Land Area and Storage Requirements for Wind and Solar Generation to Meet the US Hourly Electrical Demand.

by

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We accept this thesis as conforming
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ABSTRACT

This thesis uses the IESVic Energy System Model to estimate the minimum land area and energy storage requirements for wind or solar photovoltaic electricity generation systems to meet the entire electric demand of the United States in the year 2000. Twenty-four locations were modelled, both singly and in various combinations, using hourly climate data for the years 1981 – 1990. Solar photovoltaic systems have lower land area and storage capacity requirements than wind systems, but higher nominal power output capacities. The land areas required for the generating systems are far in excess of those for conventional energy technologies, and the storage system alone rivals the entire current generating system in size. If built, an actual renewable generation/energy storage system of this type would likely be far larger than estimated here.

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1. Introduction

The objective of this thesis is to determine the minimum land area and energy storage requirements for wind and solar photovoltaic electricity generating plants to satisfy the entire US electrical demand. The IESVic Energy System Model* is used to perform these estimates, based on actual wind and solar fluxes for the decade 1981-1990, and the total US electrical demand for the year 2000. The multi-year analysis addresses some shortcomings common to other estimates of the potential contribution of grid-connected renewable generation. In particular, energy storage—rarely given quantitative analysis in other estimates of large-scale renewable potential—serves herein as a buffer for those periods when renewable generation is insufficient to meet demand.

The basic premise of this thesis—an imaginary United States where wind and solar generation technologies supply all primary electrical energy—may strike some readers as implausible. However, since this is precisely the goal that many environmental advocates wish to realize over the next several decades [1, 2], it is worth asking just how such a system could be made to work. The analysis in this work will present a very optimistic upper limit on the potential contribution of renewable energy to today's electricity system; any real-world system of this kind will likely be much larger than estimated here, for a variety of reasons listed below.

* The IESVic Energy System Model (ESM) is a MATLAB-based program developed by the Institute for Integrated Energy Systems at the University of Victoria, which uses hourly demand and climate data to assess stand-alone renewable systems in a variety of locations and configurations.

The results presented here also provide an approximate picture of the potential for renewables to meet projected increases in electricity demand. The US Energy Information Administration forecasts a 1.9% annual increase in US electrical demand to 2020, a 45.7% total increase in demand over 2000 levels [3]. If this rate of increase continues unabated, US electricity demand will double the 2000 amount by the year 2037. There will be considerable pressure to meet this increase with renewable energy, and the results of this work will provide an order-of-magnitude estimate of the land areas and "coping technologies" required to achieve it.

1.1 Presentation of Results

The results of this work are presented in four parts: the modelling results for solar photovoltaic (PV), wind, and hybrid wind/PV systems respectively, and several sensitivity analyses. Thirteen PV and eleven wind locations are modelled, both singly and in various combinations. The hybrid systems use the best-performing locations (or combinations) from the wind and PV results, and various distributions of the wind/PV generation load are assessed. For each set of results, the modelled locations are compared on the bases of their required land areas, storage capacities, and storage output characteristics. More broadly, solar PV systems are compared to wind systems, and hybrid wind/PV systems to both.

- **Solar Photovoltaic systems** are assessed for thirteen locations across the contiguous United States, from Miami to Seattle. Each solar location is modelled over ten years of consecutive hourly climate data, for the period spanning 1981-1990.

- **Wind systems** are modelled for eleven locations, using hourly wind speed data from the years 1982-1990. The shorter modelling period and lower number of locations reflects the relative scarcity of high-quality wind speed information compared to solar data.

- **Hybrid Wind/PV systems** are modelled using the best performing wind and PV locations (or combinations), over the period 1982-1990.

- **The sensitivity analyses** test some of the default modelling assumptions made in modelling the three types of system. For instance, all the systems in the first three sets of results will use the same input parameters for energy storage, to maintain comparability across disparate locations and technologies. One sensitivity analysis investigates the effects of varying storage input and output efficiencies. Others examine the effects and implications of changing constraints on allowable plant size or storage capacity.

1.2 Limitations and Caveats

The results presented in this work underestimate by a substantial amount the land area and storage requirements of the modelled renewable systems. For the most part, this optimism is an outcome of the assumptions made to simplify the modelling process:

- **Homogeneity of Flux**. The model finds the minimum plant size and energy storage capacity required to satisfy a specified electricity demand, given hourly solar radiation or wind speed data. Most climate recording stations are located in airports, whose topography may not be representative of those of the general region. This work uses the entire hourly demand of the contiguous United States, resulting in very large renewable plant sizes. The implicit assumption is that the climate data taken at a single location will be uniform over the entire area of the renewable plant, no matter how large it becomes. This may even be roughly realistic for certain PV plant locations, since sky conditions are often uniform over thousands of square kilometres. It is unlikely to be realistic for wind systems, where wind speeds are heavily dependent on local topography, tree cover and the like [4]. Since most climate stations are situated at airports, which are relatively exposed locations, it is likely that the conditions recorded are unrepresentative of the region as a whole.

- **Land Availability.** For simplicity, the model assumes that all the land covered by the wind and solar plants is available for energy system development. In reality, these areas will include cities and towns, agricultural land, mountain ranges, national parks, wildlife sanctuaries, and other unsuitable regions. The degree to which the exclusion of these areas will affect the plant area will vary from location to location (it may even have a positive effect, if the available replacement regions have higher climatic fluxes than the excluded regions), but it is prudent to assume that it will increase it.

- **Negligible Power Conditioning and Transmission Losses.** The IESVic ESM does not include algorithms for calculating energy losses in power conditioning equipment or transmission lines. If these were included, the plant size would certainly increase to overcome the resulting losses.

- **Uniform PV Panel Efficiency.** When modelling PV systems, the ESM spends most of its computational time calculating the position of the sun in the sky and its angle of incidence to the solar panel. The panel itself is modelled in the ESM by a simple linear scaling factor representing the panel efficiency. In fact, photovoltaic panel efficiency is not uniform, tending to vary with insolation levels, temperature and seasonal conditions [5-7]. Since the rated panel efficiency is given for near-optimal conditions (25 °C temperature, 1000 $W \cdot m^{-2}$ insolation), the average panel efficiency is likely to be substantially lower than assumed, which will require an increase in plant area.

- **The Effects of Altitude on Wind Generators.** The power output of wind turbines depends not only on wind velocity but also on air density, which declines as altitude increases. The higher the altitude, the lower the wind power density for a given wind speed, and the more turbines will be needed to meet a given demand. Wind turbine manufacturers base their turbine specifications on conditions at Mean Sea Level, as defined by the ISO 2533 standard [8], and the IESVic ESM assumes that all wind locations are at that elevation, no matter where they are. This assumption results in substantial overestimates of wind plant output at higher locations. For example, the average air density at 1,500 m is 13.6% lower than the Mean Sea Level density of 1.2255 kg/m^3. The ESM does not account for this change, and therefore underestimates the size of wind plant required.

- **Wind Turbine Operating Data.** The wind turbine model in this work uses turbine manufacturers' operating specifications to calculate the power output at any given wind speed. If these specifications are incorrect, actual plant performance will vary from that modelled. Without empirical operating data for each turbine, it is impossible to say whether the average turbine performance would be better or worse than the manufacturer's predictions, but it is prudent to err on the side of conservatism, and assume that the actual operating performance will be lower than specified. Once again, the result is an increase in plant size to meet a given demand.

- **100% Plant Reliability.** The ESM does not feature an algorithm for simulating plant reliability, and instead assumes that the entire plant will be available at all times. This assumption is not particularly realistic: photovoltaic panels and wind turbines, like all machines, break down occasionally, or are taken out of service for scheduled maintenance. Generating plants as large as the ones modelled in this work will doubtless have some equipment out of order at all times. A real-world plant of this type would be slightly oversized to compensate for expected outages. Similarly, it is assumed that renewable plants will not suffer declines in output due to, say, dust on photovoltaic panels or insect buildup on wind turbine blades.

The IESVic ESM is a work in progress, and future versions may include algorithms for the more realistic modelling of photovoltaic panels and long-distance transmission, and for simulating plant reliability. For now, however, the reader should understand that the model results presented here are likely, on balance, to be *minimum* figures.

