Evaluating scenarios of capacity expansion given high seasonal variability of electricity demand: the case of Saudi Arabia

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Abstract

The Kingdom of Saudi Arabia (KSA) has experienced rapid growth in peak load and electricity consumption over the past decade. Under current demographic and economic trends, peak load is projected to nearly triple by 2032, which will require massive new investments in both conventional and alternative generation capacity. A unique aspect of KSA is that the electric load nearly doubles in the summertime, which means that high penetration of renewables and nuclear in the future will need to be supplemented by flexible, dispatchable technologies. This paper breaks down the load curve into different categories based on utilization, and then develops a technology-specific capacity expansion model to meet projected growth in these categories, net of future renewable or nuclear capacity additions. This higher-granularity approach is novel in System Dynamics, where previous work has used aggregated measures of demand and grid capacity. The paper evaluates different scenarios of demand growth, renewable and nuclear deployments, and conventional capacity plans across various economic and environmental metrics. Key tradeoffs are discussed to inform policy development, as are limitations.

Keywords: Saudi Arabia, generation capacity planning, load curves, scenario analysis

1. Introduction

1.1 Motivation

The Kingdom of Saudi Arabia (KSA) is the world's largest oil producer, endowed with abundant reserves that have created an important export industry crucial to the kingdom's economic development and improved standards of living. Total oil production in 2011 was 11.15 million barrels per day, and while most of it is exported – just over 75% in 2011 (EIA, 2013) – domestic consumption is rapidly increasing. One of the drivers of this increase is electric power demand, which is expected to grow from 50 GW in 2010 to 120 GW in 2032 (ECRA, 2008). In 2009, 55% of KSA electricity was produced from petroleum (the balance from natural gas) (IEA, 2013).

If KSA is to protect this key component of its export-oriented economy, substantial amounts of new generation capacity will need to come from alternative energy sources and/or improved end-use efficiency. New capacity decisions will also need to take into account the seasonality of electricity demand (Figure 1). This will lead to a portfolio of generation technologies suitable for supplying different portions of the time-dependent load profile. Finally, due to the large existing fleet of oil- and gas-fired power plants, as well as the need for flexible, dispatchable generators to correct supply-demand imbalances, conventional generation technologies will continue to comprise a large percentage of this portfolio. Considering these factors, it is evident that an optimal capacity expansion plan for KSA is a non-obvious strategy that warrants deeper analysis.

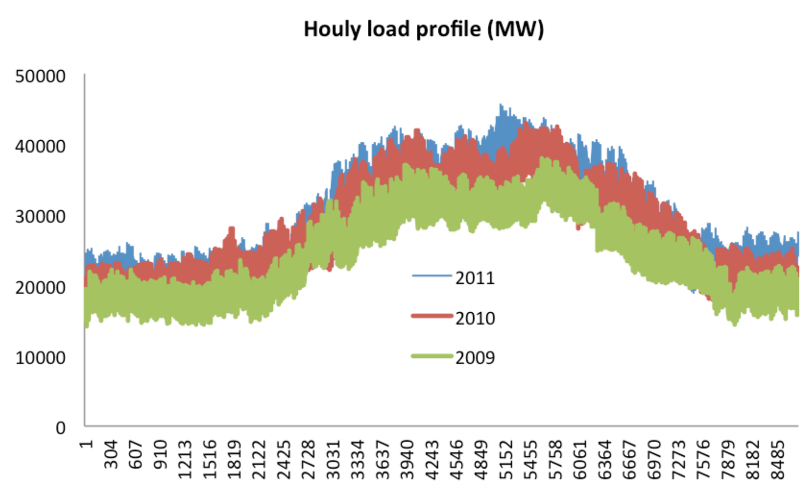

Figure 1: Summer baseload demand for electric power is nearly twice as large as winter demand, and it grew faster as well between 2009-2011 (ECRA, 2012a).

1.2 Research objectives and approach

The purpose of this paper is to evaluate different capacity expansion plans, including both alternative and conventional investments, in terms of various economic and environmental performance metrics. System Dynamics (SD) is employed because of its ability to (1) rapidly test different supply and demand policies, or scenarios, and (2) explore the potential effects of delays and supply-demand feedback loops on scenario performance.

The analytical approach combines the lexicons of the scenario analysis and SD literatures. It is outlined in Figure 2. We define a *scenario* as the combination of a capacity expansion *strategy* and an uncertain *future*. Each strategy consists of exogenous future alternative deployments and conventional investments that are endogenously formulated through parameter selection (discussed in Section 3.2). Uncertain futures stem from exogenously inputted demand scenarios, both in terms of electricity demanded (MWh) and peak load (MW). The model is structured such that additional feedbacks can be included (the dotted lines in Figure 2) to create more internally generated behavior. However, the current formulation is nonetheless useful for rapidly testing which variables have the largest impact on model outputs.

