Bertel and Lazo (2003) and adjusted to 2012 USD. Decommissioning costs for CSP plants are assumed to be insignificant and therefore not considered. Furthermore, for CSP plants, there are no fuel costs, only O&M costs. We take the highest central receiver plant IRP estimate for fixed O&M at 70 USD/kW-year, with no variable O&M cost. Like the values used for nuclear plants, these values are higher than those cited elsewhere in the literature (e.g., Kolb et al., 2011). They are assumed to fall to 60 USD/kW-year in 2030 and 55 USD/kW-year in 2030.

The total life time of plants (both CSP and nuclear ones), as well as their life-time capacity factors also affect overall cost of the power they produce. For nuclear plants, the complete data from the IAEA's PRIS database (IAEA, 2014) contains 239 currently operational reactors and 101 permanently shut down ones. Based on this data, for all currently operating plants, the lifetime mean capacity factor is 75.0%. More recent plants (construction started after 1990) achieve a lifetime capacity factor of 79.5%. The mean operational lifetime of all permanently shut down reactors was 26.4 years, while the mean lifetime so far of currently operating reactors (time since start of commercial operation) is 27.3 years. For both capacity factor and life time, higher values are often assumed in the literature (e.g., Sovacool, 2008), which appears unjustified given the IAEA's operational data, although we can assume that many currently operating reactors will operate longer than reactors shut down in the past. Another factor is construction time. Depending on how long construction takes, real investment costs can be significantly higher than overnight costs due to project financing costs. The mean construction time (begin of construction to commercial operation date) for all plants in the IAEA data is 7.1 years. For CSP plants, using data on currently operational plants from NREL (2013) for which data is available (n=54), the mean construction time was 2.0 years. The construction time of a project affects both its attractiveness to investment and the financing costs, but different financing sources are not further considered here. To compute the cost of generated power, nuclear power plants are assumed to consume 5% of their generated electricity internally, and CSP plants are assumed to consume 10%. 80% and 90% capacity factors for nuclear plants are assumed, which matches the operational performance of plants built since 1990 and serves as an estimate for possible future plants. Nuclear plants are assumed to have a life time of 30 years, and CSP plants, 25 years. While the economic book life time may differ from the physical life time, this difference is not considered in the analysis, as the book life is specific to a given country's laws and regulations (in this case, South Africa). In South Africa, it is unclear what type of financial (e.g. tax) incentives might be offered to new nuclear plants, furthermore, it is unclear how the financial regime for concentrating solar power plants could evolve by 2030.

Data on cost overruns for CSP projects specifically are not available, but Sovacool et al. (2014) compare different electricity infrastructure projects. They find that 41% of solar projects experience a cost overrun, and the mean overrun for those projects is 1%, while 97% of nuclear projects experience a cost overrun, with a mean overrun of 117% for those projects. Nuclear power plants are inherently large and complex projects, which makes them more vulnerable to cost overruns (Jahren and Ashe, 1990), whereas CSP projects are smaller and more flexible investments. Indeed, Flyvbjerg et al. (2002) found that cost underestimation in large infrastructure projects is systematic worldwide and can be "best explained by strategic misrepresentation, i.e., lying". Because individual CSP projects are orders of magnitude smaller than nuclear plants, they can be expected to suffer to a lesser degree from such effects. For this study, the total construction cost is calculated from overnight costs by assuming 4 and 7 year construction times for nuclear plants and a 2 year construction time for CSP plants, and assuming that investment is spread evenly across each year of construction.

Levelized cost of electricity (LCOE) and investment costs per installed capacity are calculated ex-post for the modeled CSP plants. LCOE are also computed for nuclear power plants with capacity factor assumptions as detailed above. In comparing costs, assumptions on interest rates and construction times can have an important effect. In order to compare overnight capital cost data with real investment costs, the investment cost, C_i, is computed as follows:

$$C_i = \frac{1}{N}\sum_n C_0(1+i)^n(1+r)^{-n} \quad (1)$$

$\frac{1}{N}C_0(1+i)^n$ is the cost paid in year n, which is based on the overnight cost C_0 and the share of cost for the year, assuming an equal spread of costs over the entire period of construction (N is the total construction time in years). i is the inflation rate, and r is the interest (discount) rate.

The impact of interest rate and construction time on investment costs is illustrated in Figure 1. These real investment costs are then entered into the levelized electricity cost calculations. An interest rate of 10% is assumed for both nuclear and CSP, so no assumptions about different investment attractiveness or project financing models are made. Table 5 gives a summary of the assumptions used in comparing the two technologies.

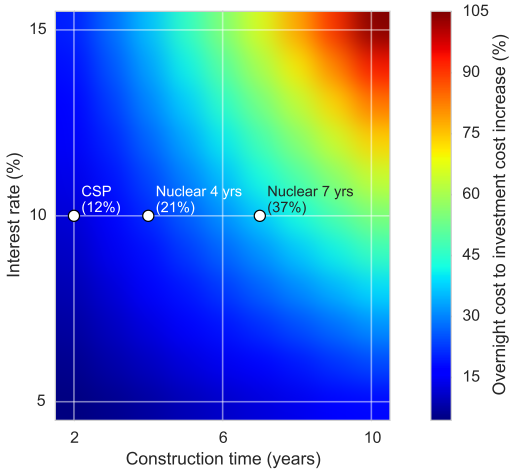

Figure 1: Impact of financing assumptions (interest rate) and construction time on real investment cost relative to overnight capital cost. An inflation rate of 2% is assumed for USD. The values used for CSP and nuclear plants are marked.

Table 5: Summary of model assumptions used in the technology comparison (also refer to the other tables and the text for more detail).

	Nuclear	CSP
Capital costs	Range of costs, see Table 1	Range of costs, see Table 4
Construction time	4 years and 7 years	2 years
Interest rate	10%	10%
Life time	30 years	25 years
Availability	80% and 90%	Endogenous to model, see results
O&M costs	Fixed 66.42 USD/kW-year, variable 0.368 cents/kWh	Fixed 70 USD/kW-year (includes variable costs, falling to 60 USD/kW-year in 2030 and 55 USD/kW-year in 2030)
Fuel costs	0.913 cents/kWh	None
Decommissioning costs	430 USD/kW	None (assumed negligible)

4. Results

4.1. Resource potential

The South African potential for CSP was estimated as 547.6 GW by Fluri (2009), for areas within 20 km of the existing transmission grid, with a daily direct normal irradiance (DNI) above 7 kWh/m^2, and with suitable land cover and slope. This is an order of magnitude above the projected 2030 peak power demand of 61.2 GW (South Africa Department of Energy, 2013). Trieb et al. (2014) gives land use for CSP as 250–550 m^2/GWh, but South Africa has large areas of low-productivity land, particularly in the desert regions with the highest solar irradiance values, so this is not a constraint (although it will be in other world regions). Rather than land, nuclear power plants primarily need fuel. Currently identified uranium resources are sufficient for at least another 100 years at 2010 rates of consumption (IAEA, 2012). This excludes undiscovered reserves, and also the ability of generation IV reactors to use additional fissile material, extending the available fuel resource for hundreds or even thousands of years (Schaffer, 2013). While fuel availability is therefore not an issue at the global scale at least until the end of this century, the possibility of a domestic fuel production cycle is an issue for national-level nuclear policy (discussed further below). 5% of globally identified uranium resources are in South Africa, and another 5% in neighboring Namibia (IAEA, 2012), although this has little strategic significance as there is currently no Namibian or South African nuclear fuel processing industry. A concern sometimes cited is the energy intensity of recovering lower grade uranium ores, but energy return on investment remains well above 1 in all cases, and no shortage of economically recoverable uranian ores is imminent (Schneider et al., 2013; Mudd, 2014). The available data suggest that for practical purposes in South Africa, there are no fundamental technical constraints for either CSP or nuclear power to potentially provide all or most of electricity demand.