Readers should note that the current version of the ESM operates in a world of fantasy economics and politics, assuming no economic or political barriers to the construction of renewable energy installations larger than, say, Vancouver Island. In the real world, renewable energy technologies rely heavily on government subsidies in order to be competitive with conventional energy technologies [9]. Photovoltaics, in particular, are still much more expensive than other energy technologies. Renewable technologies—wind systems in particular—also attract vociferous public opposition in many places where they are proposed. This work deals entirely with a pure technical evaluation of renewable technologies, a thought experiment of sorts; nowhere is it implied that a technically *feasible* renewable system is necessarily a *desirable* one, either economically or politically.

2. Renewables, Scale, and Energy Storage

This chapter provides an overview of two issues with renewables that are central to this thesis: scale and energy storage. Renewable energy generation has enjoyed nearly thirty years of widespread popularity as the purported future prime mover of society's energy system, but there has been remarkably little discussion of their very large land area requirements. Similarly, it is not widely recognized that renewables are not by themselves sufficient to satisfy energy demand; all renewable systems that rely on randomly intermittent climatic fluxes require backup or storage systems to supply energy during cloudy or windless days. The following discussion provides background to the discussions of land area and storage requirements in the results chapters of this work.

2.1 Renewables and Land Area

In a 1984 article for *American Scientist*, On Energy and Land, Vaclav Smil pointed out that, although renewable technologies were at that time highly favoured to replace nuclear and fossil-fuelled generators, little attention was being paid to their land area requirements [10]. The implications of Smil's analysis were not encouraging for advocates of renewable generation. Smil estimated the land area required for the extraction and transportation of raw materials, and for the generation and transmission of electricity. He found that wind and solar technologies required total land areas comparable in magnitude to the cities and towns to which they would be supplying electricity. In other words, the areal power densities of wind and solar technologies were roughly equal to those of the urban locations they served.

By comparison, conventional technologies such as nuclear, coal or natural gas generation had power densities an order of magnitude greater than the locations they served, requiring much less land to generate the amount of energy demanded. The implications of Smil's analysis were (and still are) striking: since very little urban land (aside from a fraction of the available rooftop space) is suitable for renewable energy generation, each city and town would require an "energy plantation" of comparable size—mostly in rural areas—to meet its demand.

Nineteen years after Smil's article was published, little has changed. Renewables are still a highly touted prospect for future electricity generation, popular with environmentalists and the public, and therefore with politicians. According to environmental advocacy groups, an increasing reliance on wind and solar electricity will be one of the methods by which society will reduce carbon dioxide emissions and stave off the worst projected effects of climate change. The other options for large-scale carbon-free power generation, nuclear fission and hydroelectricity, are unacceptable to these groups, who believe them to be unsafe and unacceptably environmentally intrusive.

If renewables are the answer to society's energy problems, one might expect that people would devote at least some attention to issues of scale and feasibility. How much land would be required to meet a given fraction of electricity demand? How would large-scale solar and wind installations affect wildlife? How would they intrude upon scenery? Whose land values would increase, and whose would fall? How would randomly intermittent wind and solar fluxes be made compatible with advanced societies' requirements for uninterrupted electricity delivery? These are serious questions deserving serious responses from the advocates of renewable electricity, but they are rarely raised and even more rarely answered.

Some renewable energy advocates have made an effort to grasp the scale of the renewable technologies required. One notable attempt was an article by J. A. Turner in a 1999 issue of the journal *Science*, titled A Realizable Renewable Energy Future [11]. Turner estimated that 27,800 km^2 of land would be required for a single solar photovoltaic plant in Nevada to supply the entire US electrical consumption in 1997. He arrived at this figure by dividing the total 1997 US electrical consumption (3.2×10^{12} kWh) by the product of the estimated photovoltaic panel efficiency (10%) and the annual average solar insolation in southwestern Nevada (2,300 $kWh \cdot m^{-2}$), as follows:

Equation 1

$$PV\ Area = \frac{3.2 \times 10^{12}\, kWh}{0.1 \times 2300\, {}^{kWh}\!/_{m^2}} = 1.39 \times 10^{10}\, m^2$$

Turner doubled this PV panel area to calculate the total plant area, which he claims is enough to "provide all of the energy needs of the United States." Since he only considers electrical energy in his calculations, which in 2001 accounts for less than 40% of total US energy consumption [12], he is mistaken on this point. Turner's use of annual aggregate figures for electricity consumption and solar supply is understandable in light of the difficulty of obtaining detailed electricity data. However, he does not recognize the extent to which the use of aggregate data distorts his results, by removing all information about supply/demand imbalances occurring over all timescales below one year. He does acknowledge that his plant would require energy storage to cope with daily and seasonal intermittencies in solar flux, but does not recognize that the storage system itself will inevitably increase the plant size. In addition to supplying current demand, the plant must be large enough to overcome storage conversion losses, and to maintain storage at a level sufficient to carry the system through the longest expected outage. Stand-alone solar plants, for instance, must gather enough energy by day to meet demand during the night hours, while simultaneously satisfying daytime consumption requirements.

Turner also neglects power conditioning and transmission losses in his estimate (as does this work), which would require a further increase in plant size. He advocates a decentralized solar generation system based on an annual average solar flux of 1,800 $kWh \cdot m^{-2}$ in the United States, but this estimate is perhaps even less “realizable” than his Nevada figure, based as it is on an average of aggregates from a variety of locations in one of the largest countries on the planet. Furthermore, he claims that the required photovoltaic area can be reduced by introducing wind and biomass energy technologies into the mix. This is true enough, but the total area requirements for a system featuring wind and biomass generation would be much *larger* than for a photovoltaic system alone, since the areal power densities of both technologies are substantially lower [13].

In short, Turner’s estimate is useful as a first approximation, but his conclusions are open to question. Contrary to his claims, his Nevada photovoltaic plant is not a “realizable” solution to the electricity needs of the United States. The true area will be substantially larger than he estimates, and one of the aims of this work is to use hourly renewable supply and electricity consumption data, along with storage, to estimate this figure.

Pacific Northwest Laboratories has released a number of detailed assessments of the available windy land area in the contiguous United States [14-17]. These are rigorous works, based on field measurement data at hundreds of sites over several years, and their results informed some of the siting choices made for wind modelling in this work. The United States has abundant wind resources; enough, the authors of one report claim, that the Great Plains states alone could satisfy total US electricity requirements many times over, even after urban areas and wilderness are excluded from consideration [14]. However, the authors of these reports are careful to qualify their claims with the caveat that their calculations do not take into account daily and seasonal supply/demand imbalances. To these concerns others may be added, for instance the willingness of rural American communities to play permanent host to enormous energy generation facilities.

Another well-known evaluation of the potential contribution of renewable energy technologies was made by Working Group III of the Intergovernmental Panel on Climate Change (IPCC WGIII), which made the following claim:

> "Most model results indicate that known technological options could achieve a broad range of atmospheric CO_2 stabilization levels, such as 550 ppm, 450 ppm or below over the next 100 years or more … Known technological options refer to technologies that exist in operation or pilot plant stage today. It does not include any new technologies that will require drastic technological breakthroughs…" [18]

In a 2002 paper, Chris Green and Douglas Lightfoot of McGill University's Centre for Climate and Global Change Research take issue with the WGIII claim [19]. They point out that WGIII assumes 100% conversion efficiency for solar energy (rather than the 10% efficiency for current photovoltaic panels in the field, perhaps rising to 30% in the next few decades). Similarly, WGIII's estimate of wind energy potential assumes 100% availability of land with average wind speeds exceeding 5.1 m/s. Green and Lightfoot calculate that WGIII's figures overestimate renewable energy potential by at least an order of magnitude. Furthermore, they add: "The calculated amounts of solar and wind energy not only assume that the required amounts of land are actually available, but that the time, cost, and energy needed to keep solar plates free of dust and sand and to keep an accumulation of dead insects on wind turbine blades from reducing wind turbine power, are not prohibitive."

The WGIII report comes in for further criticism in a 2002 article in *Science*, in which a group of authors led by Martin Hoffert assesses the prospects of a variety of energy technologies to assist in stabilizing CO_2 emissions [13]. Hoffert et al. dismiss the WGIII claims and state, "Energy sources that can produce 100 to 300% of present world power consumption without greenhouse emissions do not exist operationally or as pilot plants." Renewables, they claim, are hampered by the intermittency and dilution of solar and wind fluxes. Hoffert et al. contend that nuclear fusion—present technological challenges notwithstanding—provides the best medium-term chance of stabilizing atmospheric CO_2 concentrations.