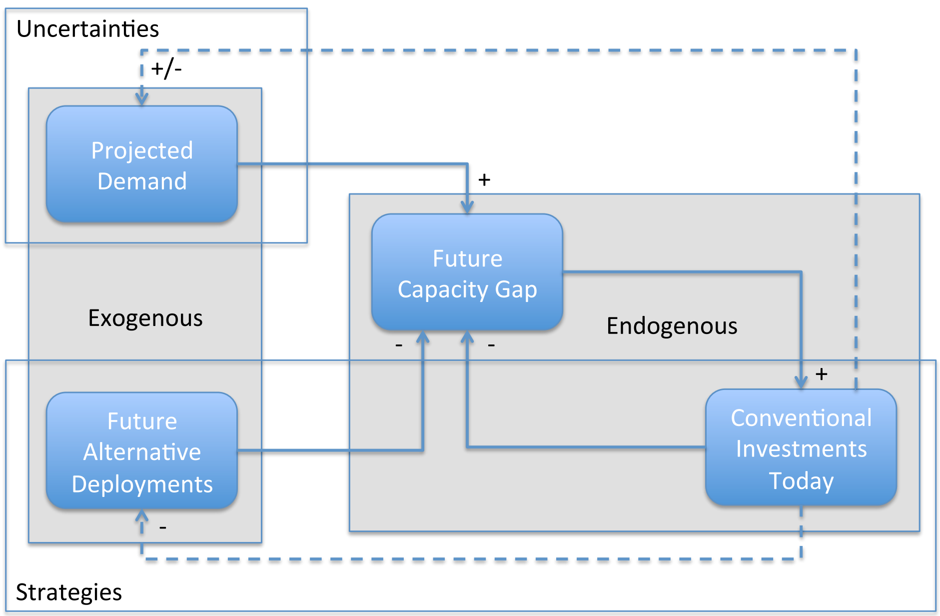

Figure 2: The approach is grounded in scenario analysis and system dynamics. Solid lines represent causality that is accounted for in the model; dotted lines will be implemented in future work.

The rest of the paper is organized as follows. Section 2 reviews the literature of relevant electricity planning models, indicating key gaps that this paper addresses. Section 3 covers the modeling approach in more detail, discussing inputs, outputs and control logic. Section 4 introduces the set of scenarios and presents results in terms of economic and environmental tradeoffs across the set. Finally, Section 5 concludes and discusses avenues for future work.

2. Review of relevant literatures

Models of electricity have evolved quite a bit over the past several decades, largely reflecting structural changes in the electric power industry[1]. The standard model for a regulated monopoly simply maximized social welfare (consumer plus producer surplus) using a demand model for some future year (including the time-dependent load duration curve and the overall electricity

[1] There is a wealth of literature on electric power systems models that span a wide spectrum of methodological approaches and decision problems beyond just capacity expansion. This paper reviews just a few in order briefly assess relative merits of particular approaches and highlight some gaps to be addressed in this work.

demand curve) and various supply costs (including capital and fixed and variable O&M costs) in order to solve for the optimal mix of base load, intermediate and peaking capacity (Murphy & Soyster, 1983). The optimization approach to capacity expansion has evolved with the restructuring and liberalization of electricity markets. For instance, Murphy & Smeers (2005) and Ventosa et al. (2002) solve the capacity expansion problem under imperfect, oligopolistic markets (specifically, Stackelberg competition) using sequential game theory, and more recent approaches incorporate stochastic demand growth into the problem (Garcia & Shen, 2010; García-Bertrand et al., 2008). These approaches are all similar in that they seek to derive a sole optimal (or equilibrium) solution. While mathematically attractive, an optimal long-term (20 or more years) plan is rarely, if ever, adhered to completely due to changes in circumstances along the way.

An alternative approach to capacity expansion is scenario analysis, sometimes simply referred to as scenario planning. The purpose of scenario analysis is to develop an ensemble of scenarios that encapsulate different strategies and uncertain futures in order to discover the strategies that are most robust to future uncertainties (Lempert et al., 2002). Visioning these future uncertainties or conditions is part of the managerial exercise for companies, governments or other decision makers. Furthermore, the outcomes of alternative scenarios are typically compared against a baseline or reference scenario. Energy companies such as Royal Dutch/Shell have employed the approach with some success (Wack, 1985) and nearly all of the climate change analysis done at the IPCC uses some quantitative variant of scenario analysis. Connors et al. (2002) used scenario analysis to evaluate tradeoffs across different capacity expansion plans in Shandong Province, China. The advantage of scenario analysis over optimization is that it permits exploration of many different capacity expansion possibilities that are equally likely to unfold in the future, as opposed to constraining these possibilities via rigid assumptions.