4.2. Costs

For the purposes of comparison, we assume an 1000 MW power plant. Figure 2 shows the range of overnight costs for CSP plants that together provide 1000 MW of baseload capacity, along with the overall investment cost for that CSP plant fleet. These costs are for plants dimensioned to supply stable baseload power throughout the three years modeled. There is a significant range between individual plants (along the y-axis), but there is also the potential for significant cost reductions, as illustrated by the different learning rate scenarios along the x-axis. While it would be technically possible to construct a single CSP plant with a solar field and storage facility large enough to provide stable baseload power throughout the year, this is not as cost-effective as having multiple plants together provide this service (see further discussion below). Therefore, the idea of a "metaplant", which consists of several individual plants together providing baseload capability is a useful concept to compare CSP with nuclear power. In Figure 3, CSP investment costs are compared to those of nuclear power. The CSP cost points represent the cost of such a metaplant, with different learning rate assumptions, spread between the three model years 2012, 2020 and 2030. Note that if plants are built sequentially rather than in parallel, it would be reasonable to assume that later plants are cheaper due to additional technological learning, resulting in lower total costs than those shown here. The nuclear costs are shown with two construction time assumptions spanning a range of construction times seen in the historical data.

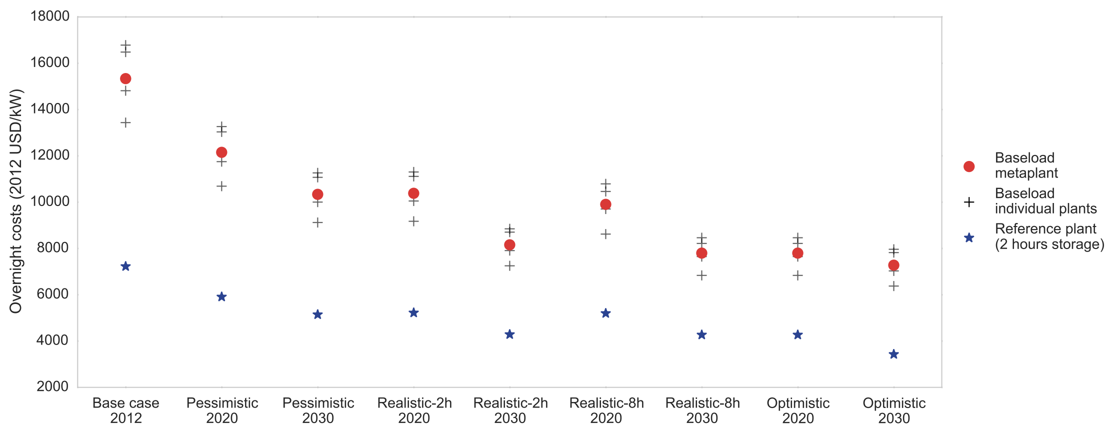

Figure 2: Overnight construction costs for a baseload-capable CSP metaplant, together with the individual CSP plants that together deliver baseload capability. For comparison, investment costs for a typical non-baseload capable reference plant with 2 hours of storage is shown (corresponding to the dimensions of the !Khi Solar One plant currently under construction in South Africa).

Figure 3 also shows a separate type of CSP plant labeled "dynamic baseload", to which we turn our attention next. Because the CSP plants modeled here depend entirely on the sun (no fossil fuel hybridization is assumed), the overcapacity necessary to guarantee stable baseload power throughout the three modeled years results in high levelized electricity costs. More realistically, a set of plants forming a metaplant could guarantee to meet a certain minimum baseload power, but be designed to also produce additional power when weather conditions are favorable. This is simulated by doubling the installed capacity to 2000 MW, but still guaranteeing a minimum of 1000 MW baseload. In other words, a CSP metaplant guarantees to always deliver 1000 MW of power, but can also sell additional output above 1000 MW, up to its total output of 2000 MW, depending on demand and weather conditions. This leads to significantly lower levelized electricity costs. Figure 4 shows the dispatch schedule of CSP plants over a week with low irradiance, indicating how in the dynamic baseload case, plants can still burst their output temporarily. Figure 5 shows the LCOE for both technologies, again with varying assumptions. For nuclear power, a capacity factor of 80% and 90% is compared. For CSP plants, the capacity factor shown is calculated based on the dispatch schedule determined by the planning model. The "dynamic baseload" case moves projected 2030 CSP LCOEs in all scenarios well within the range of (baseload) nuclear costs. Even in the strict baseload case, however, if favorable learning rate scenarios for CSP and the higher end of the cost range for nuclear are assumed, baseload power from CSP would become cheaper than nuclear baseload power by 2030.

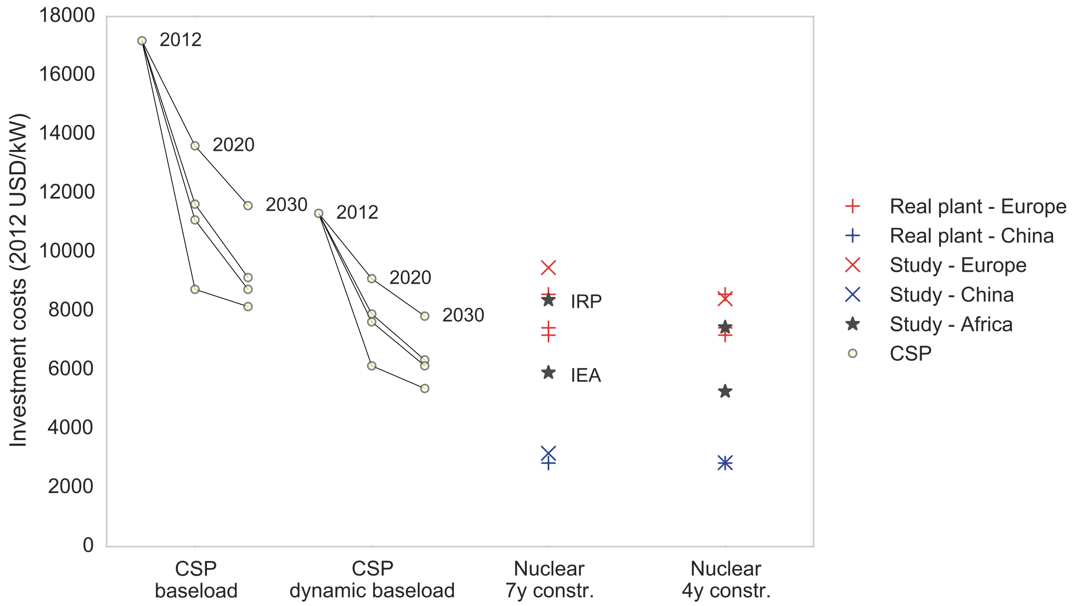

Figure 3: Ranges of investment costs in 2012 USD for CSP metaplants and nuclear plants. The CSP metaplants are spread between 2012, 2020, and 2030 costs, for both regular baseload and dynamic baseload configurations (see text). For nuclear plants, a comparison assuming 4 years and 7 years of construction duration is shown. The two sources of published estimates for African/South African plants are marked.

One advantage of CSP over nuclear is that several individual CSP plants can be built instead of one large nuclear plant, thus spreading the financial, construction and operating risk. Table 6 compares different constraints on the maximum installed capacity per site for both the baseload and dynamic baseload configurations. If only 100 MW are allowed per site, all sites must be included to reach the desired 1000 MW total capacity. On the other hand, if no restriction is set, 5 sites are selected in the planning optimization. There is, of course, a trade-off: selecting only few optimal sites would lead to higher vulnerability towards adverse weather conditions at one location. The results from Table 6 suggest that reducing from 8 to 5 sites brings little gain in cost, so there is a point at which it may be more desirable to spread out sites in exchange for a slightly higher cost. In addition, the "500 MW, close to grid" case only allows sites close to the existing power grid. This excludes some sites with higher annual irradiance, and thus leads to an LCOE 1.7 cents/kWh higher (2012 costs) than in the unconstrained case. The cost difference can be interpreted such that for this particular set of sites, picking sites further away from the existing transmission system only makes economic sense if the added levelized cost of additional transmission lines is below about 1.7 cents/kWh.