A few other writers warn of the potential scale-related problems of renewables. Science writer Matt Ridley echoes Smil in a 2002 article for the online magazine *Spiked*, warning that a return to renewable energy will result in the reindustrialization of the landscape, reversing the ecological benefits of the industrial-era move to "point-source" power generation [20]. Robert L. Bradley and Howard Hayden write skeptical and contrarian critiques of the prospects for renewable technologies, but their work does not reach a mass audience [21, 22]. Paul Kruger, of Princeton University, concludes that renewables will simply be incapable of meeting the huge increase in electricity generation required to produce hydrogen for a fuel cell-powered US vehicle fleet, recommending instead a massive increase in nuclear fission capacity [23]. For the most part, however, the public discussion of our society's energy options takes place with little acknowledgement of the scale-based limitations of very large-scale wind and solar renewable generation.

2.2 *The Need for Energy Storage*

In European countries such as Germany and Denmark, wind energy is generating a substantial and increasing fraction of the net electricity generation. And it is in these leading-edge countries that evidence is emerging that intermittently available renewable technologies place burdens on the electricity system, which it is presently ill-equipped to manage. These countries' experiences suggest that the current model of renewable penetration—incremental additions of renewables adding up to a substantial fraction of generation—is unsustainable, due to their tendency to destabilize the electricity grid. Solving these problems will require a variety of measures, including the use of intelligent controls to manage power fluctuations, but this work focuses on the use of bulk energy storage to allow renewable technologies to approach the energy service quality that only conventional technologies can deliver at present.

Although energy storage technologies are present in current electrical systems—most often large-scale pumped hydro facilities—they have not yet been used on a large scale to improve the quality of energy services provided by renewable technologies. To date, renewables have been introduced into electrical systems as if they were conventional generating technologies like any other, but this is not the case. From an energy service standpoint, renewables produce inferior quality electricity—neither dependable nor proportionate to demand. In contrast, most conventional generating technologies fall into one of two broad categories:

- **Baseload generators** are large power plants—often coal, nuclear, or hydroelectric generation—that produce large amounts of electricity at constant output. These plants typically produce low-cost electricity due to low fuel and operating costs, although plant capital costs are often high. Baseload generators are usually unable to change output levels quickly enough to respond to fluctuations in demand, a fact that limits their ability to function properly in an electrical system featuring large amounts of intermittent renewable generation, as shown below.

- **Peaking generators** are often oil, natural gas or hydroelectric plants that are capable of rapidly adjusting output levels to respond to fluctuations in demand. Peaking plants often produce higher-cost electricity due to higher fuel costs and the necessity of remaining on standby to deal with anticipated changes in demand. **Spinning reserves** and **regulation** services are also forms of peaking generation held in reserve to manage very short-term or unexpected changes in demand.

It is unclear how solar and wind generation fit into this picture. They are incapable of generating baseload electricity, since they rely on intermittent solar and wind fluxes, but are also unable to generate specific amounts of electricity as required, as peaking services do. In fact, renewables currently act in the grid as a kind of *negative demand* [24]. Renewable generation is similar to electrical demand in that it is not under the control of utility planners, and conventional technologies must adjust their output in order to prevent the renewable generators from disrupting electrical supply.

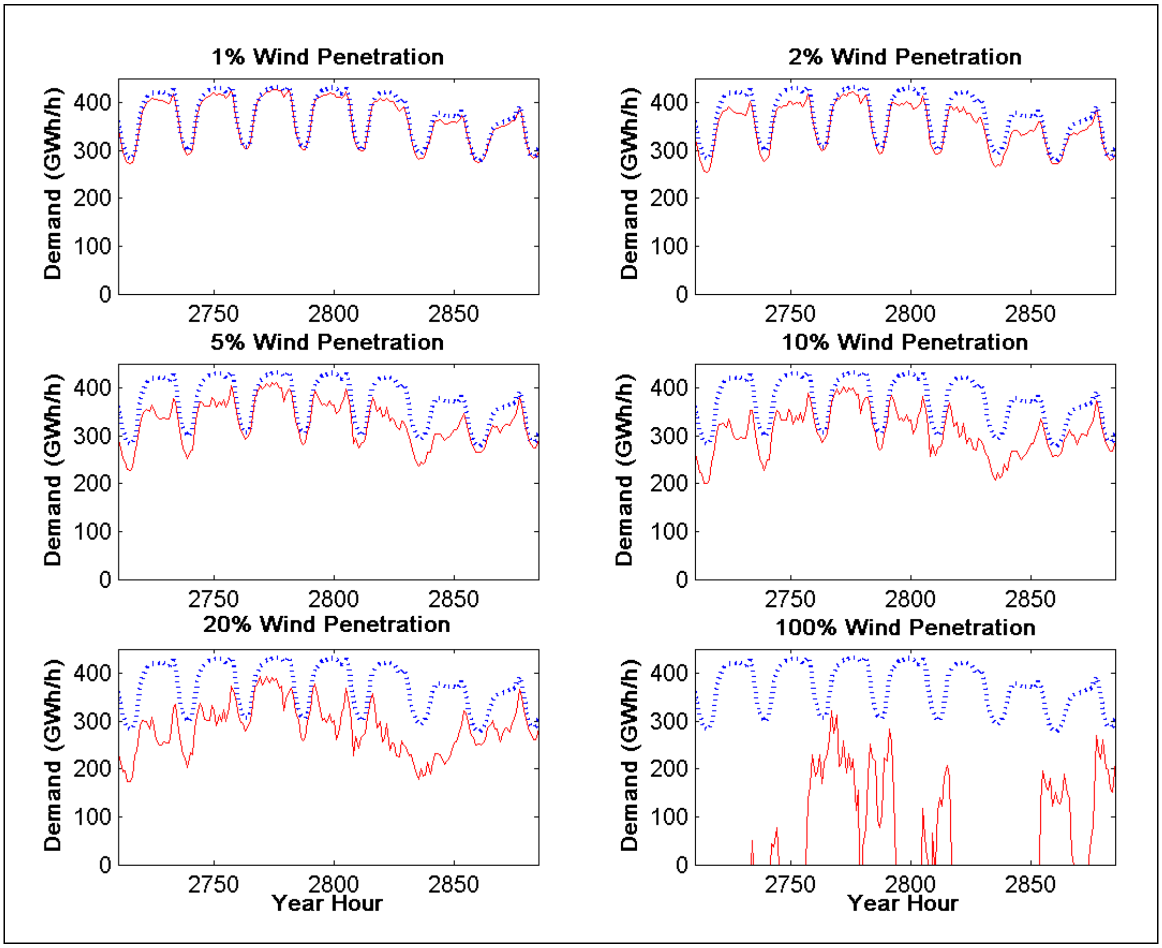

Figure 1: Effect of various levels of wind generation on electricity demand

Figure 1, above, illustrates this point. The IESVic ESM was used to generate six wind penetration scenarios of increasing magnitude, from the top left, where wind generation is equivalent to 1% of the annual electricity consumption, to the bottom right, which represents the situation where total annual wind generation is equal to 100% of that year's electricity consumption. The dashed line represents the total US electricity consumption for the week 24 – 30 April, 2000 (year hours 2713 – 2880 inclusive); the solid line represents the same demand curve less generation output from eleven dispersed wind plants. The residual demand in the 100% penetration illustration occurs because a large portion of wind energy is generated in excess of demand, and therefore wasted.

The unmodified demand curve illustrates society's predictable electricity consumption habits: each day's minimum demand occurs in the early morning, around 2 a.m., and climbs to a small peak in the early afternoon, then to a higher peak in the early evening as people arrive home and turn on lights and appliances. The two rightmost peaks on the charts represent the weekend, showing that electricity consumption on Saturdays and Sundays follows a different pattern than on the other five days: the peaks are lower in magnitude and different in distribution. The overall pattern is predictable and regular, with a baseload of approximately 280 GW, and utility planners—armed with historical demand data and weather forecasts—are able to anticipate demand levels in order to bring generators online as needed.

