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# Incorporating Electrical Distribution Network Structure into Energy Portfolio Optimization for an Isolated Grid

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**Abstract**

In large scale electricity grids, the goal to reduce fossil fuel dependence can be addressed in multiple ways: generation, storage technologies, demand response, etc. In an isolated grid not connected to a transmission infrastructure, such as a military base or isolated resort, the problem is more difficult to address because of space and funding limitations, less efficient supply chains, and reliability concerns. Design for zero fossil fuel reliance in an isolated grid should combine these solutions in a portfolio while accounting for the limitations of isolation. In this paper, a methodology is formulated to optimize energy portfolios for small scale independently operated grids. Previous studies have achieved this but do not include the structure and constraints imposed by the isolated distribution grid. To address this need, the standard optimization tool, NREL's HOMER, has been linked with a grid analysis tool, PowerWorld, to take into account the design variables arising from the structure of the distribution grid, such as the need for replacement or extension of lines, extra construction space, or transformers. These added optimization factors modify HOMER's ranking of optimized portfolios as well as the economic analysis. A discussion of implications of the results to larger grid systems modeling is provided.

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## 1. Introduction

In large scale electricity grids, the goal to reduce fossil fuel dependence can be addressed in multiple ways: generation, storage technologies or demand response. In independently operated grids, such as a college campus (connected to a large scale grid) or military base (stand-alone grid, often in remote locations), the problem is more difficult to address. Space and funding are limited. Supply chains are less efficient, because the organization does not have the critical mass required to optimize it, or because of the remoteness and safety issues that are commonly experienced in military bases in times of war. Reliability concerns are also more pressing. Whether the users are tourists in a remote location, military in a base abroad or researchers in a university, outages are ill perceived. Design for zero fossil fuel reliance in an independently operated grid should combine the solutions (renewable generation, storage technologies and demand response) in a portfolio while accounting for its inherent limitations. Thus it is necessary to develop a methodology to create and evaluate potential technology portfolios and make sure they are implementable onto the isolated grid of interest. The implementation of such a methodology into an


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integrated tool would have many uses in the industry, including helping the US Navy achieve its energy goals of having 50% net-zero installations by 2020 [1].

The technology portfolio selection problem can be expressed mathematically as an optimization problem:
Minimize cost of power ($/kWh)
–As a function of {generation portfolio, demand response, efficiency improvements}
–Under constraints {load, capital, emissions, generation constraints, grid structure, space availability}

The goal of the decision maker is to find the cheapest portfolio (Cost of Energy wise) of renewable generators, demand response solutions and efficiency improvements that will meet the load, be implementable on the grid, and respect constraints on emissions and generation portfolio breakdown. Note that other Key Performance Indicators could be taken into account in the decision by formulating an Overall Evaluation Criterion. However, Cost of Energy was chosen as the only KPI in the present study as the authors felt that it is in practice what will drive the choice of decision makers. Other KPIs (emissions, noise and so on) are often heavily constraining and render portfolios that do not meet required levels downright infeasible. Decisions want to meet regulations and other design constraints the cheapest way possible.

To solve this selection problem, the standard energy portfolio optimization tool, NREL's HOMER [2], has been linked with a grid analysis tool, PowerWorld [3], to take into account the design variables arising from the structure of the distribution grid, such as the need for replacement or extension of lines, extra construction space, or transformers. These added requirements may modify HOMER's ranking of optimized portfolios as well as the economic analysis. This paper explains the methodology formulation and initial implementation as a linked HOMER-PowerWorld tool set.

## 2. Motivation for an Integrated Preliminary Study Tool

### *2.1. Current Practice Limitations*

The authors did not find prior examples of an integrated tool performing the portfolio optimization and implementing grid constraints. Many studies on portfolio optimization exist [4-8]; however, they are done over large scales (not taking into account grid constraints) and do not propose any toolset useable by decision makers on small grids. The closest toolset available, HOMER, was initially created by the National Renewable Energy Laboratories, then incorporated in HOMER ENERGY, Inc. It lets the user model loads and power sources (manually or from presets) and create a design space, then performs a full factorial optimization to find the cheapest portfolio meeting the load. HOMER by itself considers the generation and storage technologies that go into a portfolio; however, the program assumes sources and loads to be co-located points without consideration of the distribution from sources to loads via a grid. In practice, a portfolio recommended by HOMER might require extra initial capital for line upgrades (if some lines are close to their power flow limit) or voltage transformation (if the only possible node to connect a generator or battery bank has a different voltage level). HOMER's ranking might even change when taking into account these constraints. In addition, decision makers would also be interested in knowing the optimum connection layout of the portfolio in their grid (minimizing losses and maximizing power flow leeway in the lines) in addition to the optimum portfolio. Thus, most decision makers have incomplete quantitative results before committing to a decision using HOMER alone. This limits current practice to issuing Request For Proposals from contractors and examining them individually, performing the grid analysis in house if possible or hiring consultants at extra cost which may over constrain an already heavily financially constrained problem. They may compare the estimates they receive from contractors against one another but have no more comprehensive frame of reference;