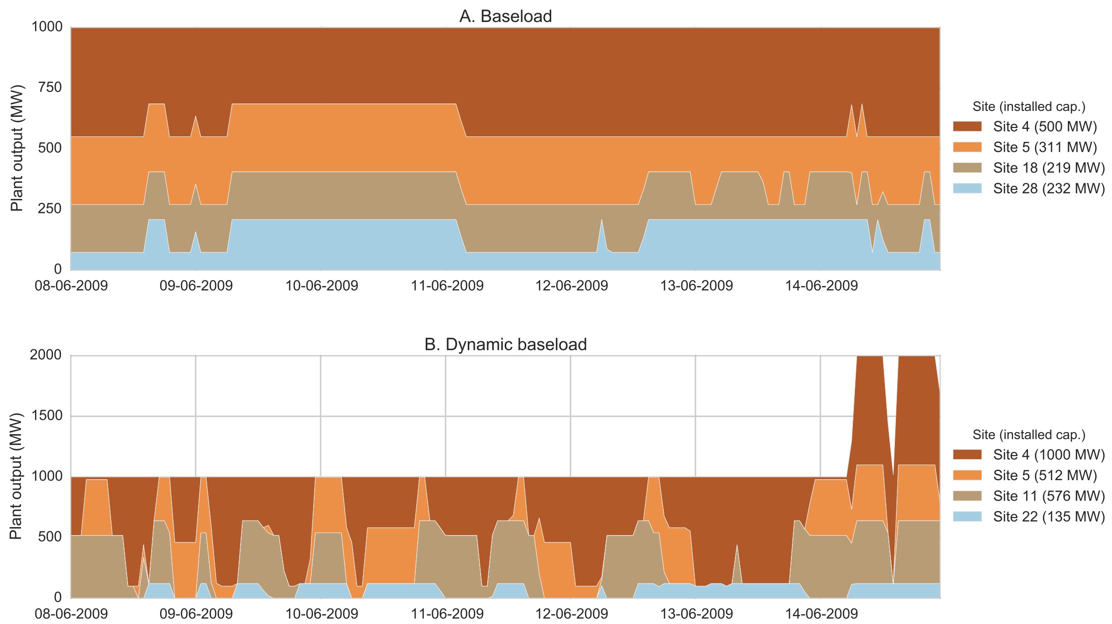

Figure 4: Dispatch of CSP plants during the week of lowest solar irradiance across all possible sites. A: baseload plants, B: dynamic baseload plants.

Table 6: LCOE comparison for different allowed maximum installed capacities per site. The "500 MW, close to grid" case additionally shows the cost increase by allowing only sites close to the existing grid. All costs are in 2012 USD.

	Used sites	LCOE (2012)	LCOE (2030)
Baseload (100 MW)	15	0.226	0.129
Baseload (200 MW)	10	0.215	0.122
Baseload (500 MW)	4	0.207	0.118
Baseload (no limit)	2	0.200	0.113
Baseload (500 MW, close to grid)	5	0.224	0.128
Dynamic baseload (400 MW)	8	0.130	0.077
Dynamic baseload (1000 MW)	4	0.127	0.076

4.3. Greenhouse gas emissions and environmental impacts

Assessing life-cycle greenhouse gas emissions is fraught with uncertainty, and published estimates vary widely. For nuclear, Warner and Heath (2012) perform a harmonized meta-analysis of published life cycle analyses and report a median emissions intensity of 12 gCO_2eq/kWh with an interquartile range (IQR) of 6.8 to 24 gCO_2eq/kWh, and a total range from 3.7 to 110 gCO_2eq/kWh, for light water reactors (LWRs). They include additional reactor types in their supplementary material: heavy water reactors show significantly worse results, gas-cooled reactors similar ones, and fast breeder reactors significantly better results, but those data

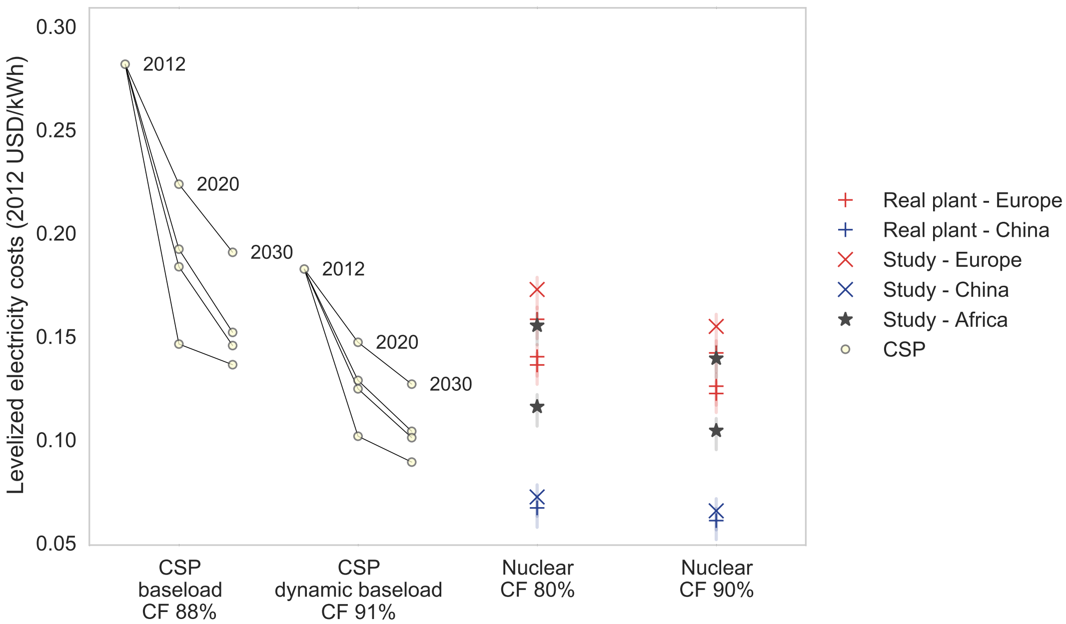

Figure 5: Levelized cost of electricity (LCOE) for CSP metaplants and nuclear plants. Lines indicate progression of costs from 2012 to 2020 and 2030 for CSP metaplants under different learning rate scenarios, for both classic baseload and dynamic baseload configurations (see text). For nuclear power plants, a 7 year construction time is assumed, and two scenarios with 80% and 90% capacity factors are compared. The two nuclear power scenarios include the range of uncertainty spanned by the high and low maintenance and fuel cost estimates (see text).

are based on only few studies. The LWR range is in the same order of magnitude as previous peer-reviewed meta-analyses (Sovacool, 2008; Fthenakis and Kim, 2007; Lenzen, 2008). The primary energy used for fuel mining and processing can have a large influence on life-cycle emissions. For example, Sovacool (2008) reports values from near zero to around 120 gCO_2eq/kWh for the emissions contribution of the fuel cycle's front end. Assuming that the electricity system powering the nuclear fuel cycle is dominated by coal, the life cycle emissions range in Warner and Heath (2012) rises to between 30 and 110 gCO_2eq/kWh. This is still well below the emissions intensity of fossil fuel power plants, but relevant given South Africa's stated plans for a renewed domestic fuel processing industry and the country's currently coal-heavy power sector. Declining uranium ore grades also negatively affect future nuclear plants' emissions, but not by orders of magnitude as sometimes claimed (Warner and Heath, 2012; Schneider et al., 2013). For CSP plants, Burkhardt et al. (2012) perform a meta-analysis using light harmonization (excluding harmonization of embodied emissions of plant materials and construction activities), resulting in a mean for parabolic trough plants