The situation changes once wind enters the generation mix. At 2% wind penetration, baseload generators are largely unaffected, but the previously smooth daily peaks of the demand curve become jagged, creating an unpredictable curve for peaking generators to follow. A 10% wind penetration so alters the demand curve that it is difficult to distinguish weekdays from weekends. This penetration level disrupts baseload generation severely, requiring fast responding but expensive peaking generators to replace most of the cheaper baseload supply. When wind supplies energy equivalent to 100% of annual electricity consumption, there is no longer any point to maintaining any baseload capacity, but it is still necessary to provide peaking generation to satisfy electricity consumption requirements when wind power is insufficient to do so.

Consider the case of Denmark. In 2000, wind generators in Denmark produced electricity equivalent to 12.1% of the country's annual electricity consumption [25]. However, due to the randomly intermittent nature of wind generation, the Danish electricity system suffers regular supply/demand imbalances of 800 – 1,000 MW in western Denmark alone, and these are expected to rise to as much as 2,900 MW by 2005, as more wind turbines are installed [26]. These imbalances are aggravated by regulations granting priority access to the grid for small-scale power producers; the electricity system operator must accept whatever is generated, whether it is needed or not. Fortunately, Denmark has high-capacity transmission corridors (relative to its electricity generating capacity) to Sweden, Germany, and Norway—the last the most important because of its large hydroelectric capacity, which can respond quickly enough to absorb the stochastic peaks and troughs characteristic of unbuffered wind generation. However, it is unclear whether Denmark can continue to rely on its neighbours to buffer its growing electricity imbalances. Other regions, such as the United Kingdom or the United States, whose transmission corridors to their neighbours are small relative to their generating capacity, will not be able to so easily slough off the overflows resulting from excess renewable generation, nor import electricity to make up for shortfalls in wind generation [27].

Although some of the shortcomings of renewable energy can be addressed with technological improvements to allow renewable power plants to monitor and react to grid imbalances [28], little can be done about its intermittency, except to use backup conventional generation or energy storage to act as buffers between generation and demand. In a conventional power plant, such buffering is performed by withholding fuel, but this approach is not possible with wind and solar plants whose "fuels" are climatic fluxes. Since the basic premise of this work is to imagine a situation in which conventional energy technologies are unavailable (or otherwise occupied), large-scale energy storage is the only recourse for coping with the intermittent nature of renewable technologies.

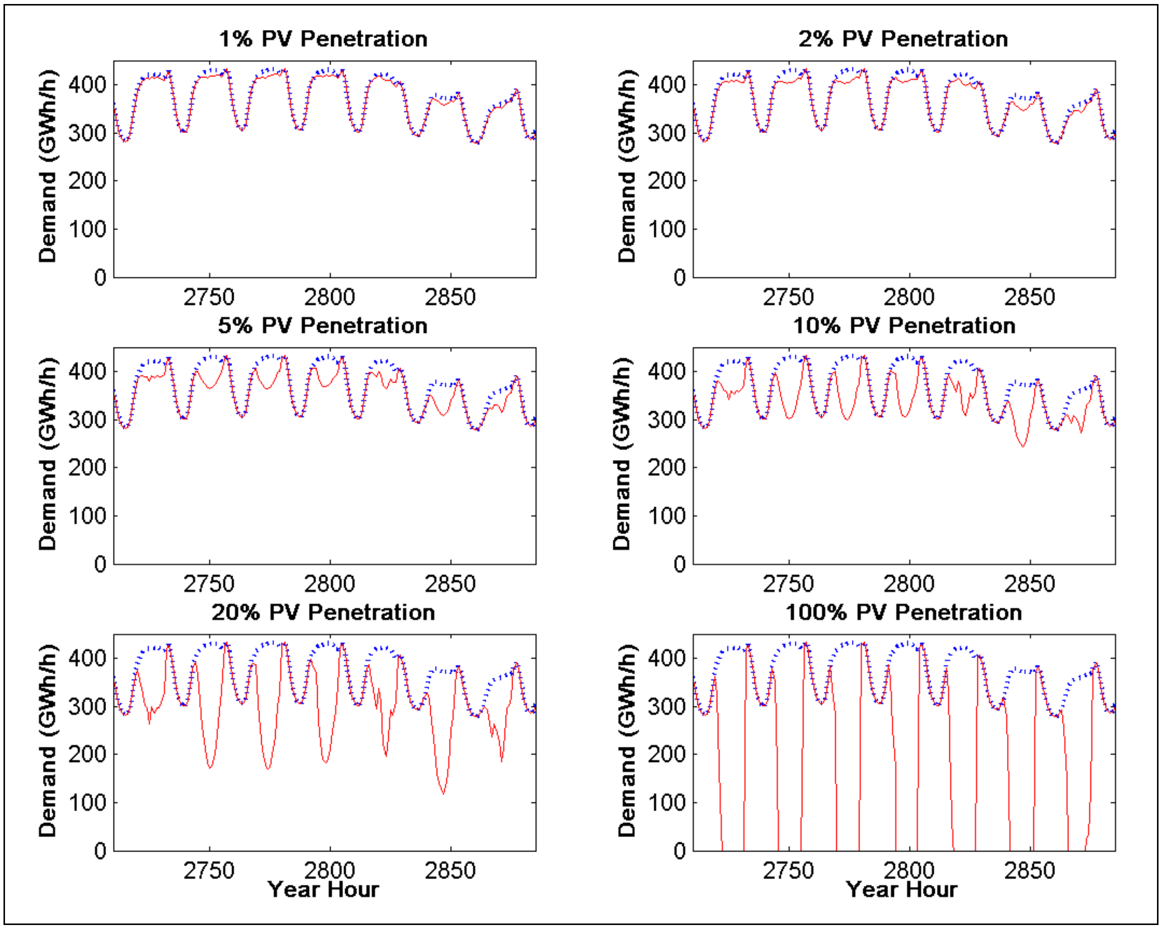

Figure 2: Effects of various levels of solar PV penetration on electricity demand.

The preceding discussion concerns wind generation, but also applies to solar photovoltaics, albeit to a lesser degree, as shown in Figure 2. In this figure, the dashed line once again represents unmodified US electricity demand for the same one-week period in April 2000, while the solid line represents the electricity demand less the output from a single photovoltaic plant located near Midland-Odessa, Texas. Unlike wind, solar fluxes are predictably absent every night, and always present to some degree during daytime hours. Due to the greater reliability of solar output, the modified demand curve in Figure 2 is far more predictable than the one shown in Figure 1.

In the absence of energy storage, renewables tend to have a destabilizing effect on existing electricity systems, which are not designed to cope with randomly intermittent generation technologies. Problems are beginning to surface in Denmark, where large supply/demand imbalances are now common. Energy storage provides a means by which the renewable technologies can be buffered and protect the rest of the electricity system from damage.

3. The IESVic Energy System Model

The IESVic Energy System Model (or ESM) is an energy balance model designed to simulate wind or solar photovoltaic renewable energy generation systems. The ESM uses mathematical representations of photovoltaic panels and wind turbines to convert climatic fluxes into an hourly power output, which is balanced against an electricity demand. Energy generated in excess of demand is placed in storage whenever possible, while insufficient generation is supplemented by storage output. The model can make use of either historical data or stochastic mathematical techniques to simulate hourly climate fluxes and electricity demands, although this work relies exclusively on the former.

The strengths of the IESVic ESM lie in its flexibility, transparency, and use of generic parameters to allow simulation of a very wide range of systems. This chapter will describe the background of the IESVic ESM, provide an overview of the energy balance calculations at the heart of the ESM, and compare the ESM to other energy system models.

3.1 IESVic Model Background

The IESVic ESM was first developed to evaluate renewable energy options for Race Rocks, a small archipelago about 2 km off the southernmost tip of Vancouver Island. Race Rocks is located in Canada's first Marine Protected Area (MPA)—managed by Lester B. Pearson College of the Pacific—and is home to the first lighthouse on the country's west coast. Although the lighthouse has been de-staffed, the former lightkeepers continue to live on the main island, employed as custodians of the MPA. Electrical services on the ~10,000 m^2 (one hectare) main island is supplied by two Lister diesel generators, and includes the domestic requirements of the custodians' residence, a guest house, a water desalinator, a crane at the loading dock, and a web server that posts images and information on the islands and the MPA to the website www.racerocks.com. (The electricity used by the lighthouse and foghorn is already supplied by two sets of solar panels with battery backup.) The island's average electricity demand is about eight kilowatts.