consequently they may choose the best solution relatively to the set of RFPs but it could be a subpar solution compared to the absolute state of the art.

### *2.2. Industry Need for Integrated Tool*

Increasing environmental awareness and regulations, renewable generators technologies improvement, rising cost of fuel, and energy dependency concerns are powerful drivers advocating fossil fuel consumption reduction. For military stand-alone grids, especially abroad, the sheer impossibility of perfectly securing fuel supply chains also drives the need for an increase in renewable generation. These combined factors lead many independent grid operators (residences, businesses, organizations, universities) to undertake fossil fuel reduction projects. One of the most prominent of such projects is the US Navy's ambitious set of energy goals:

*"Increase Alternative Energy Ashore: By 2020, DON will produce at least 50% of shore-based energy requirements from alternative sources; 50% of DON installations will be net-zero".* [1]

If an integrated tool existed, decision makers could perform a preliminary analysis which would provide them with valuable information regarding:

- Capital investment
  - A good estimate would allow decision makers to make arrangements for project funding earlier in the decision making process, subsequently letting them negotiate better terms resulting in additional savings.
  - It would also provide them with a reference to compare contractor quotes against.
- Portfolio composition
  - Decision makers would have a better idea of what is feasible on their particular grid, helping them orient their search towards similar solutions and thus gain time in the RFP process.
  - Also they would be able to compare the contractors' estimates against the simulated performance of a similar solution and discuss differences.
- Preparatory work to implement the generation sources onto the grid
  - Decision makers would know sooner in the process about other work to complete before the actual fossil fuel consumption project (line replacement, new buildings, feeders, transformers, etc) rather than find out at the last moment and encountering expensive delays.

These advantages can be categorized as better project management and knowledge gap to the experts' reduction.

### *2.3. Challenges to Creating an Integrated Tool Set*

PowerWorld is capable of performing the grid analysis that HOMER lacks. A solution to building the integrated tool is leveraging those two useful tools to combine their functionalities. Such a project presents many challenges, such as finding relevant data, modeling the effect of current (and if possible future) technologies, and accounting for potentially limited building space available in an independent grid. In particular, the spatial limitations of independent grids are very important to keep in mind because they are the major constraint preventing decision makers from simply employing a global, first order analysis. There are also inherent programming challenges in interfacing tools not initially designed to exchange information.

## 3. Solution Formulation: Proposed Optimization Process

### *3.1. Functional Decomposition of the Optimization Process (High-level View)*

Figure 1 presents a simplified view of the functions necessary to bring grid and geographic constraints into consideration for the portfolio optimization. The process starts by generating the portfolios to evaluate further via HOMER. The user inputs general details concerning the scenario (be it financial discount rates, fuel prices or renewable resource availability, among others) and defines the portfolio design space to explore by defining the generation sizes to consider for the renewable mix. HOMER also allows for inclusion of efficiency improvements and demand response in to the portfolio by quantifying how they would reduce load by a percentage. The general assumption is that these non-generation measures would be part of any optimized portfolio, since saving power has more impact than producing it more cheaply, on the condition that the sunk cost is low enough. This can be checked by sensitivity analysis within HOMER.