While there is likely to be disagreement in terminology, comprehensive System Dynamics (SD) studies will essentially perform scenario analysis, whereby alternative policies are tested against a baseline policy (or operating condition). Thus, the overall objective of scenario analysis and SD is not dissimilar; though, many could argue that systemic understanding as a result of SD modeling is an objective in and of itself. As such, numerous SD studies in the electric power sector have explored alternative scenarios at various levels of decision-making to inform policy/strategy; Ford (1997) provides a comprehensive review. The advantage of using SD for scenario analysis is the ability to capture the effect of time delays and endogenous feedback on outcomes. In energy/electricity, this means better understanding of the dynamics between supply, available resources, demand, pollution etc. Expansion of generation capacity has been central to these dynamics in a number of studies – again, see Ford (1997) – but most recently from last year's SD conference in the context of Nigeria (Momodu et al., 2012) and Iran (Owlia & Dastkhan, 2012). The first, like this paper, is from the vantage point of a national centralized planner, while the second concerns an individual electricity company. Others have explored capacity expansion within deregulated electricity markets (Jaeger et al., 2009; Vogstad, 2004).

Still, a number of gaps remain in current SD approaches to capacity expansion analysis. For example, much of the prior art aggregates capacity investments into a single stock of "grid" capacity, or stocks of just thermal and hydro capacity. Furthermore, different demand scenarios often encapsulate aggregate increases in peak demand (MW) or total electricity sales (MWh), without consideration of how the load profile (i.e. composition of peak, intermediate and base load demand) is changing each year. By disaggregating both generation capacity and the demand curve, this paper permits higher-granularity analysis of technology- and fuel-specific capacity expansion plans. Jaeger et al. (2009) use a similar approach but in the context of the liberalized German market. Saudi Arabian electricity, by contrast, is still provided mostly by one regulated company, the Saudi Electricity Company (SEC, 2010), therefore electricity price does not currently play a central role in technology build decisions.

3. Model development

3.1 Data processing for reference scenario construction

As mentioned previously, scenario analysis requires construction of a baseline, or reference, scenario against which alternative scenarios can be compared. In the case of the Saudi Arabian electricity system, this requires past, present and future estimates of supply (including conventional and alternative capacity) and demand. Figure 3 shows the evolution of installed capacity by generation technology and fuel type. While there is currently zero nuclear and renewable energy capacity in the kingdom, plans are in place to drastically increase deployments over the next two decades (Table 1). Historical and current conventional capacity, as well as projections of alternative capacity, provides the basis for the supply-side of the reference scenario.

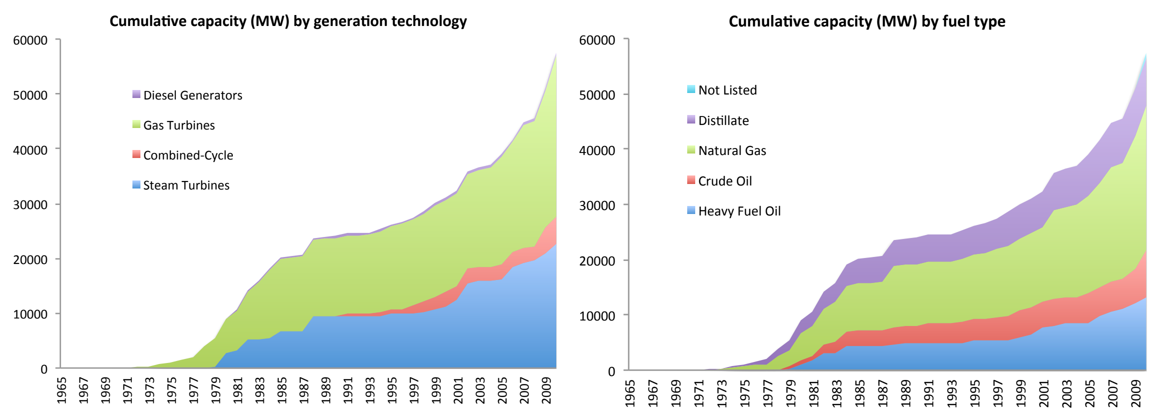

Figure 3: KSA electricity generation is 100% thermal, consisting primarily of steam and gas (combustion) turbines fired by natural gas and various fuel oils. As can be seen from both graphs, cumulative installed capacity has grown tremendously over the past several decades. (ECRA, 2012b)

Table 1: The source that informed this table only provided a capacity target for some future year (KACARE, 2013). Thus, the year-to-year deployments represent the best guess of the research team for constructing a plausible reference scenario.

Reference scenario deployments of renewable/nuclear (GW)

	PV	CSP	Wind	Geo & Waste	Nuclear
2012					
2013					
2014	0.30	0.30	0.10		
2015	0.75	1.09	0.58	0.27	
2016	0.53	0.70	0.34	0.14	
2017	0.93	1.23	0.60	0.24	
2018	1.75	2.32	1.13	0.45	
2019	1.27	1.68	0.82	0.33	
2020	1.86	2.46	1.20	0.48	
2021	0.61	1.22	0.50	0.32	2.00
2022	1.00	2.00	0.50	0.33	2.00
2023	0.00	1.00	0.50	0.36	1.60
2024	1.00	2.00	0.50	0.38	1.60
2025	1.00	1.00	0.50	0.36	1.60
2026	1.00	2.00	0.50	0.37	1.60
2027	1.00	1.00	0.50	0.35	1.60
2028	2.00	2.00	0.50	0.36	1.60
2029	1.00	3.00	0.50	0.36	2.00
2030	0.00	0.00	0.00	0.00	2.00
Total	16.00	25.00	9.27	5.09	17.60