In 2000, IESVic and Pearson College began investigating the possibility of supplying all of Race Rocks' energy services with renewable energy. Race Rocks is, in many ways, a near-ideal location for a renewable energy laboratory. Situated in the rain shadow of the Olympic Mountains, the archipelago receives plenty of sunlight, and experiences high average wind speeds. Furthermore, its location at the entrance to the Strait of Juan de Fuca makes it a promising spot for the evaluation of tidal flow generation technologies. The IESVic ESM was developed—first as a spreadsheet model, then as a MATLAB program—to assess the potential for solar photovoltaic, wind, and tidal generation to satisfy the energy demand on race Rocks.

IESVic researchers initially estimated that wind and solar technologies—each available about 20% of the time—would require (8 kW/0.2 =) 40 kW of installed capacity. Tidal technologies were estimated to be available 40% of the time, for an installed capacity of 20 kW. A power meter was installed at the site to measure hourly electric demand. For wind and tidal data, Race Rocks site information was available from Environment Canada and the Institute for Ocean Sciences at Sidney, BC respectively. Solar data was gathered from Victoria International Airport, the closest measurement location to Race Rocks. Since neither the wind nor the solar information was in the form of hourly historical data, it was necessary to use stochastic mathematical methods to synthesize hourly fluxes. The Race Rocks tidal flux data was adjusted to evaluate the feasibility of installing tidal turbines at a different location from the measurement site [29].

The IESVic ESM was designed to be maximally flexible in its ability to evaluate a wide range of renewable technologies. It can accept as inputs multiple loads, multiple solar, wind and tidal technologies and/or locations, and multiple storage systems. Each load and technology is specified by a variety of generic parameters, allowing the evaluation of a huge range of energy system scenarios. As mentioned above, the model can make use of climatic averages to simulate hourly fluxes or historical hourly data, when available. For the Race Rocks project, storage was modelled as an electrolyzer/fuel cell combination with an input efficiency of 75% and an output efficiency of 45%.

The results of the modelling for Race Rocks were unexpected. The wind and solar technologies required installed capacities an order of magnitude greater than the 40 kW expected, at 472 kW and 395 kW respectively*. The modelled tidal system, at 35.4 kW, came in close to its expected 20 kW capacity. The very large PV and wind plant results have much to do with the storage system. Race Rocks experiences long periods in which solar and wind fluxes are minimal, necessitating a storage system with sufficient capacity to meet the island's demand during these outages. This requirement alone increases the size of the renewable plant at Race Rocks, since it is in effect required to supply the entire year's demand during the ~20% of the year when renewable fluxes are available. To make matters worse, the storage system efficiencies exact

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* Installed capacity figures for the Race Rocks project are based on systems with identical storage requirements of 2,688 kWh.

substantial penalties on all energy passing through storage, driving the renewable system to an even larger size in order to overcome them. The randomly intermittent wind and solar fluxes were hit particularly hard by these factors, while tidal generation—a highly predictable and regular energy source—was much less affected.

The main conclusion of the Race Rocks project was that stand-alone renewable energy systems are much more difficult to design than expected. Without conventional backup such as diesel generators, the renewable generation system is forced to carry the burden of generating not only the total demand energy, but also all the energy that will be lost in the storage conversions. The storage system must itself be large enough to satisfy demand through the longest anticipated climatic outage, leading to a further expansion of the renewable plant size.

3.2 *Model Description*

This section provides an overview of the energy balance relations at the heart of the ESM's algorithm. The IESVic ESM performs two energy balances in order to arrive at its results. The first subtracts each hour's demand from the available generation resources, arriving at a raw energy balance, here called $BalanceBeforeStorage_i$. The second set of balance equations attempts to sink energy into storage (if the *BalanceBeforeStorage* equation yields an energy surplus) or draw energy from storage (if the initial balance yields a deficit) to arrive at a final energy balance for each hour ($Balance_i$). Ideally, each hour's *Balance* will always be zero: if it is positive, this means that surplus energy is available but being wasted; if negative, the combined supply from generation and storage has failed to meet demand, and there is unserved electric demand for that hour. In reality, any system based on stochastically intermittent renewables must grapple with the likelihood of these two outcomes.

Some other major variables used in the model are as follows (the subscripted *i* denotes an hourly time-step variable):

$SolarOutput_i$	-	Hourly output from the photovoltaic plant, in kW.
$WindOutput_i$	-	Hourly output from the wind plant, in kW.
$ElectricDemand_i$	-	Hourly electric demand, in kW.
$Storage_i$	-	The amount of energy in storage.
StartingStorage	-	The amount of energy in storage at the beginning of the hour, after hourly losses are taken into account.
HourlyLoss	-	Fraction of stored energy lost every hour due to leakage.
InputEfficiency	-	The efficiency of the storage input technology.
InputRating	-	The maximum sinking rate into storage, in kW.
OutputEfficiency	-	The efficiency of the storage output technology.
OutputRating	-	The maximum sourcing rate from storage, in kW.
StorageCapacity	-	Overall capacity of the storage system, in kWh.

3.3 *Model Equations*

The ESM first performs a simple energy balance on each hour's electricity generation and demand. Tidal turbine generation was not evaluated for this project due to the lack of suitable sites around the coast of the United States:

Equation 2

$$BalanceBeforeStorage_i = SolarOutput_i + WindOutput_i - ElectricDemand_i$$

$BalanceBeforeStorage_i$ is the raw energy balance, before storage calculations are performed.

If *BalanceBeforeStorage*$_i$ is positive, renewable output exceeds demand, and the ESM will attempt to sink the excess energy into storage whenever possible (Case 1). If the result is negative, the ESM attempts to eliminate the energy deficit by drawing energy from storage (Case 2).

The second relation calculates the storage level at the beginning of each hour:

Equation 3

$$StartingStorage = Storage_{i-1} \cdot (1 - HourlyLoss)$$

StartingStorage is the previous hour's storage level, less any losses that occurred in the past hour. *HourlyLoss* is a number between zero and one, indicating the fraction of energy lost within the storage system every hour (boil-off of liquid hydrogen, for example, or self-discharge of batteries). For the first hour in the series, *StartingStorage* is specified by one of the model's input parameters.

3.3.1 Case 1: Positive Energy Balance

There are three possible outcomes for the storage calculation. The hour's *Storage* figure is the **minimum** of the following:

Equation 4

$$Storage_i = \begin{cases} \text{A) } StartingStorage + (BalanceBeforeStorage_i \cdot InputEfficiency) \\ \text{B) } StartingStorage + (InputRating \cdot InputEfficiency) \\ \text{C) } StorageCapacity \end{cases}$$

Equation 4A corresponds to the most common situation, when the storage system is not full and the rate of energy supply does not exceed the maximum storage input rate. In this case, storage is increased by an amount equal to the available energy multiplied by the storage input efficiency. Equation 4B occurs when the rate of energy supply exceeds the storage system's maximum input rate, and the storage level increases by an amount equal to the storage input rating multiplied by the input efficiency. Equation 4C corresponds to the situation when the storage system is full and can accept no more energy. In this case, the new storage amount corresponds to the storage capacity, and all excess energy is wasted.

The new *Balance* is calculated as follows:

Equation 5

$$Balance_i = BalanceBeforeStorage_i - \frac{Storage_i - StartingStorage}{InputEfficiency}$$

In Case 1, the storage level will never decrease, since the system is dealing with energy generated in excess of demand. The numerator in Equation 5 will therefore always be positive, and $Balance_i$ will not increase. By substituting the three possibilities in Equation 4 into Equation 5, there are likewise three possible outcomes for the new *Balance*:

$$Balance_i = \begin{cases} \text{A) } 0 \\ \text{B) } BalanceBeforeStorage_i - InputRating \\ \text{C) } BalanceBeforeStorage_i - \dfrac{StorageCapacity - StartingStorage}{InputEfficiency} \end{cases}$$

These three equations are in decreasing order of "desirability". If the balance is zero, it means that the storage system has been able to accept all the available energy, with none wasted. Equation B reduces $Balance_i$, but not to zero, since the storage system has been unable to sink all the available energy. Equation C reflects the case where storage is full and almost all the available energy is wasted. Since *StorageCapacity* and *StartingStorage* are nearly equal in this case, the second term in equation C will be near to zero, leaving $Balance_i$ almost unchanged from $BalanceBeforeStorage_i$.