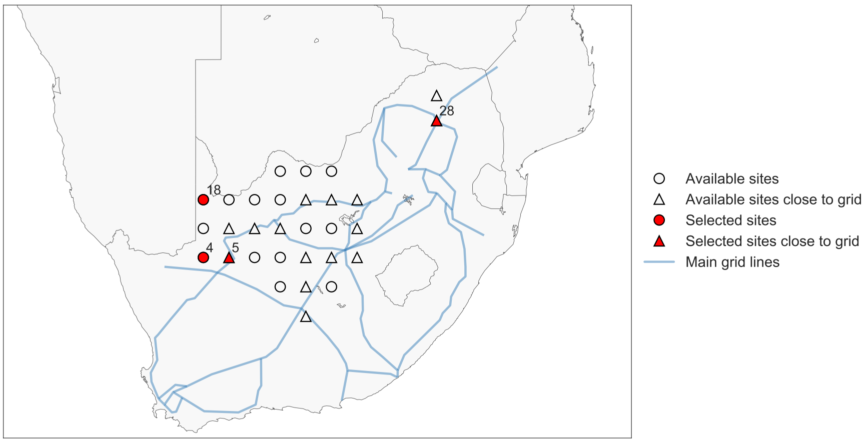

Figure 6: All available CSP sites, and those sites chosen in the scenario labelled "Baseload (500 MW)" in Table 6. Includes, schematically, the currently existing transmission system.

of 23 gCO_2eq/kWh with an IQR of 15 to 26 gCO_2eq/kWh, and a mean for central receivers of 22 gCO_2eq/kWh with an IQR of 16 to 29 gCO_2eq/kWh. Overall, both CSP and nuclear life cycle greenhouse gas emissions are much lower than those of fossil-fired plants (mean of 980 gCO_2eq/kWh for all coal technologies according to Whitaker et al., 2012). Yet, nuclear emissions may be up to an order of magnitude higher than those of CSP under worst-case assumptions. It should be noted that assumptions such as plant life and capacity factors can significantly affect reported emissions intensities. For example, the assumptions made for the harmonization of nuclear plants in Warner and Heath (2012) (92% capacity factor, 40 years lifetime) may be too optimistic given the IAEA's historical operational data (see above).

In addition to greenhouse gas emissions, energy production also has wider impacts on human health and the environment, including water use, land use and biodiversity. All three CSP plants currently under construction in SA use dry cooling (NREL, 2013), and the same can be assumed for future projects. All of the nuclear plants currently operating or under construction worldwide use wet cooling, primarily for safety reasons. Meldrum et al. (2013) give harmonized life-cycle water withdrawal and consumption (i.e. the portion of withdrawn water "not returned to the immediate water environment"). The following figures are their median estimates for life cycle water use. Depending on the cooling technology the withdrawal for nuclear is between 1297 and 47197 gallons/MWh (consumption: 544 - 864 gallons/MWh). For dry-cooled CSP central receiver plants, withdrawal and consumption is 186 gallons/MWh, for dry-cooled parabolic trough plants, 238 gallons/MWh. For nuclear plants, almost all water is used in the fuel cycle and plant cooling, while for dry-cooled CSP, almost all water is used during plant construction. This assessment does not take into account water quality issues, such as the remediation of uranium mill tailing ponds. According to Mudd (2014), mine rehabilitation frequently shows poor success and leads to problems including acid drainage, erosion, public health risks and constrained land use challenges (Mudd, 2014). However, data on direct ecological impacts of either technology are scarce. An appraisal of avian deaths associated with different power generation technologies found similar rates of death for wind and nuclear power (Sovacool, 2009), but there is no data for CSP plants. Both CSP and nuclear are large-scale construction projects, with all the accompanying environmental impacts. Nuclear power has the additional unresolved issue of long-term storage for spent nuclear fuel with its associated environmental and health risks, and the difficulties of finding suitable storage sites that are publicly acceptable (Sjoberg and Drottz-Sjoberg, 2009).

4.4. Other risks

There are additional risks with both CSP and nuclear plants both today and in the future. The key risk with CSP is twofold: first, costs may not reduce to the degree suggested by the learning rate analyses given above. While the results show that CSP could nevertheless be cost-competitive to nuclear in some cases, it may still be uncompetitive in the wider renewable energy market, or against fossil fuels in absence of strong climate mitigation commitments. Second, CSP depends on variable solar irradiance, and therefore on possible changes in irradiance trends or extreme events affecting irradiance over a period of days or weeks. Infrequent periods of low irradiance (which may not show up in the 3 years of data used here) could be countered by hybrid plants that can also burn fossil fuels or biomass, or the ability to charge the plants' heat storage from the grid (Silinga and Gauché, 2014). Furthermore, if only individual sites are affected, the overall capability of a well-distributed metaplant to deliver power would only marginally be affected. Figure 7 shows thirty years of total daily DNI across the 30 possible sites, based on CM-SAF data (Mueller et al., 2012; Amillo et al., 2014). It suggests that the three chosen years are well within the range of variation over these decades, and that the year 2009 is even a particularly bad year (in the month of June). A major advantage of CSP over nuclear power is that CSP plants can be built at a much smaller scale. The assumption in this paper is to provide 1000 MW of baseload capacity, and that this requires either a single nuclear plant or a variable number of CSP plants (while technically possible, no small nuclear plants are available on the market yet). Splitting investment into several smaller projects may spread out or reduce various other risks, such as those of corruption, or construction delays at specific sites.

The possibility of a catastrophic accident is one of the reasons for popular opposition to nuclear power, as are the health risks associated with radiation (Christodouleas et al., 2011). The idea of "normal accidents" introduced by Perrow (1984) is that due to their inherent complexity and tight coupling, a residual risk of catastrophic failure cannot be prevented

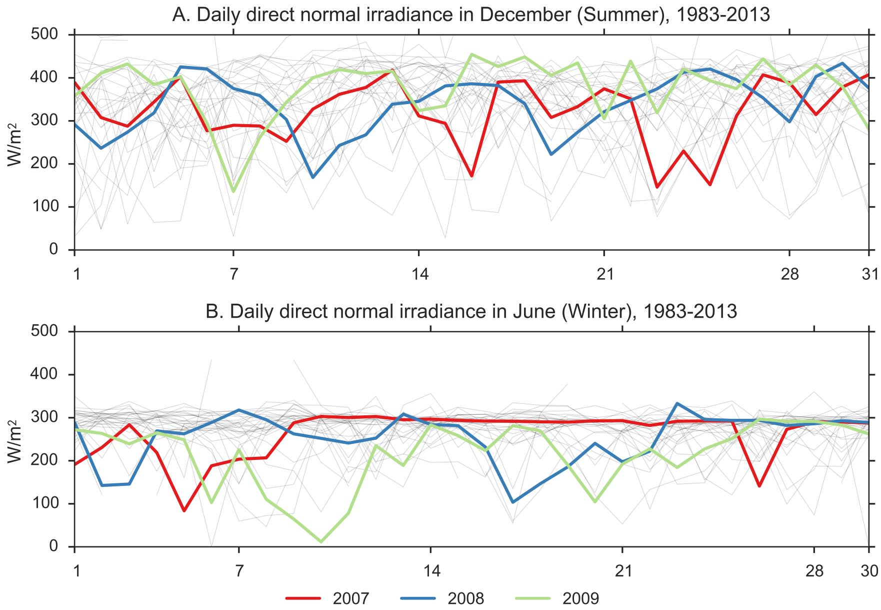

Figure 7: Daily DNI data for the months of June and December, averaged over all 30 possible sites, for the years 1983-2013. Each line represents one year, and the three years used for the detailed site selection are marked in color.