Demand, in a lot of ways, is the more important element of the reference scenario given that it drives supply decisions (Figure 2). Demand for electricity in KSA increased over 70% from 2002-2011, and today roughly 50% is residential consumption (Figure 4). Demand also spikes dramatically in the summertime due primarily to the huge air conditioning loads (Figure 1), increasing the need for intermediate and peaking generation on both a daily and seasonal basis. Given that these growth trends are expected to continue, the reference scenario will require additional investments in conventional capacity despite the aggressive alternative build-outs shown in Table 1. There are numerous other parameters and assumptions that go into the reference scenario and development of the model overall (of which some are discussed in the following subsections). The reader can consult the supplementary material, which includes the model, for additional details.

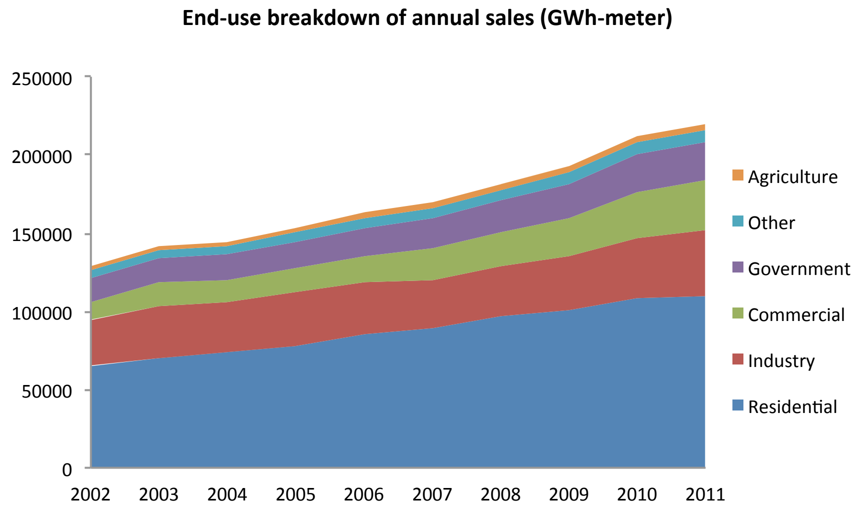

Figure 4: Consumption has grown across all end-uses from 2002-2011; the largest percent increase was in commercial, though residential is by far the largest overall (MOWE, 2010; SEC, 2010).

3.2 Model control logic

The model functions according to the process flow of Figure 2. For each scenario, the first step is to establish an exogenous demand schedule. This schedule includes various measures of demand (peak, intermediate, base load, etc.) for the time period 2010-2035. The second step is to establish an exogenous schedule of alternative energy deployments, again over the same time period. The capacity expansion logic for the conventional technologies consists of looking some number of years into the future at demand and alternative capacity, calculating the capacity gap, and then filling that gap through new builds. The general, oft-used structure for capacity expansion (Ford, 1997; Steel, 2008; Sterman, 2000) is shown in Figure 5 for the combined-cycle technology; the other conventional technologies have the same form.

The variable *CCCapAdj* takes the difference between projected demand for combined-cycle (*CCLoadProj*) and the current installed base (*InstalledCC*) as well as capacity under construction (*CCUnderConstr*), and then initiates new capacity builds mediated by a capital adjustment time (*CCAdjTime*). For the combined-cycle technology, no renewables or nuclear capacity are subtracted out. *NumYearsCCProj* governs how many years into the future the demand projection is based. These initiations are delayed according to technology-specific lead times and eventually become new installed capacity. This goal-seeking negative feedback loop occurs throughout the simulation time horizon (2010-2035).

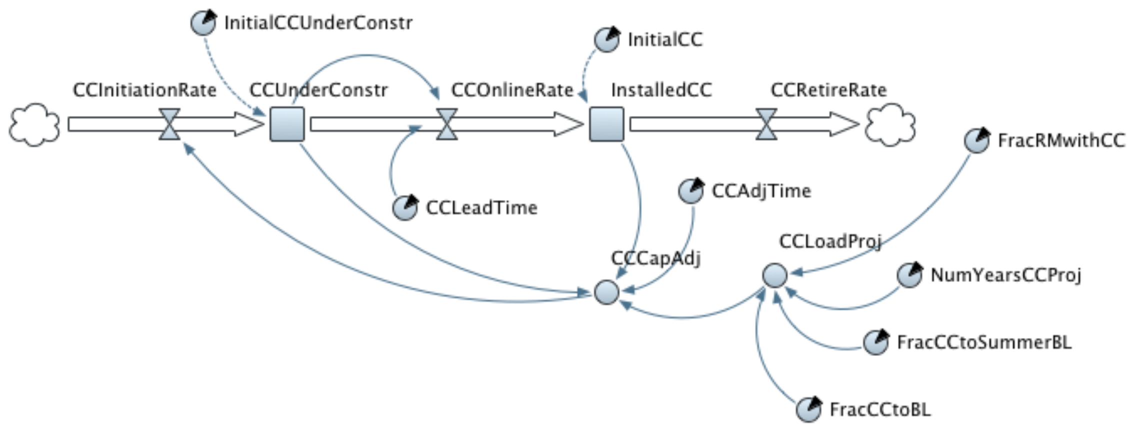

Figure 5: New additions of conventional capacity initiate according to a balancing feedback loop that seeks to close the gap between demand and alternative supply.