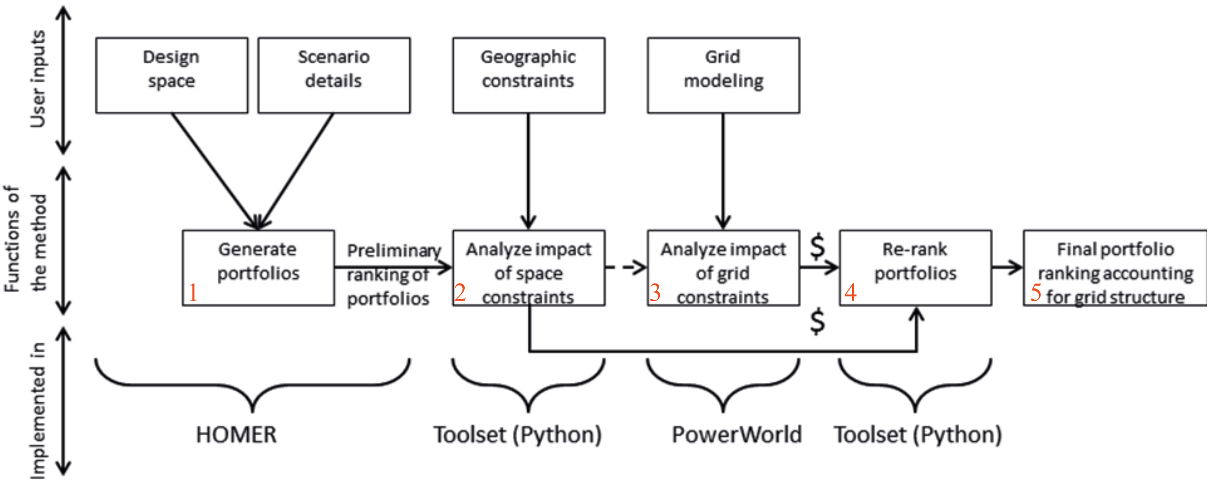


Fig. 1. Functional Decomposition of the Optimization Process

After HOMER generates an initial set of portfolios, additional constraints are considered that drive cost burdens. Each portfolio is subjected to an "implementability check", calculating the added cost of implementing a given portfolio on the grid arising from grid and geographic constraints. This implies finding the portfolio connection layout requiring the least additional initial investment to implement, the "most implementable" layout for that given portfolio. The user inputs where and how much space is available, as well as some cost data for building, then the effect of connecting the portfolio on the grid is analyzed using PowerWorld. Since there are many different possible connection layouts, finding the "most implementable" layout is non-trivial. Trying every possible layout is impractical (perhaps infeasible) from the perspective of computation time. Thus it is necessary to use knowledge from the grid to more accurately rate and filter out options. If a power flow calculation is performed on the "sample" grid (i.e. the grid before any modification), we can deduce the "most implementable" layout which would be the only one to check. That layout is obtained by adding power on buses where incoming lines are the most overloaded (or outgoing lines are the least loaded) and a generator can be added. (Adding a generator is sometimes unacceptable for noise and space reasons). Once a portfolio's implementability is checked, its total cost is updated, and the implementability check is performed on all portfolios in HOMER's ranking, after which the final ranking is updated.

### *3.2. Optimization Process (Low-level View)*

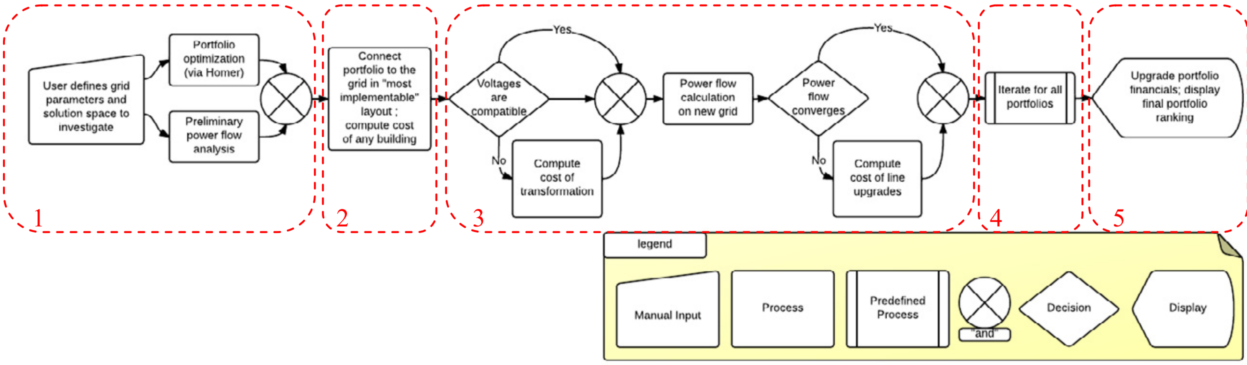


Fig. 2. Proposed Optimization Process

Figure 2 shows the proposed optimization process that achieves the needed functions described in Figure 1. The high-level functions are numbered in Figure 1 and are mapped to the low-level functions in Figure 2. Most of the process can be automated, reducing user actions to only a data input (albeit extensive) at the very beginning. Then, the initial portfolio ranking is provided by HOMER; in parallel, an initial power flow analysis is performed via PowerWorld to find the "most implementable layout". The cost of any building or transformation system is added to the portfolio's financial analysis (Present Cost Value and Initial Capital Investment). Another power flow analysis is performed via PowerWorld, this time on the grid modified with the most implementable layout of the portfolio, to find out if the transmission lines can sustain the power flows and compute the cost of upgrades if necessary. This process is repeated for all portfolios, which are then re-ranked to obtain the final results.