in systems such as nuclear reactors. This fact was once again demonstrated by the 2011 Fukushima disaster. A further risk, both technical and financial in nature, is that there is currently no long-term solution for nuclear waste. Spent fuel rods are stored on-site at reactors in many countries (including South Africa's Koeberg reactor) due to a lack of secure storage facilities. Irrespective of how improved reactor designs may affect the safety of future nuclear plants, and irrespective of new ways to deal with nuclear waste, CSP plants (like other renewable energy sources) do not suffer from such problems. The most common principles of liability for nuclear power, which SA follows, place liability in case of accidents on the operator of a nuclear power plant, but also limit the operator's maximum liability (Republic of South Africa, 1999). Without this liability cap, higher insurance costs could follow, which may discourage investment in nuclear. The cap has therefore been called an implicit subsidy (Dubin and Rothwell, 1990), remaining hidden in most cost assessments (including the one performed in this study). Furthermore, arguments have been made that capping liability leads to inadequate incentives for safe reactor designs and operating procedures (Trebilcock and Winter, 1997; Eberl and Jus, 2012). Decommissioning costs are uncertain and the value used in this study may be too optimistic for problematic cases or accident remediation. The Japanese government has estimated the cost of decommissioning the four Fukushima power plants alone at 13.6 Billion USD (Aoki and Rothwell, 2013), which, combined with a decommissioning before their planned end of life, will drastically increase the levelized power costs for those reactors. In summary, nuclear power has numerous potential technical and financial risks for which insufficiently accurate data are available.

Finally, there is the the degree to which either nuclear or CSP are vulnerable to climate change. Existing nuclear plant designs rely on wet cooling and thus need either a seaside location, potentially making them vulnerable to sea level rise (Kopytko and Perkins, 2011), or a nearby river, making them vulnerable to hydrological flow changes or high surface water temperatures (Förster and Lilliestam, 2010; van Vliet et al., 2012). CSP plants are vulnerable to changing irradiance patterns or prolonged periods of low irradiance driven by climate change. Without further work, little can be said on whether and how these vulnerabilities can be addressed, and how severe they potentially are under different climate change scenarios.

4.5. Indirect economic effects

There are also considerations of local economic development and job creation. One of the South African government's stated goals is to re-establish a domestic nuclear fuel production cycle. However, establishing a fuel production cycle that is economically viable would require nuclear deployment on the order of 10,000 MW (Campbell, 2014b). For the United States, Wei et al. (2010) give average job-years per GWh of 0.23 for CSP, and 0.14 for Nuclear, but assuming high availability for nuclear and low availability for CSP. So the jobs per GWh, if both have similar (baseload) availability, may in reality be closer to each other. However, many of the nuclear-related jobs that accrue in the U.S. may not accrue in South Africa because of the limited domestic nuclear industry relying substantially on imported experts and technology. In contrast, South Africa has been actively developing technologies in the CSP area and with more domestic deployment experience, it might become a CSP technology exporter, rather than an importer as in the case of nuclear. Furthermore, evidence suggests that market-related jobs outnumber those in manufacturing in other industries (Dicken, 2007). This suggests that the promotion of a fledgling domestic technology market alongside its service and support suppliers may be a more viable economic strategy than the large-scale import of an established technology.

5. Discussion and conclusion

We compare nuclear and concentrating solar power as baseload providers, from the perspective of resource potential, costs, emissions and other environmental impacts, risks and vulnerabilities. The results suggest that in terms of cost, baseload-capable CSP could become competitive with nuclear power by 2030 if it sees sufficient deployment to drive costs down, and in some cases (at the higher end of the nuclear cost scale), it can already be competitive now. Furthermore, CSP plants are a smaller investment with lower environmental and financial risks. Thus, the results indicate that in countries with substantial solar resource,

Table 7: Summarized comparison between the two technologies. See results discussed above for details.

	Nuclear	CSP	Likely development
Resource potential	No practical limits for at least the next 100 years	No practical limits, sufficient land with high solar resource available in South Africa	Newer generation reactors would further extend the nuclear resource by hundreds of years
Costs	Wide range of costs but most of them high, unlikely to fall substantially, and historically liable to cost overruns	Costs likely to fall significantly as global deployment accelerates	Baseload-capable CSP increasingly competitive with nuclear towards 2030
Greenhouse gas emissions	Reported values from below 10 gCO_2eq/kWh to above 100 gCO_2eq/kWh, most likely real value below 50 gCO_2eq/kWh	Similar order of magnitude as nuclear	Nuclear emissions would rise if increasingly lower-grade uranium is used
Other environmental effects	Mining and remediation, decommissioning, substantial cooling water use	No major issues currently known, apart from land use from heliostats, water use lower and primarily in construction rather than operation	More studies on the effect of CSP plants on wildlife may yet reveal ecological damage
Risks	Risk of nuclear accidents and contamination, severe financial risks, liabilities of decommissioning costs, may face political and popular opposition, climate vulnerabilities due to coastal locations and water use	Risk of low irradiance periods, climate vulnerabilities due to changing weather patterns	Uncertain future climate effects, cost uncertainty for both could change relative attractiveness
Ease of deployment	Slow regulatory and construction process based on global experience so far, negative public opinion may block or delay deployment	Fast and timely construction based on global experience so far, less likely to face public opposition	Investment prospects for CSP may become more favorable as construction and operating experience increases

like South Africa, CSP could be a viable alternative as a baseload providing technology. Table 7 summarizes the comparison on the other criteria.

Future work could improve on the analysis in several ways. The consideration of climate variation and the vulnerability of both technologies is an important question for longer-term planning. Maintenance downtimes are not explicitly considered in this study for either CSP or nuclear plants, although the availability for both does not exceed about 90%. Their consideration might be favorable to CSP, as CSP plants would generally be smaller (so the capacity going offline at any given moment would be small), furthermore, nuclear power plants, due to their complexity, can be expected to be more maintenance-intensive. However, more work would be needed to quantify their effect.

There are also several key uncertainties that could significantly affect the analysis. Firstly, there is uncertainty in the cost data used here. In the case of nuclear, cost data from China suggest that plants can be built at significantly lower costs. On the other hand, insufficient information on these cost data is available, and it is possible that they do not cover the full costs, or that savings achieved will translate to higher operational costs or lower availabilities. The future costs of both technologies are uncertain, yet historical evidence suggests that nuclear costs do not fall over time, while CSP costs could significantly decrease as learning takes place (but that is also uncertain). Furthermore, we have considered the physical lifetime of plants, but not the potential impact different economic "book" lifetimes would have on the analysis, due to a lack of conclusive data to underpin such a study for South Africa. Future comparative work between different tax and incentive regimes could analyze their effect on the relative investment value of the two options discussed here. In addition to cost data uncertainty, further uncertainties exist in input data used here, including the solar irradiance data (for CSP), technology performance data (for both CSP and nuclear), and emissions data, as discussed above. Finally, the integration of CSP and nuclear plants into future power grids with potentially high shares of variable renewable generation (wind and solar PV) may significantly affect the costs and feasibilities reported here. This topic warrants more in-depth analysis using fully-fledged power system models better able to represent the operational implications of adding baseload generation. For example, the relative inflexibility and high capital cost of nuclear plants make it possible that their relative competitiveness to CSP would decrease when considering the full power system dynamics.