One of the novelties of this work is using countrywide power plant and hourly electricity demand data in order to inform technology-specific capacity expansion plans. To do this requires two tasks. First, the load duration curve (which is the same thing as Figure 1 except sorted descending) is broken up into categories. Traditionally these have consisted of base load, intermediate and peak demand. However, the summer increase is so large that we created a fourth category, Summer Baseload. Summer Baseload plants provide (more or less) baseload power during the summertime (high capacity factor) but resort back to intermediate application outside of summer (lower capacity factor). Analysis of the power plant portfolio in KSA shows a wide range of individual plant capacities for gas turbines, indicating that smaller units are used for peaking and intermediate operations, while larger ones likely also fill a baseload role. Figure 6 shows the KSA load duration curve broken down by the four load categories.

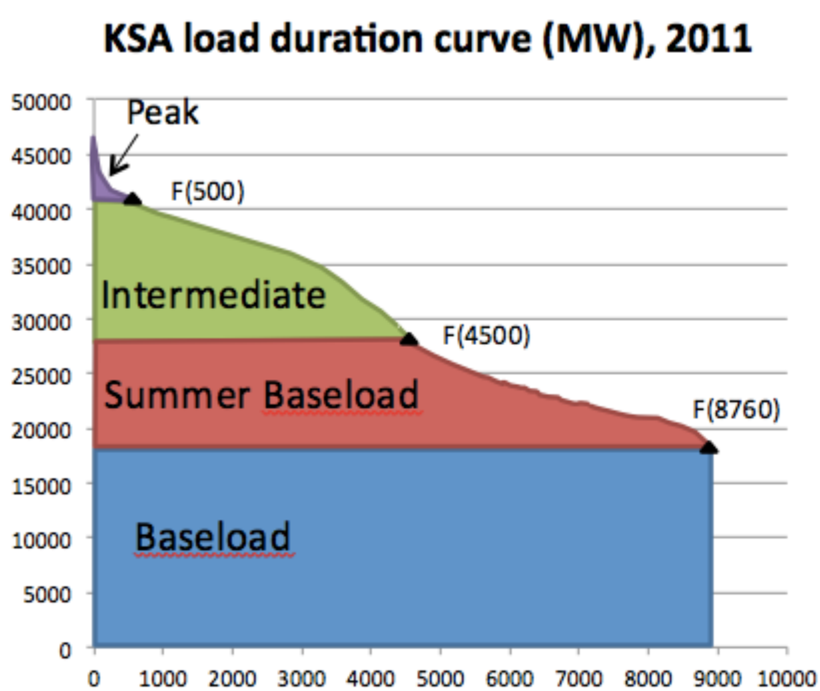

Figure 6: The fourth category, Summer Baseload, is a unique feature of Saudi Arabia. It is used to better inform tech-specific capacity expansions.

The second task concerns assigning capacity from each technology to the load categories using fractional allocations (between 0 and 1). The allocations for the reference scenario are based on our best understanding of the data and how the current system operates. For instance, in Figure 5 the combined-cycle technology contributes to both baseload and summer baseload demand (via the *FracCCtoBL* and *FracCCtoSummerBL* parameters). These allocations are a key decision variable for building alternative scenarios. The only constraint is that the technology-specific allocations to each load category sum to one. Furthermore, there is an allocation of new capacity for each technology assigned to fill the planned reserve margin (*FracRMwithCC*). The reserve margin functions to keep total electricity supply around 15% above projected demand, taking into account building delays of new capacity as well as retirements of old fossil-fired plants. As an example, Figure 7 displays the capacity mix for the reference scenario produced over the simulation time horizon (graphs are directly from AnyLogic).