3.3.2 Case 2: Negative Energy Balance

In Case 2, the renewable generation output is insufficient to meet demand, and energy must be sourced from storage. Once again, there are three possible results for the storage calculation. The new storage is the **maximum** of the three equations below (recall that $BalanceBeforeStorage_i$ is **negative** in this case):

Equation 6

$$Storage_i = \begin{cases} \text{A) } StartingStorage + \dfrac{BalanceBeforeStorage_i}{OutputEfficiency} \\ \text{B) } StartingStorage - \dfrac{OutputRating}{OutputEfficiency} \\ \text{C) } MinStorage \end{cases}$$

Equation 6A covers the situation when storage is not empty and the rate of energy demand does not exceed the storage output rating. Equation 6B occurs when the required rate of output exceeds the storage output rating, and equation 6C corresponds to the situation when the storage is at its minimum allowable level, and cannot supply any energy.

The new balance is calculated as follows:

Equation 7

$$Balance_i = BalanceBeforeStorage_i - (Storage_i - StartingStorage) \cdot OutputEfficiency$$

In Case 2, the storage level must decrease in order to supplement inadequate renewable generation, $Storage - StartingStorage$ will always be negative and $Balance_i$ will never decrease. Substituting the three forms of Equation 6 into Equation 7, there are three possible outcomes:

$$Balance_i = \begin{cases} \text{A) } 0 \\ \text{B) } BalanceBeforeStorage_i + OutputRating \\ \text{C) } BalanceBeforeStorage_i + (MinStorage - StartingStorage) \cdot OutputEfficiency \end{cases}$$

Once again, the A situation successfully brings *Balance* up to zero, the optimal result, meaning that the storage system has been able to compensate for the insufficient renewable generation. In situation B, the storage system has been unable to supply energy above the maximum output rating, and an hour's worth of *OutputRating* is added to $BalanceBeforeStorage_i$, resulting in a smaller but still negative $Balance_i$. In situation C, the storage system will be near its minimum level and therefore cannot supply energy. *MinStorage – StartingStorage* will be close to zero, and $Balance_i$ will therefore be almost equal to $BalanceBeforeStorage_i$. Situations B and C will result in unserved demand for that hour, since the combined output of generation and storage will not be capable of meeting demand.

3.4 Other Renewable Energy System Models

This section will describe some other renewable energy system models in use, as described in journal articles, as well as the National Renewable Energy Laboratory's HOMER (Hybrid Optimization Model for Electric Renewables), and compare them to the IESVic ESM.

Most extant renewable energy system models are designed for siting and evaluating small-scale renewable energy systems, either stand-alone or grid-connected. (Indeed, the Race Rocks project was of this nature, although the present version of the IESVic ESM lacks a module for evaluating the economic feasibility of such a system.) As a result, most models have built-in assumptions about the nature of the renewable and storage technologies that will be used, or about the character of the demand that the renewable energy system must satisfy. For example, Ding et al. describe the modelling of a particular hybrid wind/solar photovoltaic/hydro system that will be used to provide "sustainable walkway illumination for a university campus" [30]. Similarly, Jatseck and Robinson present an optimization algorithm for a hybrid wind/photovoltaic system for a small farm near Edmonton, Alberta [31]. Their algorithm is designed to find the lowest cost system to meet daytime demand for the farm in question, and their system has a diesel backup system for the times when renewable generation and storage output are insufficient to meet demand.

In another paper, Iniyan and Sumathy describe an "Optimal Renewable Energy Model that minimizes the cost/efficiency ratio and determines the optimum allocation of different renewable energy sources for various end-uses" [32]. Their paper aims to paint a broad picture of the potential for renewable energy to meet specific end-uses in a socially acceptable fashion, and appears to use simple estimates of solar, biomass, and wind systems rather than detailed time-step modelling.

Kohle et al present a more sophisticated renewable energy model that matches a hybrid wind/photovoltaic generation system with a hydrogen-based storage system [33]. The objective of their model is to predict the performance of a stand-alone renewable energy laboratory at the Université du Quebec à Trois-Rivières, based on daily average meteorological data and the actual output of a Bergey Excel 10 kW wind turbine (the same model was used for modelling wind generation at Race Rocks). As with the paper by Jatseck and Robinson, Kohle et al describe a solar photovoltaic modelling algorithm considerably more sophisticated than the one used in the IESVic ESM.

All the above models are useful and interesting methods for determining renewable capacity and storage requirements for specific locations and technologies, and all have features that the IESVic ESM lacks (particularly for performing economic analyses); however, none appear to have ESM's the flexibility in choosing generation and storage technologies and evaluating a wide variety of scenarios. The only likely exception is NREL's HOMER, a model that comes close to (and in some ways exceeds) the ESM's functionality [34]. Like the IESVic ESM, HOMER is an hourly energy balance model, concerned with finding the optimal combination of renewable plant and storage to meet a given load. It can use historical hourly data as inputs or generate hourly data from climatic averages. HOMER is in many ways more sophisticated than the ESM: it features a user-friendly interface which provides many ways to view model inputs and outputs, it can simulate a variety of small hydro and biomass technologies in addition to their wind and solar counterparts, and it allows the user to distinguish between primary and deferrable loads, among other things. However, the current version of HOMER does not feature any storage technologies other than batteries, and allows the user to specify only the storage system's roundtrip efficiency, rather than individual input and output efficiencies. Furthermore, HOMER only models one year at a time, a disadvantage in designing integrated renewable/storage systems that will be required to operate for many years under a wide variety of climatic conditions. The ESM, on the other hand, is capable of modelling an arbitrary number of consecutive years.

Most importantly, HOMER is proprietary software. It is not possible for the user to look under the hood and evaluate the assumptions and algorithms built into the model. The IESVic ESM, by contrast, is entirely a known quantity; it can be analyzed and refined at will. There are, of course, many assumptions and simplifications underlying the ESM, but unlike HOMER, it is within our power to recognize and address these. The familiarity of the ESM allows IESVic to have confidence in the model's results, allowing for known shortcomings.

4. Demand Modelling

Most estimates of renewable energy land and storage requirements do not analyze imbalances between electricity supply and demand, on time scales ranging from hours to months. Society's demand for electricity never ceases, but renewable fluxes are highly variable and intermittent, and even the best locations can experience days or weeks with little significant renewable generation output. The same climatic fluctuations that reduce renewable supply often increase electricity demand; lights are left on longer in cloudy weather and air conditioners are switched on more readily on hot, windless days, to mention just two common examples. If detailed demand data are unavailable, such phenomena cannot be accounted for, and any resulting analysis would be flawed. This chapter describes how the hourly US demand used in this work was gathered and verified.

Estimates such as Turner's [11] aggregate demand and supply into one single annual figure each, thereby discarding all the information contained in the interplay between the two. A single aggregated figure implies that the sun shines year-round at an average intensity and that demand is likewise invariant. If these were true, it would be a simple matter indeed to determine the size of the solar plant required to meet these conditions: just increase the plant area until its total output matches the total demand. And this *is*, in fact, Turner's approach. As a first approximation, this method has some merit, but it is an insufficient basis for making sweeping predictions about the potential for renewable technologies to supply a nation's electricity requirements. To his credit, Turner does point out that energy storage will be required to cover supply deficiencies, but his choice of aggregated data makes quantitative analysis of storage requirements impossible. Since energy storage systems invariably increase the size of a stand-alone renewable energy plant (due to efficiency losses in the storage and retrieval phases), Turner's calculations certainly underestimate the size of the solar plant required.

In order to perform a more realistic estimate of renewable plant size, it is necessary to obtain energy supply and demand information for time scales much shorter than a year. The IESVic ESM takes hourly climate and electricity demand data as input arguments, and is therefore capable of a far more accurate quantitative description of the combination renewable plant and storage system required for any given set of circumstances. The Race Rocks project made use of stochastically generated data derived from sample and short-term datasets, but it was decided at the outset of this work that this project would use historical hourly electricity demand data. Another, more laborious alternative would have been to generate an hourly US electrical demand using aggregate energy statistics and other data, taking into account the enormous variability of climatic, economic, and demographic conditions across the country.

Historical hourly electric demand data is generally unavailable directly from electric utilities. Electric utilities often regard their demand data as proprietary, and do not make it available to the public. (This situation is beginning to change in deregulated markets, where legislation often forces the market operators to make hourly price and demand data available.) Faced with a shortage of high-quality hourly demand data, modellers often rely on monthly or seasonal aggregate electricity consumption statistics to generate synthetic hourly demands using stochastic methods [35]. There are many papers available that describe the mathematical methods used to arrive at a given set of synthetic demand figures. However, most of these attempt to estimate the demand for a single utility or even a space within a building [35-38]. There are no modelling techniques yet available for generating an hourly synthetic demand on a national scale.