There are, of course, other technological possibilities: for example, a breakthrough in electricity storage technologies, coupled with continuing cost decreases of wind and solar PV, could accelerate the transition to a new paradigm of power systems and leave both CSP and nuclear unable to compete. The technical analysis performed here – the ability of solar power plants with integrated storage to provide stable baseload power – would hold equally well for PV power plants combined with a form of battery storage. Yet CSP plants have other unique properties, for example, a contribution to grid stability due to their spinning turbine, so they may still have applications in any case. In Southern Africa specifically, there is some evidence for increasing regional collaboration, for instance through the treaty signed to deliver power to South Africa from the proposed Grand Inga dam in the Democratic Republic of Congo (Manson, 2014). This and similar projects could provide another substantial source of emissions-free baseload power to the entire region, but it is unclear whether and how soon such projects might be realized. Finally, there is the also possibility of technological development leading to smaller, safer, and cheaper nuclear power reactors, but again, it is uncertain if and when such technology would be available.

Technology choice is often not driven by costs or perceived environmental benefits. For example, there is evidence of a lock-in effect, i.e. that countries with existing nuclear power capacity continue investing in it (Csereklyei, 2014). On the other hand, strategic energy policy may suggest one technology over another for reasons to do with long-term energy security or other governmental interests. The results presented here suggest that with a moderate deployment of non-baseload capable CSP worldwide, the cost of CSP technology may have fallen enough by 2030 to make baseload-capable CSP generation economically competitive with nuclear power. Given these results, a cautious approach of delaying investment decisions into new nuclear power plants in South Africa may be prudent, which indeed was also suggested by the IRP 2013 update. Globally, this also means that as countries reach higher and higher shares of renewables, and start experiencing difficulties with grid integration and balancing, cheaper, fully dispatchable or baseload-capable CSP plants will be able to ease pressure on existing grids. The results presented here should be equally valid for other regions with an abundant solar resource. For regions without the necessary solar resource, in particular Europe, domestic CSP production is not an option, but imports from neighboring deserts may be (this has been shown to be economically feasible including the added transmission costs, e.g. in Williges et al., 2010). Ultimately, the question of technology choice is also one of societal and political decision-making on which risks are more desirable, but the results and data presented here can help shape those decisions.

6. Acknowledgments

The authors would like to thank Paul Gauché for substantial assistance particularly in acquiring data, Christina Auret and Maria Carvalho for helpful suggestions, and GeoModel Solar for providing solar irradiance data.

Funding for this work was provided by the Grantham Institute at Imperial College London and by the European Institute of Innovation & Technology's Climate-KIC program.

References

T. Abram and S. Ion. 2008. Generation-IV nuclear power: A review of the state of the science. *Energy Policy*, 36(12):4323–4330. DOI: 10.1016/j.enpol.2008.09.059.

ACWA Power. Our Investments - Bokpoort CSP Project. http://www.acwapower.com/project/15/bokpoort-csp-project.html, 2014. Available at http://www.acwapower.com/project/15/bokpoort-csp-project.html, [Accessed: 2014-09-11].

A. Amillo, T. Huld, and R. Müller. 2014. A New Database of Global and Direct Solar Radiation Using the Eastern Meteosat Satellite, Models and Validation. *Remote Sensing*, 6(9):8165–8189. DOI: 10.3390/rs6098165.

M. Aoki and G. Rothwell. 2013. A comparative institutional analysis of the Fukushima nuclear disaster: Lessons and policy implications. *Energy Policy*, 53:240–247. DOI: 10.1016/j.enpol.2012.10.058.

C. Auret and P. Gauché. 2014. Replacing Intermittent Renewable Capacity in the 2010 IRP with CSP: Effect on Coal Fired Power Station Capacity Factors in 2030. In *Proceedings of SASEC 2014*, Port Elizabeth, South Africa, 2014. Available at http://blogs.sun.ac.za/sterg/files/2014/02/61.pdf, [Accessed: 2014-09-02].

F. d. Beaupuy and T. Patel. China Builds Nuclear Reactor for 40% Less Than Cost in France, Areva Says. http://www.bloomberg.com/news/2010-11-24/china-builds-french-designed-nuclear-reactor-for-40-less-areva-ceo-says.html, 2010. Available at http://www.bloomberg.com/news/2010-11-24/china-builds-french-designed-nuclear-reactor-for-40-less-areva-ceo-says.html, [Accessed: 2014-10-10].

E. Bertel and T. Lazo. 2003. Decommissioning policies, strategies and costs: an international overview. Technical Report NEA News 2003 – No. 21.2, OECD, Paris. Available at https://www.oecd-nea.org/nea-news/2003/21-2-decommissioning.pdf, [Accessed: 2014-10-10].

B. W. Brook. 2012. Could nuclear fission energy, etc., solve the greenhouse problem? The affirmative case. *Energy Policy*, 42:4–8. DOI: 10.1016/j.enpol.2011.11.041.

C. Budischak, D. Sewell, H. Thomson, L. Mach, D. E. Veron, and W. Kempton. 2013. Cost-minimized combinations of wind power, solar power and electrochemical storage, powering the grid up to 99.9% of the time. *Journal of Power Sources*, 225:60–74. DOI: 10.1016/j.jpowsour.2012.09.054.

J. J. Burkhardt, G. Heath, and E. Cohen. 2012. Life Cycle Greenhouse Gas Emissions of Trough and Tower Concentrating Solar Power Electricity Generation. *Journal of Industrial Ecology*, 16:S93–S109. DOI: 10.1111/j.1530-9290.2012.00474.x.

K. Campbell. SA nuclear sector needs to convince authorities of its capabilities. http://www.engineeringnews.co.za/article/sa-nuclear-sector-needs-to-convince-authorities-of-its-capabilities-2014-03-18, 2014a. Available at http://www.engineeringnews.co.za/article/sa-nuclear-sector-needs-to-convince-authorities-of-its-capabilities-2014-03-18, [Accessed: 2014-09-04].

K. Campbell. SA still committed to new nuclear build, but much remains unclear. http://www.engineeringnews.co.za/article/sa-still-committed-to-new-nuclear-build-but-much-remains-unclear-2014-04-09, 2014b. Available at http://www.engineeringnews.co.za/article/sa-still-committed-to-new-nuclear-build-but-much-remains-unclear-2014-04-09, [Accessed: 2014-09-04].

J. P. Christodouleas, R. D. Forrest, C. G. Ainsley, Z. Tochner, S. M. Hahn, and E. Glatstein. 2011. Short-Term and Long-Term Health Risks of Nuclear-Power-Plant Accidents. *New England Journal of Medicine*, 364(24):2334–2341. DOI: 10.1056/NEJMra1103676. PMID: 21506737.

Z. Csereklyei. 2014. Measuring the impact of nuclear accidents on energy policy. *Ecological Economics*, 99:121–129. DOI: 10.1016/j.ecolecon.2014.01.010.

P. Denholm and M. Mehos. 2011. Enabling Greater Penetration of Solar Power via the Use of CSP with Thermal Energy Storage. Technical report, NREL.

P. Denholm, J. C. King, C. F. Kutcher, and P. P. H. Wilson. 2012. Decarbonizing the electric sector: Combining renewable and nuclear energy using thermal storage. *Energy Policy*, 44:301–311. DOI: 10.1016/j.enpol.2012.01.055.

P. Dicken. 2007. *Global shift: mapping the changing contours of the world economy*. SAGE, London. ISBN 9781412929547 1412929547 1412929555 9781412929554.

Y. Du and J. E. Parsons. 2009. Update on the Cost of Nuclear Power. SSRN Scholarly Paper ID 1470903, Social Science Research Network, Rochester, NY. Available at http://papers.ssrn.com/abstract=1470903, [Accessed: 2014-09-11].

J. A. Dubin and G. S. Rothwell. 1990. Subsidy to Nuclear Power Through Price-Anderson Liability Limit. *Contemporary Economic Policy*, 8(3):73–79. DOI: 10.1111/j.1465-7287.1990.tb00645.x.