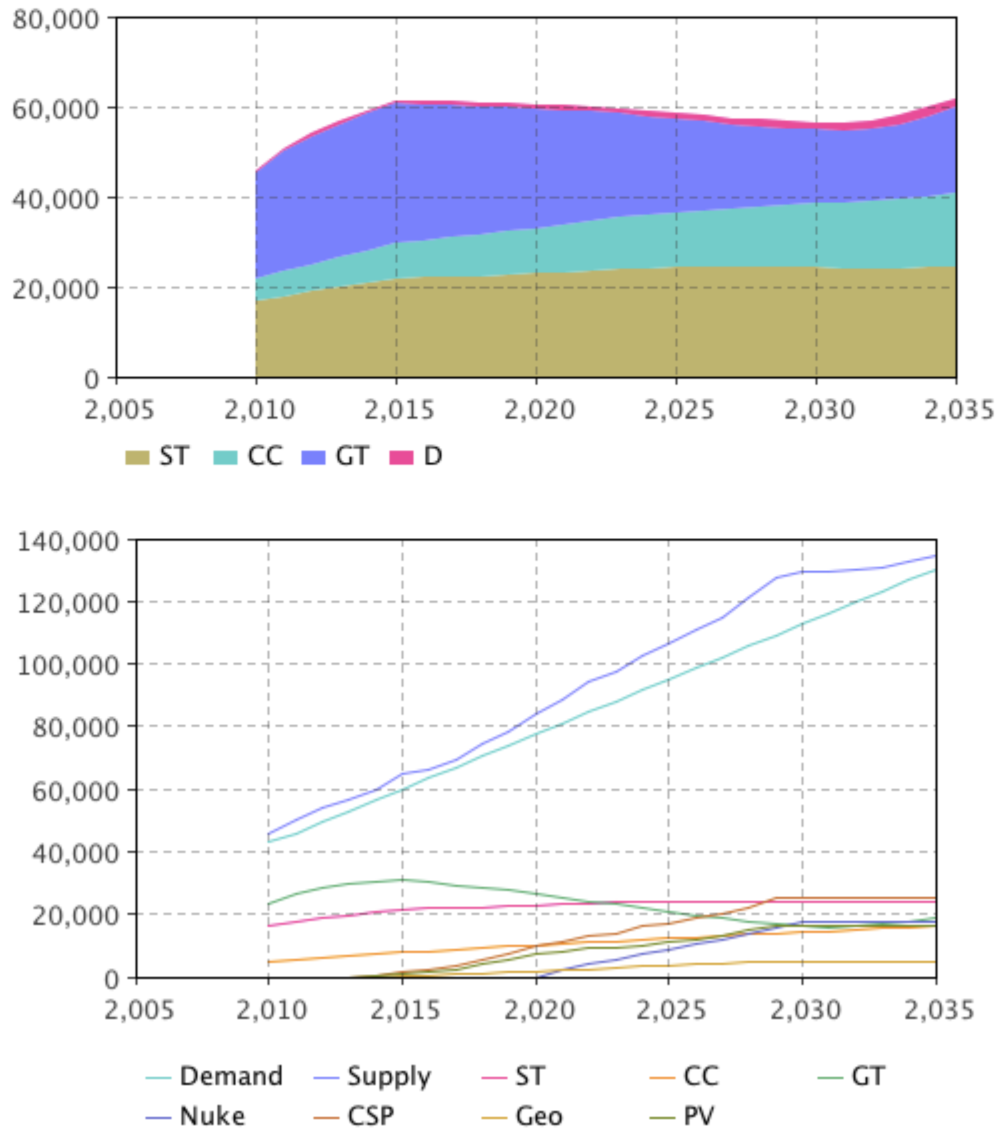

Figure 7: Top graph shows mix of conventional technology capacities over time (ST = steam turbine, CC = combined-cycle, GT = gas turbine, D = diesel generator); bottom graph shows total supply, demand, and all technology capacities over time, including alternatives (Nuke = nuclear, CSP = concentrating solar power, Geo = Geothermal, PV = photovoltaic). Both graphs are in MW.

The four load categories comprise the demand schedules (together they sum to total projected demand). Further, capacity from each alternative technology is applied to a particular category (e.g. nuclear provides baseload, wind provides intermediate, etc.). Thus, to summarize, each conventional technology will use its allocations to different load categories and the exogenous demand and alternative capacity schedules to initiate new builds. This novel approach increases both the accuracy and the utility of the results, since it considers technology-specific performance parameters and realistic operational considerations for technology expansion (e.g. the solar resource in KSA is high, but it is unlikely to provide baseload functionality in the power system).

3.3 Economic and environmental metrics for scenario evaluation

The capital expenditures (CAPEX) are the total costs associated with initiating and building new generation capacity. We calculate a non-amortized estimate of CAPEX by multiplying the $/MW cost of new capacity across technologies by the associated initiation rate. Operational expenditures (OPEX) refer to the costs of running and maintaining the generation technologies. There are two components of OPEX. The first is variable, where the produced energy is multiplied by the $/MWh cost across technologies. The second is fixed, where total installed capacity across technologies is multiplied by the $/MW-yr cost. Cost assumptions across technologies were informed by (EIA, 2010; Tidball et al., 2010).

To date, there have been no policies enacted in KSA to govern the CO_2 emissions from conventional generation. However, the model nonetheless calculates total CO_2 emissions produced by the technology mix from petroleum fuels in each scenario. To provide a rough estimate we calculate the consumed primary fuels across conventional technologies and convert to barrels of oil equivalent. Then, we multiply the total barrels of consumed oil by the heat content of crude oil, its carbon coefficient, and the oxidized CO_2 fraction in order to get an aggregate estimate.