Although they do not publicize the fact, utilities are required to submit annual hourly demand data to the United States Federal Energy Regulatory Commission (FERC). The US Federal Power Act authorizes FERC to collect detailed data from North American electric utilities to assist in planning and regulation of the electrical supply system. Utilities submit each year's hourly demand data as part of FERC Form no. 714 (FERC-714), used by FERC to "monitor forecasted demands by electric utility entities with fundamental demand responsibility, and to develop hourly demand characteristics" [39]. All FERC-714 data is publicly available for download from the FERC website, for the years between 1993-2001. Taken together, this data paints a complete and accurate picture of hourly electric demand in the United States, Canada, and a small part of Mexico.

Individual utilities do not submit FERC-714 forms directly; instead, each utility submits as a member of one of ten Regional Councils of the North American Electric Reliability Council (NERC), a not-for-profit corporation that promotes electric system reliability and security, and whose member entities account for almost all the electricity supplied in North America [40]. Figure 3, below, shows the North American geographic region represented by each NERC Regional Council. Three of the ten Regional Councils include Canadian generators as members: the Western Electricity Coordinating Council (WECC) covers British Columbia and Alberta; the Mid-Continent Area Power Poll (MAPP) covers Saskatchewan and Alberta; and the Northeast Power Coordinating Council (NPCC) covers Ontario, Quebec and the Maritime provinces.

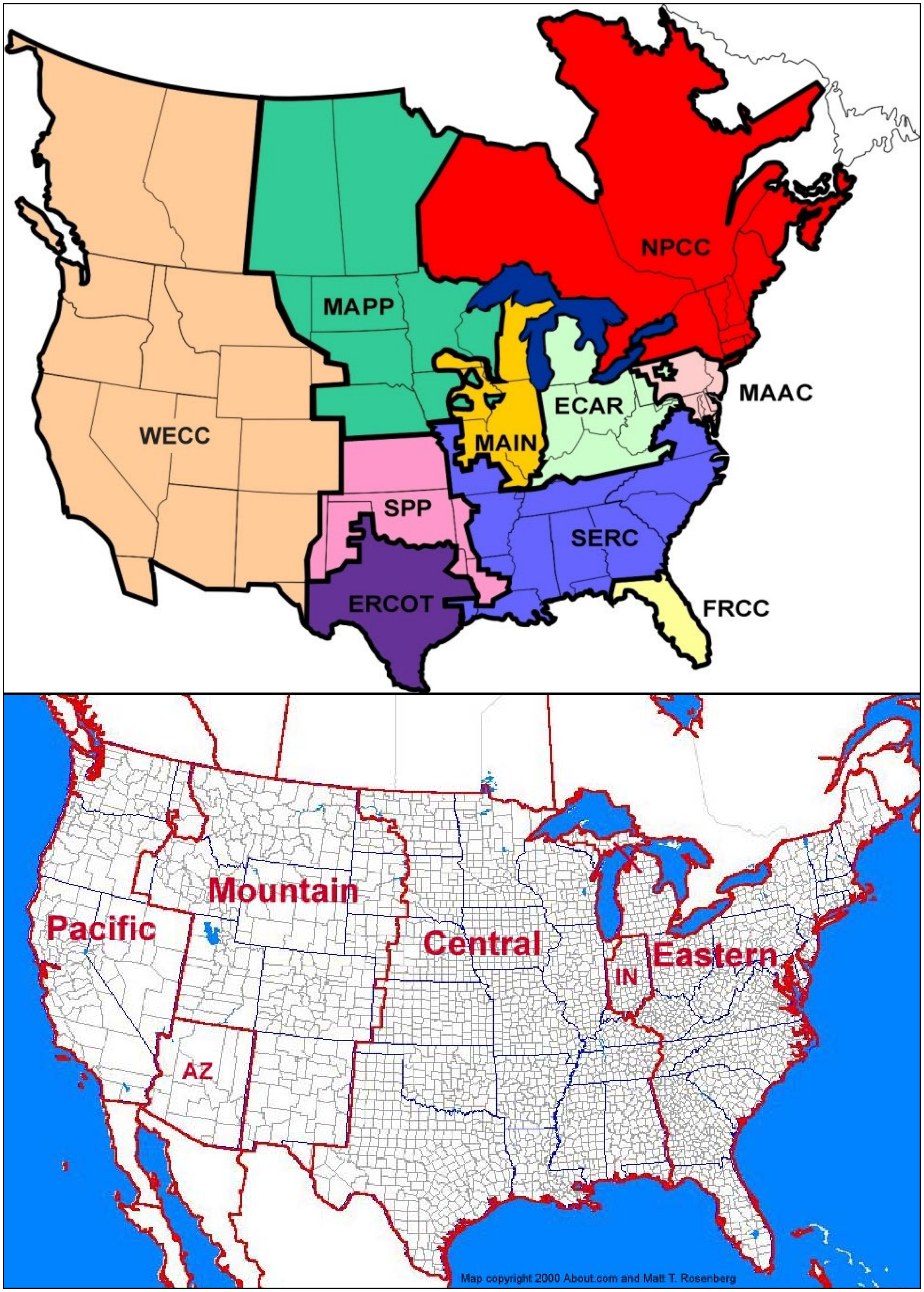


Figure 3: NERC Regional Councils (above) and US time zones (below, reproduced by permission of the owner) [40, 41].

The inclusion of Canadian demand data in FERC-714 submissions is understandable, given that there is only a single North American electrical grid, with electricity flowing freely across the US-Canada border, but it presented some difficulties for this project. For the model to be a true estimate of the potential for wind and solar technologies to meet North American electrical needs, it would be necessary to include climatic data for both the US and Canada, in order to place wind and solar facilities in both countries (particularly on Canada's windy Prairie provinces). Unfortunately, and in marked contrast to the United States, there was little detailed climatic data available for Canada at the time this work was performed. As a result, it was decided to remove Canadian demand data from the FERC-714 data, and restrict the modelling to the United States alone.

Although the FERC-714 data files are a most useful resource for energy modelling, they are far from ready to be used as is. The 2000 dataset contains 190 separate filings (disregarding demand data from Hawaii and Alaska), from both individual utilities and larger regional organizations, in a wide variety of formats. In many cases, a utility submitted the same demand data twice, once on its own behalf and again as a member of a larger regional body. Of the ten NERC Regional Councils, only WECC—with the lowest total demand—provided an index file detailing the nature of each submission, allowing the user to remove double-counted data. For most other Councils, there was a certain amount of guesswork involved in determining which data to discard.

The Canadian demand data posed another difficulty. For WECC and MAPP, the Canadian hourly demand figures were easily identifiable and therefore removable from the datasets; however, NPCC data subsumed Canadian hourly demand within regional figures. The only Canadian data available for NPCC in 2000 was the annual total, available on NERC's website, equivalent to about 47.2 TWh, or 1.3% of total US electric demand for 2000 [42]. On average, this is equal to a net baseload of 5.39 GW. Since the eastern Canadian provinces trade electricity with the northeastern states of the US under a range of demand conditions, it was not possible to reconstruct the hourly interchange. Instead, 5.39 GWh was subtracted from each hour of NPCC demand. This results in an erroneous demand figure for NPCC, but it is small compared to the total US demand.

The FERC-714 datasets for the contiguous United States cover four time zones: Pacific, Mountain, Central, and Eastern. All utilities provided demand information in terms of the local time, and it was necessary to determine each utility's time zone and modify its hourly data accordingly. The Eastern time zone was chosen as the reference location, since the bulk of the electricity consumption in the United States is concentrated there. The demand data for the three non-Eastern time zones was "shifted" so that, for example, the 7am demand for a utility located in the Pacific time zone corresponded to the 10am demand in the Eastern time zone.

Most of the NERC regions are located entirely within one time zone; only WECC, MAIN, and SERC span two time zones. Of these, both WECC and SERC have substantial footprints in both their time zones, while MAIN is almost entirely located in the Eastern time zone. As a result, these regions were examined on a utility-by-utility basis, in an attempt to determine to which time zone each belonged. In most cases, utilities included time zone information along with demand data; in others, it was necessary to allocate utilities to one time zone or another based on an educated guess. The resulting error, if any, would be small relative to the total US figure.