J. Eberl and D. Jus. 2012. The year of the cat: Taxing nuclear risk with the help of capital markets. *Energy Policy*, 51:364–373. DOI: 10.1016/j.enpol.2012.08.037.

EDF Energy. News Releases - Agreement reached on commercial terms for the planned Hinkley Point C nuclear power station. http://newsroom.edfenergy.com/News-

Releases/Agreement-reached-on-commercial-terms-for-the-planned-Hinkley-Point-C-nuclear-power-station-82.aspx, 2013. Available at http://newsroom.edfenergy.com/News-Releases/Agreement-reached-on-commercial-terms-for-the-planned-Hinkley-Point-C-nuclear-power-station-82.aspx, [Accessed: 2014-09-02].

EIA. 2013. Updated Capital Cost Estimates for Utility Scale Electricity Generating Plants. Technical report, U.S. Department of Energy, Washington, D.C. Available at http://www.eia.gov/forecasts/capitalcost/, [Accessed: 2014-10-10].

T. Fluri. 2009. The potential of concentrating solar power in South Africa. *Energy Policy*, 37 (12):5075–5080. DOI: 10.1016/j.enpol.2009.07.017.

B. Flyvbjerg, M. S. Holm, and S. Buhl. 2002. Underestimating Costs in Public Works Projects: Error or Lie? *Journal of the American Planning Association*, 68(3):279–295. DOI: 10.1080/01944360208976273.

C. Forsberg. 2013. Hybrid systems to address seasonal mismatches between electricity production and demand in nuclear renewable electrical grids. *Energy Policy*, 62:333–341. DOI: 10.1016/j.enpol.2013.07.057.

H. Förster and J. Lilliestam. 2010. Modeling thermoelectric power generation in view of climate change. *Regional Environmental Change*, 10(4):327–338. DOI: 10.1007/s10113-009-0104-x.

V. M. Fthenakis and H. C. Kim. 2007. Greenhouse-gas emissions from solar electric- and nuclear power: A life-cycle study. *Energy Policy*, 35(4):2549–2557. DOI: 10.1016/j.enpol.2006.06.022.

P. Gauché, T. W. von Backström, and A. C. Brent. 2011. CSP Modeling Methodology for Macro Decision Making - Emphasis on the Central Receiver Type. Granada, Spain, 2011.

GeoModel Solar. SolarGIS data © 2012 GeoModel Solar s.r.o, 2012. Available at http://solargis.info/, [Accessed: 2014-11-07].

Government of South Africa. 2011. National Climate Change Response White Paper. Technical report. Available at http://www.pmg.org.za/files/docs/111012nccr-whitepaper.pdf, [Accessed: 2014-10-10].

R. W. Grimes and W. J. Nuttall. 2010. Generating the Option of a Two-Stage Nuclear Renaissance. *Science*, 329(5993):799–803. DOI: 10.1126/science.1188928. PMID: 20705854.

A. Grubler. 2010. The costs of the French nuclear scale-up: A case of negative learning by doing. *Energy Policy*, 38(9):5174–5188. DOI: 10.1016/j.enpol.2010.05.003.

R. S. Haszeldine. 2009. Carbon Capture and Storage: How Green Can Black Be? *Science*, 325(5948):1647–1652. DOI: 10.1126/science.1172246.

N. E. Hultman, J. G. Koomey, and D. M. Kammen. 2007. What History Can Teach Us About the Future Costs of U.S. Nuclear Power. *Environmental Science & Technology*, 41(7):2087–2094. DOI: 10.1021/es0725089.

IAEA. 2012. Uranium 2011. Technical Report 1996-3459, OECD, Paris. Available at http://www.oecd-ilibrary.org/content/serial/20725310, [Accessed: 2014-09-04].

IAEA. PRIS (Power Reactor Information System) Update 2014-09-08. http://www.iaea.org/PRIS/home.aspx, 2014. Available at http://www.iaea.org/PRIS/home.aspx, [Accessed: 2014-09-09].

IDC. IDC - Your partner in development finance | Investing in the economy. http://www.idc.co.za/IR2013/ie-case-khi-solar.php, 2013. Available at http://www.idc.co.za/IR2013/ie-case-khi-solar.php, [Accessed: 2014-09-11].

IEA. 2013. World Energy Outlook 2013. Technical report, Organisation for Economic Co-operation and Development, Paris. Available at http://www.oecd-ilibrary.org/content/serial/20725302, [Accessed: 2014-05-27].

IEA. World Energy Outlook 2014 Power Generation Investment Assumptions. http://www.worldenergyoutlook.org/weomodel/investmentcosts/, 2014. Available at http://www.worldenergyoutlook.org/weomodel/investmentcosts/, [Accessed: 2014-10-10].

C. Jahren and A. Ashe. 1990. Predictors of Cost-Overrun Rates. *Journal of Construction Engineering and Management*, 116(3):548–552. DOI: 10.1061/(ASCE)0733-9364(1990)116:3(548).

JRC. Global Land Cover 2000. http://bioval.jrc.ec.europa.eu/products/glc2000/legend.php, 2010. Available at http://bioval.jrc.ec.europa.eu/products/glc2000/legend.php, [Accessed: 2014-11-07].

G. J. Kolb, C. K. Ko, T. R. Mancini, and J. A. Gary. 2011. Power Tower Technology Roadmap and Cost Reduction Plan. Technical Report SAND2011-2419, Sandia National Laboratories.

J. Koomey and N. E. Hultman. 2007. A reactor-level analysis of busbar costs for US nuclear plants, 1970–2005. *Energy Policy*, 35(11):5630–5642. DOI: 10.1016/j.enpol.2007.06.005.

N. Kopytko and J. Perkins. 2011. Climate change, nuclear power, and the adaptation–mitigation dilemma. *Energy Policy*, 39(1):318–333. DOI: 10.1016/j.enpol.2010.09.046.

M. Lenzen. 2008. Life cycle energy and greenhouse gas emissions of nuclear energy: A review. *Energy Conversion and Management*, 49(8):2178–2199. DOI: 10.1016/j.enconman.2008.01.033.

J. Lovelock. 2007. *The Revenge of Gaia: Earth's Climate in Crisis and the Fate of Humanity*. Basic Books. ISBN 9780465041695.

G. MacKerron. 1992. Nuclear costs: Why do they keep rising? *Energy Policy*, 20(7):641–652. DOI: 10.1016/0301-4215(92)90006-N.

T. Mai, M. Hand, S. Baldwin, R. Wiser, G. Brinkman, P. Denholm, D. Arent, G. Porro, D. Sandor, D. Hostick, M. Milligan, E. DeMeo, and M. Bazilian. 2014a. Renewable Electricity Futures for the United States. *IEEE Transactions on Sustainable Energy*, 5(2):372–378. DOI: 10.1109/TSTE.2013.2290472.

T. Mai, D. Mulcahy, M. M. Hand, and S. F. Baldwin. 2014b. Envisioning a renewable electricity future for the United States. *Energy*, 65:374–386. DOI: 10.1016/j.energy.2013.11.029.

K. Manson. 2014. Congo renews push for Grand Inga dam, an African white elephant. *Financial Times*.

E. Martinot, C. Dienst, L. Weiliang, and C. Qimin. 2007. Renewable Energy Futures: Targets, Scenarios, and Pathways. *Annual Review of Environment and Resources*, 32(1):205–239. DOI: 10.1146/annurev.energy.32.080106.133554.

J. Meldrum, S. Nettles-Anderson, G. Heath, and J. Macknick. 2013. Life cycle water use for electricity generation: a review and harmonization of literature estimates. *Environmental Research Letters*, 8(1):015031. DOI: 10.1088/1748-9326/8/1/015031.

L. Mez. 2012. Nuclear and renewables: compatible or contradicting? *Wiley Interdisciplinary Reviews: Energy and Environment*, 1(2):218–224. DOI: 10.1002/wene.14.