4. Scenario analysis and results

This section uses three scenarios, in addition to the reference scenario, to demonstrate how demand uncertainty and different capacity expansion plans impact economic and environmental metrics. The scenarios are first described, and then results are discussed in terms of relevant tradeoffs. Limitations and further modeling considerations are also discussed.

4.1 Description of scenario set

Reference Scenario (Ref)

The reference scenario represents what is most likely to happen under current policy in KSA. Section 3.1 discussed briefly what demand- and supply-side information was used to construct this scenario. Demand is expected to grow more or less linearly, with peak load peaking at about 130 GW in 2035. This is consistent with government projections (ECRA, 2008). Furthermore, alternative capacity deployments are shown in Table 1. These include aggressive deployments of solar and nuclear resources, and moderate deployments of wind and geothermal.

High Demand (HD)

Under this scenario, GDP and population growth cause electricity demand to increase at a faster than linear rate. In particular, demand in the summer months is expected to grow rapidly, leading to growth in both peak and summer baseload demand. The alternative deployment schedule is the same as under the reference scenario, but due to the faster demand growth, the conventional capacity expansion plan must accommodate a larger gap between demand and alternative supply.

No Nuclear (NN)

This scenario assumes political and social opposition to nuclear capacity expansion such that it is never developed in the kingdom. The renewable deployments stay the same, and demand is assumed to grow as it did in the reference scenario. The lack of baseload nuclear capacity translates to extensive deployments of dirty, oil-fired steam turbines.

More Combined-Cycle (MCC)

This scenario changes the fractional allocations of conventional supply to the four load categories such that more combined-cycle generation capacity is deployed. Specifically, combined-cycle accounts for 50% of baseload growth (net any nuclear) and 50% of intermediate growth (net any renewables) in addition to the 50% that it supplies to summer baseload growth (in the previous three scenarios, combined-cycle only supplied summer baseload). The combined-cycle fleet in KSA is currently quite small compared to the rest of the generation capacity, so this scenario represents rapid growth in deployment of this flexible and efficient technology.

4.2 Discussion of scenario results

The below figures give a sense of the tradeoffs across these four scenarios in terms of CAPEX, OPEX and CO_2 emissions (does not include costs and emissions of renewables, since the deployments do not change across the four scenarios). The high capital and fixed O&M costs of nuclear is apparent, given that the No Nuclear scenario is generally less expensive than the others. However, less nuclear capacity means additional oil-fired steam turbines, which emit more CO_2. The High Demand scenario is clearly the worst in terms of cost and emissions, and this makes sense given that both should rise with increased demand. The high seasonality of demand in Saudi Arabia explains why the More Combined-Cycle scenario performs favorably across the metrics. The reason is that the system requires generators that can serve both a baseload (in the summer) and intermediate (in the winter) role. Such generators will need relatively low variable and fixed O&M costs in order to cheaply deliver electricity when its needed, but also not suffer too much from being idle. This is the case with combined-cycle gas turbines, which also benefit from lower emissions since they utilize natural gas a fuel and benefit from higher efficiencies. These preliminary results indicate that combined-cycle power plants should be a major part of Saudi Arabia's long-term capacity expansion plan.

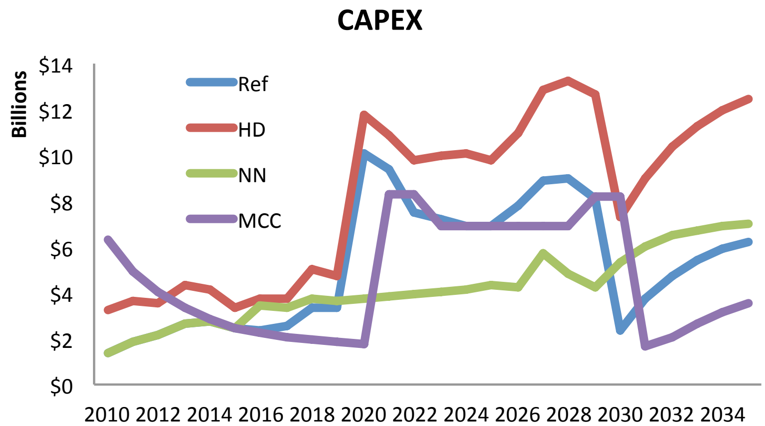

Figure 8: Capital expenditures are driven largely by nuclear deployments (the hump in all four scenarios except No Nuclear).