## 4. Case Study

### *4.1. Introduction*

The proposed methodology was tested on an example problem to demonstrate the value of combining the HOMER and PowerWorld tool sets.

A simple case was studied: an 85 kW totally islanded small business stand-alone grid located in the Wyoming Bridger-Teton National Forest, operating seasonally between May and September. This is a good example to demonstrate the methodology because:

- The grid is heavily constrained by the quality of the lines, National Forest regulations as well as demanding business operation (the business is a "guest ranch": generator placement in the grid is also constrained by noise and scenery considerations inherent to the tourist industry). Consequently, final optimization results are expected to differ from those of HOMER.
- All major modeling data and parameters can be gathered.
- The problem is relevant as the US Environmental Protection Agency and National Forest both threaten to pass stricter emissions and renewable generation regulation.[9]

The grid is composed of 2 propane generators (85 and 45 kW) producing the power consumed by 13 regular houses (light bulbs, outlets and water heaters), a restaurant (including light bulbs, TVs, A/C, walk-in fridge and freezer, kitchen), a laundry, a pool area (pool and hot tub heaters) and a water pump. The 85kW generator operates during the day (7:00am to 9:00pm) and the smaller generator operates the rest of the time.

We investigated a scenario were a strong regulatory constraint applied on the generation portfolio: the National Forest imposes 50% of renewable generation on businesses operating in the forest; the capital investment necessary to reach this goal is investigated. No demand response can be implemented and no further energy efficiency improvements are made. The grid operator and business owner would like to investigate the economic feasibility of installing wind turbines, PV arrays and batteries.

### *4.2. Portfolio Optimization via HOMER*

#### *4.2.1. Wind Turbines Modeling*

Wind turbine costs are approximated as linear with rated power for the range of applications of small businesses (10-100kW), but the approximation does not hold for larger applications (several hundreds of kW or MW applications) as several large scale gains reduce the marginal cost of wind power. For our purposes, that approximation holds, so two different wind turbines were investigated:

- The Bergey Excel 10kW:

A grid inter-tie (able to synchronize to the frequency of a grid), 240VAC 60Hz wind turbine, which all inclusive price is around $50,000, not including USDA grants or accelerated depreciation; hub height is most commonly 18m [10]. Grants were assumed to be around 20% of the investment cost.

- The Northern Power NW100/19

A larger wind turbine, which hub height is most commonly 25 to 32 meters; however the business owner judged the hub height and turbine diameter would be too detrimental to the scenery and discarded that option.

Yearly Operation and Maintenance (O&M) costs for a wind turbine were estimated to 8% of the capital cost to account for the low duty cycle of the wind turbine (5 months a year) and the existence of a qualified in house maintenance service.

Wind resources had to be estimated for lack of anemometer data. The monthly trend was estimated from the data measured on the nearby Jackson Hole Airport (30 miles away but in the same valley) [11], normalized by the average yearly wind speed measured by NREL's station 24865 [12], very close to the premises but only reporting the average wind speed over a year and not monthly averages.

#### *4.2.2. PV Arrays Modeling*

PV costs were estimated from Berkeley Lab's "Tracking the Sun IV" report published in September 2011 [13]; the solar resource data is imported by HOMER from NASA's Atmospheric Science Data Center for the coordinates of the premises (43°33' North, 110 °16' West). O&M was estimated at 10% of the capital cost.

#### *4.2.3. Battery Modeling*

Preliminary battery sizing determined that the most applicable battery model was a bank of Hoppecke 24 OPzS 3000 batteries, with 12 batteries per string to bring the nominal voltage to 24V which corresponds to the most common type of heavy duty inverter[14]. The number of strings to mount in parallel, which determines the capacity of the bank, was left to be investigated by HOMER as a design variable. Capital and O&M costs were discussed with Hoppecke's customer representatives.

#### *4.2.4. DC-AC Converter Modeling*

Costs and sizes where directly taken from the data sheets on the Burgey Wind Power website[10].

*4.2.5. Propane Generators Modeling*

Fuel consumption and price were determined from the business owner's data over the previous years of operation. The cumulated consumption of both generators over the course of a season (May-September) is 16,000 gallons, for a price of $45,000.