G. M. Mudd. 2014. The future of Yellowcake: A global assessment of uranium resources and mining. *Science of The Total Environment*, 472:590–607. DOI: 10.1016/j.scitotenv.2013.11.070.

R. Mueller, T. Behrendt, A. Hammer, and A. Kemper. 2012. A New Algorithm for the Satellite-Based Retrieval of Solar Surface Irradiance in Spectral Bands. *Remote Sensing*, 4(12):622–647. DOI: 10.3390/rs4030622.

L. Neij. 2008. Cost development of future technologies for power generation—A study based on experience curves and complementary bottom-up assessments. *Energy Policy*, 36(6):2200–2211. DOI: 10.1016/j.enpol.2008.02.029.

NREL. NREL: Concentrating Solar Power Projects. http://www.nrel.gov/csp/solarpaces/, 2013. Available at http://www.nrel.gov/csp/solarpaces/, [Accessed: 2014-09-09].

C. Paton. Eskom not taking part in nuclear acquisition. http://www.bdlive.co.za/business/energy/2014/09/15/eskom-not-taking-part-in-nuclear-acquisition?PageSpeed=noscript, 2014. Available at http://www.bdlive.co.za/business/energy/2014/09/15/eskom-not-taking-part-in-nuclear-acquisition?PageSpeed=noscript, [Accessed: 2014-09-16].

C. Perrow. 1984. *Normal Accidents: Living with High Risk Technologies*. Princeton University Press, Princeton, NJ. ISBN 0691004129.

S. Pfenninger. Calliope: a multi-scale energy systems (MUSES) modeling framework. http://www.callio.pe/, 2014. Available at http://www.callio.pe/, [Accessed: 2014-12-17].

S. Pfenninger, P. Gauché, J. Lilliestam, K. Damerau, F. Wagner, and A. Patt. 2014. Potential for concentrating solar power to provide baseload and dispatchable power. *Nature Climate Change*, 4(8):689–692. DOI: 10.1038/nclimate2276.

M. Ramana. 2009. Nuclear Power: Economic, Safety, Health, and Environmental Issues of Near-Term Technologies. *Annual Review of Environment and Resources*, 34(1):127–152. DOI: 10.1146/annurev.environ.033108.092057.

Republic of South Africa. National Nuclear Regulator Act, 1999. Available at http://www.nnr.co.za/wp-content/uploads/2011/07/act47.pdf, [Accessed: 2014-09-16].

M. Rudolf, R. Seidl, C. Moser, P. Krütli, and M. Stauffacher. 2014. Public preference of electricity options before and after Fukushima. *Journal of Integrative Environmental Sciences*, 11(1):1–15. DOI: 10.1080/1943815X.2014.881887.

M. B. Schaffer. 2013. Abundant thorium as an alternative nuclear fuel: Important waste disposal and weapon proliferation advantages. *Energy Policy*, 60:4–12. DOI: 10.1016/j.enpol.2013.04.062.

E. Schneider, B. Carlsen, E. Tavrides, C. van der Hoeven, and U. Phathanapirom. 2013. A top-down assessment of energy, water and land use in uranium mining, milling, and refining. *Energy Economics*, 40:911–926. DOI: 10.1016/j.eneco.2013.08.006.

M. Schneider, A. Froggatt, Y. Ayukawa, S. Burnie, R. Piria, S. Thomas, and J. Hazemann. 2014. The World Nuclear Industry Status Report 2014. Technical report, Mycle Schneider Consulting. Available at http://www.worldnuclearreport.org/IMG/pdf/201408msc-worldnuclearreport2014-lr-v4.pdf, [Accessed: 2014-09-02].

C. Silinga and P. Gauché. 2014. Scenarios for a South African CSP Peaking System in the Short Term. *Energy Procedia*, 49:1543–1552. DOI: 10.1016/j.egypro.2014.03.163.

L. Sjoberg and B.-M. Drottz-Sjoberg. 2009. Public risk perception of nuclear waste. *International Journal of Risk Assessment and Management*, 11(3):248–280. DOI: 10.1504/IJRAM.2009.023156.

South Africa Department of Energy. 2011. Integrated Resource Plan for Electricity 2010-2030. Technical report. Available at `http://www.energy.gov.za/IRP/irp%20files/IRP2010_2030_Final_Report_20110325.pdf`, [Accessed: 2014-08-12].

South Africa Department of Energy. 2013. Integrated Resource Plan for Electricity 2010-2030: 2013 Update. Technical report. Available at `http://www.doe-irp.co.za/content/IRP2010_updatea.pdf`, [Accessed: 2014-08-12].

B. K. Sovacool. 2008. Valuing the greenhouse gas emissions from nuclear power: A critical survey. *Energy Policy*, 36(8):2950–2963. DOI: 10.1016/j.enpol.2008.04.017.

B. K. Sovacool. 2009. Contextualizing avian mortality: A preliminary appraisal of bird and bat fatalities from wind, fossil-fuel, and nuclear electricity. *Energy Policy*, 37(6):2241–2248. DOI: 10.1016/j.enpol.2009.02.011.

B. K. Sovacool, A. Gilbert, and D. Nugent. 2014. Risk, innovation, electricity infrastructure and construction cost overruns: Testing six hypotheses. *Energy*, 74:906–917. DOI: 10.1016/j.energy.2014.07.070.

S. Thomas. 2011. The Pebble Bed Modular Reactor: An obituary. *Energy Policy*, 39(5):2431–2440. DOI: 10.1016/j.enpol.2011.01.066.

M. Trebilcock and R. A. Winter. 1997. The economics of nuclear accident law. *International Review of Law and Economics*, 17(2):215–243. DOI: 10.1016/S0144-8188(97)00004-5.

F. Trieb, T. Fichter, and M. Moser. 2014. Concentrating solar power in a sustainable future electricity mix. *Sustainability Science*, 9(1):47–60. DOI: 10.1007/s11625-013-0229-1.

M. T. H. van Vliet, J. R. Yearsley, F. Ludwig, S. Vögele, D. P. Lettenmaier, and P. Kabat. 2012. Vulnerability of US and European electricity supply to climate change. *Nature Climate Change*, 2(9):676–681. DOI: 10.1038/nclimate1546.

P. Viebahn, Y. Lechon, and F. Trieb. 2011. The potential role of concentrated solar power (CSP) in Africa and Europe—A dynamic assessment of technology development, cost development and life cycle inventories until 2050. *Energy Policy*, 39(8):4420–4430. DOI: 10.1016/j.enpol.2010.09.026.

E. S. Warner and G. A. Heath. 2012. Life Cycle Greenhouse Gas Emissions of Nuclear Electricity Generation. *Journal of Industrial Ecology*, 16:S73–S92. DOI: 10.1111/j.1530-9290.2012.00472.x.

M. Wei, S. Patadia, and D. M. Kammen. 2010. Putting renewables and energy efficiency to work: How many jobs can the clean energy industry generate in the US? *Energy Policy*, 38(2):919–931. DOI: 10.1016/j.enpol.2009.10.044.

M. Whitaker, G. A. Heath, P. O'Donoughue, and M. Vorum. 2012. Life Cycle Greenhouse Gas Emissions of Coal-Fired Electricity Generation. *Journal of Industrial Ecology*, 16:S53–S72. DOI: 10.1111/j.1530-9290.2012.00465.x.

K. Williges, J. Lilliestam, and A. Patt. 2010. Making concentrated solar power competitive with coal: The costs of a European feed-in tariff. *Energy Policy*, 38(6):3089–3097. DOI: 10.1016/j.enpol.2010.01.049.

B. B. F. Wittneben. 2012. The impact of the Fukushima nuclear accident on European energy policy. *Environmental Science & Policy*, 15(1):1–3. DOI: 10.1016/j.envsci.2011.09.002.