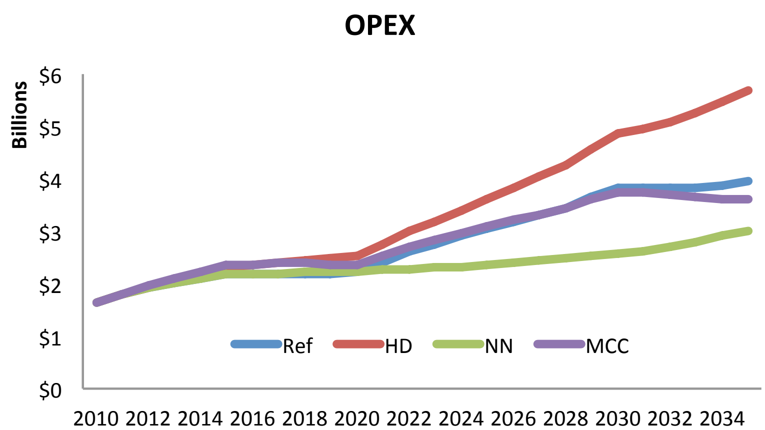

Figure 9: Operational expenditures rise with increased demand; nuclear fixed O&M also drive OPEX.

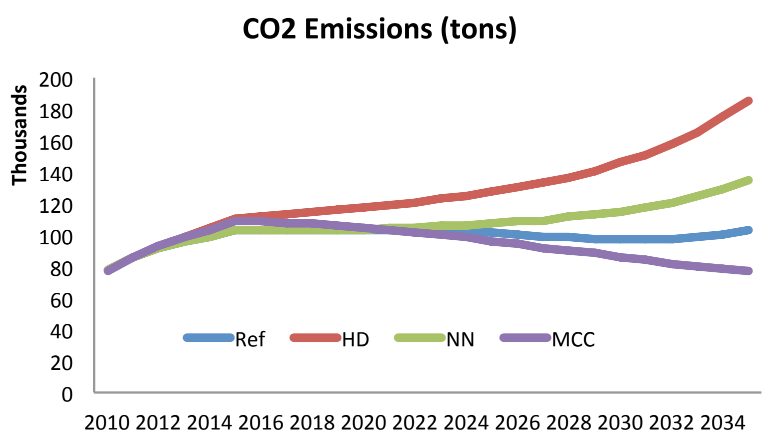

Figure 10:Higher demand drives CO_2 emissions, so too does the use of natural gas in combined-cycle (instead of petroleum).

While CAPEX, OPEX and CO_2 emissions offer an aggregate picture of performance across scenarios, they do not capture some of the more nuanced impacts. For instance, as mentioned at the beginning of the paper, the Saudi economy relies heavily on oil export revenues to finance public infrastructure investments. Furthermore, other industries outside of electricity generation, in particular petrochemicals, require large amounts of oil and natural gas as inputs into their production processes. The feedback effects on other sectors and industries of different oil and natural gas use scenarios, however, are not captured. Finally, since CO_2 emissions scale with oil usage, it is clear that high demand growth and an inability or unwillingness to deploy nuclear (or renewables) will have a negative impact on the economy and environment.

The day-to-day (and hour-to-hour) considerations of the capacity mixes in each scenario are also not explicitly addressed in the model. For example, the ability of combined-cycle power plants to ramp up or down quickly in response to demand changes will render them even more effective as a generation asset than is currently captured in the model. Furthermore, siting of new generators in Saudi Arabia is a non-trivial task given the dearth of available cooling water, which is an operational input to any new steam plant. As such, new nuclear power plants are likely to develop on the coasts, which will require additional transmission investments to supply the inland load centers. Finally, the set of scenarios evaluated ignores any changes in renewable deployments, which could be substantial under different scenarios (e.g. new oil discoveries vs. government subsidization of solar).

Nonetheless, a richer understanding of capacity expansion is possible with evaluation of additional scenarios. For instance, the combination of more combined-cycle plants in the No Nuclear scenario may help reduce emissions and adequately fill the gap in baseload demand left by eliminating nuclear. Future work will evaluate these combinations, as well as some additional ones, though the transparency of the approach also caters to manipulation by other users of the model.

5. Conclusions

This paper advances the System Dynamics literature on electricity planning by incorporating load seasonality and technology operations into the generation capacity expansion problem. The approach allows rapid testing of different capacity scenarios through alteration of various demand- and supply-side factors. Preliminary results using a small scenario set indicate that combined-cycle plants are likely to be a necessity in Saudi Arabia due to their low operational costs and use of natural gas as a fuel. Furthermore, usage of nuclear power in the kingdom may ultimately depend on where policymakers sit in the cost versus environmental performance debate.

Future work will, first and foremost, expand the set of scenarios evaluated to achieve a better understanding of relevant tradeoffs across different capacity expansion plans. The ultimate objective is to determine which plans are most robust to future demand uncertainties. It is obvious, from the results of the model, that high demand growth will strain the rest of the Saudi economy and worsen the environmental footprint, but what's not obvious is how the effects of the demand growth can be best mitigated. While combined-cycle looks to be a favorable generation technology, it will need to be supplemented by other technologies in order to supply the highly seasonal electricity demand in Saudi Arabia. A more comprehensive set of scenarios, analyzed along additional metrics of performance, will help guide investment that addresses this seasonality problem. Finally, next iterations of the model will develop causal relationships between electric power and other economic sectors in order to evaluate the ripple effects of capacity and fuel choices.

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