*4.2.6. Load Modeling*

The hourly load profile remains similar during the five months of operation and is presented on Figure 3:

- A 40kW base during the night hours (21:00 to 7:00)
- 80 kW during the meal hours
- 60 to 70kW during the remaining hours

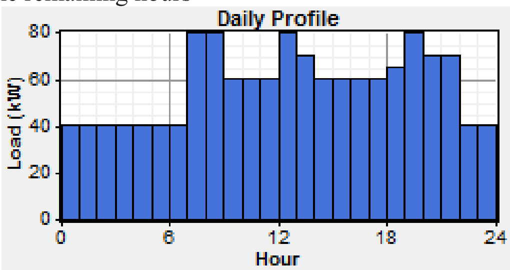


Fig. 3. Estimated hourly power profile.

*4.2.7. Optimization Results*

| PV (kW) | XLS | dpr (kW) | npr (kW) | H3000 | Conv. (kW) | Initial Capital | Operating Cost ($/yr) | Total NPC | COE ($/kWh) | Ren. Frac. | Propane (L) | dpr (hrs) | npr (hrs) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 7 | 85 | 45 | | | $ 280,000 | 69,379 | $ 1,166,896 | 0.434 | 0.54 | 36,138 | 2,247 | 1,798 |
| 8.8 | 6 | 85 | 45 | | 4.4 | $ 276,405 | 69,735 | $ 1,167,855 | 0.435 | 0.52 | 36,542 | 2,261 | 1,779 |
| | 7 | 85 | 45 | 12 | 26.4 | $ 475,790 | 73,858 | $ 1,419,938 | 0.528 | 0.55 | 35,128 | 1,402 | 2,163 |
| 8.8 | 6 | 85 | 45 | 12 | 26.4 | $ 469,230 | 74,476 | $ 1,421,281 | 0.529 | 0.52 | 35,715 | 1,430 | 2,185 |
| | 7 | 85 | | 24 | 39.6 | $ 662,685 | 87,081 | $ 1,775,873 | 0.661 | 0.54 | 36,134 | 3,292 | |
| 8.8 | 6 | 85 | | 24 | 39.6 | $ 656,125 | 87,796 | $ 1,778,453 | 0.662 | 0.52 | 36,641 | 3,365 | |

Fig. 4. HOMER optimization results for the average sensitivity setting.

Figure 4 is a typical solution output returned by the HOMER software. It shows that a solution implementing seven wind turbines is preferred to six wind turbines with PV arrays, which Net Present Cost (NPC) is slightly higher. The other portfolios do not compete so well, with largely increased Net Present Costs. The portfolios are split between two main variants, either including seven wind turbines, or six and some PV arrays. So, the next step investigated whether those portfolios are compatible with the structure of the grid or not.

*4.3. Sample Grid Modeling via PowerWorld*


Fig. 5. Simplified structure of the grid and its main components, spatially

Figure 5 presents a simplified structure of the grid: the generators are in two different areas of the business premises, and feed power to the loads, which have been lumped into a single load for ease of representation. The amount of generation which can be added on these two spots was determined from the space available as well as the scenary and noise considerations that are so important to the the business owner, i.e. the decision maker in this case. The grid is quite simple in this case study, thus the PowerWorld model is not presented here. The generators both output two phases at 110V, which are stepped up to 480V and transported in aluminum lines to the other groups of building were step down transformers bring the voltage down to 220V. In PowerWorld, the line impedance was calculated by using a linear impedance of $0.0255 + j0.655\ \Omega/\text{km}$ for aluminum lines and estimating the length of the line from the map. The lines leaving the day generator were upgraded and have a power flow limit of 150 kVA; the lines leaving the night generator were dimensioned with little leeway and have a total flow limit of 50kVA.

*4.4. Implementability Checks*

The two first portfolios from the HOMER optimization will be developed in more detail.

*4.4.1. Portfolio 1: 7 Additional 10kW Wind Turbines*

- Power flow:

There is only one way of fitting the turbines (5 at the night generator site, 2 at the day generator site), which results in overloading the lines from the night generator during times of high wind power output during the day. This portfolio is not implementable in the current state of the grid.

- Additional Action Required:

The lines would need to be upgraded in a similar fashion to the day generator lines, which were replaced after being struck by thunder at a cost of about $120,000. Additionally, custom transformers would be needed to adapt the turbines' 3 phase at 220V output to the 480V over two phases used for transmission. Cost data could not be located for such a system, which is not so important for comparison's sake, as in this case study every portfolio will require such a system. A conservative guess could be around $40,000 total.

Implementability study result: the initial capital cost rises from $280,000 to $440,000, raising the Net Present Cost (NPC) to $1,327,000.

### 4.4.2. Portfolio 2: 6 Wind Turbines and 8.8kW of PV Arrays

- Power flow:

Adding two turbines at the day generator site and 4 at the night generator is the most implementable combination. There would be no problem during the day, but the turbines at the night site would need to be stopped during the night to avoid overloading the lines. Using an estimate power density of 155W per square meter, the PV arrays would require around 57 square meters, which would be easily found on any roof.

- Additional Action Required:

Transforming the turbines' output for transmission would require an estimated additional $40,000.

Implementability study result: the initial capital cost rose from $276,405 to around $320,000, raising the Net Present Cost (NPC) to $1,208,000.

Both of these portfolios are still cheaper than the following ones in HOMER's ranking, so the implementability checks were finished.

## 4.5. Case Study Results

It was shown that grid constraints that are not taken into account by HOMER may modify the actual ranking of portfolios. In this case, the two first results were quite close. The implementability study changed the ranking and established a clear hierarchy, since the two first portfolios now differ by $120,000. Thus, going with HOMER's ranking might have ended in a costly mistake. Indeed, knowing that projects are usually carried out between March and the opening of the season in May for weather reasons, delays in the project arising from unforeseen expenses could delay opening or cause power failures, with dire economic consequences, even more so at the start of the season when treasury is at its lowest. Funding unplanned grid additions and issuing refunds to disgruntled customers could require the opening of costly credit lines and seriously dent revenue, delaying future investments.

## 4.6. Challenges Identified Along the Way

### 4.6.1. Computing Time

In HOMER, the optimization is performed by running a full factorial simulation on the solution space. This makes optimization computing time impractical. This can be improved by implementing a design of experiments and creating response surfaces to enable a real time parametric analysis. This could be done in two different ways:

- By modifying HOMER's source code to make it run only the subset of experiments required by a DOE,
- By writing a Model Center wrapper running the DOE by performing one HOMER analysis (with every parameter fixed in HOMER, i.e. a solution space cardinality of 1) per experiment and then bringing all the results together.

Both solutions were outside the scope of the study at hand. Computing time was kept low by defining the solution space wisely and parallelizing analyses over two computers.

### 4.6.2. Model Relevance

HOMER's preset models' relevance is to be investigated as the state of the art in renewable generation is constantly changing. In order for HOMER to produce exploitable results, it is necessary to make sure that:

- The modeled products' specifications are up to date. It is then possible to correct Homer's models, which use the standard industry specifications.
- The costs data is estimated or quoted from distributors as accurately as possible.

- The wind data is accurate. However, it is hard to come by. The ideal case would be to have anemometer measurements over a year, taken in the actual place where a wind turbine addition is considered; lacking that and as a preliminary analysis, data from the closest source (airport, weather or agricultural station) may be deemed acceptable, if sensitivities over the wind speed are added to the analysis.
- Finally it is to be noted that the preset models for batteries and wind turbines are mostly from home or small business sized products; adequate models may have to be created for more consequent grids.

That last challenge limits the scaling of this methodology to larger grids. For the moment, employing this methodology on a utility wide grid would be very difficult.

## 5. Conclusion and Future Work

As postulated at the start of the project, the proposed methodology is useful in providing additional information to decision makers compared to just portfolio ranking results obtainable by HOMER. The methodology presented, via use of HOMER augmented by PowerWorld, enables decision makers to initiate preliminary portfolio analysis of fossil fuel consumption reduction projects that reflect geographic spatial and grid considerations. It was seen in the example problem that these considerations did change the ranking of preferred portfolios and more accurately reflect implementation costs. The initial capital investment required to implement Homer's first portfolio rose 55%, rendering it less interesting than the formerly second portfolio. The methodology effectively breaches the gap between Homer, aimed at very small grids, and PowerWorld, aimed at utility wide modeling.

Other interesting future work would be reducing HOMER's analysis time by implementing Design of Experiment and Response Surface Methodology, using ModelCenter and JMP for example; or leveraging the wealth of analysis that Powerworld can accomplish to optimize the grid not only by checking implementability from calculating the power flow but also by analyzing contingency and fault resilience. It is believed that an integrated, parametric tool would be of value to decision makers, consultants and contractors and would have considerable commercial potential.

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