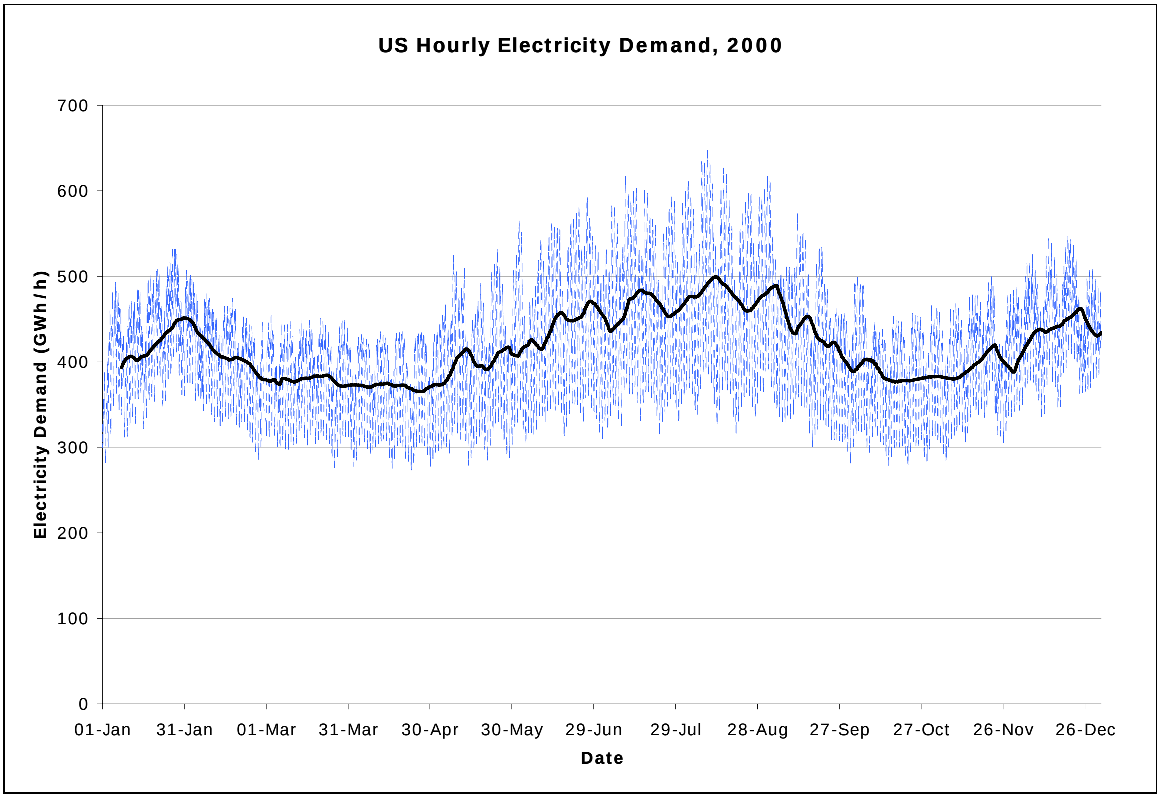


Figure 4: 2000 US hourly demand.
The bold line is a one-week moving average, illuminating seasonal trends.

Once the double-counted and Canadian data were removed, and time zone differences accounted for, the demand datasets were aggregated to give the total electrical demand for the United States for the year 2000, shown in Figure 4, above. The units of demand are GWh/h, since each data point in the FERC-714 submissions is a cumulative demand over the previous hour.

The demand peaks in the summer months at about 650 GWh/h, when the air conditioning load reaches its maximum, with smaller local maxima in the winter months. The summer peak demand compares to the 811 GW of generating capacity in the United States at the end of 2000 [12]; the 25% of excess generation capacity exists to cover outages and other contingencies.

		2000 Electricity Consumption (TWh)		Discrepancy Between NERC & FERC-714	
NERC Region - US ONLY	Time Zone	NERC Data	FERC-714 Data	TWh	Percent
MAAC	Eastern	262.3	261.4	-0.9	0.03%
ECAR	Eastern	546.0	637.8	91.8	2.51%
NPCC (Cdn. data removed)	Eastern	281.5	329.2	47.7	1.30%
FRCC	Eastern	196.6	184.9	-11.6	0.32%
SERC (62.3%)	Eastern	499.6	330.6	-169.0	4.61%
Eastern Time Zone Subtotal		***1786.0***	***1744.0***	***-42.0***	***1.15%***
SERC (37.7%)	Central	303.1	200.3	-102.7	2.80%
MAPP	Central	146.0	148.2	2.2	0.06%
ERCOT	Central	286.3	288.7	2.3	0.06%
MAIN	Central	259.6	265.5	5.9	0.16%
SPP	Central	193.7	336.1	142.4	3.89%
Central Time Zone Subtotal		***1188.6***	***1238.8***	***50.2***	***1.37%***
WECC (24.5%)	Mountain	122.6	125.7	3.0	0.08%
WECC (75.5%)	Pacific	501.6	514.0	12.4	0.34%
TOTAL		**3639.0**	**3663.2**	**24.1**	**0.66%**

Table 1: Demand data summary and comparison

Table 1 compares the 2000 demand information for each Regional Council available on the NERC website [42] with the same information taken from the FERC-714 submissions. For the most part, the differences between NERC and FERC data are small, and the total demand figures are very close in magnitude. Of the ten datasets, only the discrepancies in the SERC, SPP, and ECAR datasets exceed 2% of total demand. However, the errors in the SERC and SPP datasets are large enough to require some attempt at explanation, however conjectural. The low discrepancy in the total demand, despite the large SERC and SPP errors, may simply be the result of error values cancelling each other out: the sum of the magnitudes of the SERC, SPP, ECAR, and NPCC errors is only 9.7 TWh, 0.26% of total demand. An alternative explanation may be that there could be “bleeding” across the borders of these contiguous NERC regions; energy exported across Regional Council borders could be improperly assigned to one Regional Council in the FERC-714 data.

Table 1 also subtotals the demand data by time zone. Nearly half of the 2000 US electrical demand occurs in the Eastern time zone, where the population and industrial densities are highest. The Central time zone also has a high demand, about one-third of the total, due largely to the high industrial density of states such as Wisconsin, Illinois, and Texas. The Mountain and Pacific time zones, taken together, have only about half the demand of the Central time zone, with the Pacific utilities making up the bulk of this figure.

5. Modelling Renewable Resources and Technologies

Over the past four decades, extensive climate data has been collected for thousands of locations worldwide. The most reliable data—and the most desirable for the purposes of modelling renewable energy systems—is collected on an hourly or sub-hourly basis. However, this is also the least common kind of data, and hourly climate information—especially data that spans multiple consecutive years—is unavailable for most locations outside the United States. Where hourly data is incomplete or nonexistent but daily or monthly averages are available, synthetic hourly climate data can be generated using stochastic mathematical methods. Stochastic methods simulate the natural variation of climate for a specific location based on a limited number of parameters. One such method was used in the Race Rocks project, to overcome the difficulties posed by the paucity of climate information for that location.

Stochastic methods are generally accepted for the modelling of renewable resources in single locations where detailed historical data is sparse or unavailable, but would quickly become unwieldy in projects such as this one, where both wind and solar resources are to be evaluated for multiple locations over several consecutive years. Weather patterns are correlated both regionally and temporally, wind and solar resources likewise. If it is blowing a gale in Texas, it is likely that Kansas and Oklahoma will also be experiencing strong winds. Similarly, sunny weather in one location will create a high-pressure cell, causing high winds elsewhere. Stochastic methods can generate plausible synthetic data for each location, but fail to replicate the correlated behaviour of multiple simultaneously modelled wind and solar resources. The best choice for a project of this nature is to use historical hourly climate data, where available.

The National Climate Data Center (NCDC), in the United States, serves as a clearinghouse for historical climate information for locations in the US and worldwide, although the most comprehensive climate data available is to be found for stations within the US. Originally, the objective of this project was to assess the ability of renewable resources to meet the electricity service needs of both Canada and the US, but this objective had to be modified in light of the sparse hourly climate data available for Canadian locations. It would hardly be fair to require US renewable resources to satisfy the electricity demand for both countries, especially when the Prairie Provinces have wind resources rivalling the best below the border. However, the absence of concurrent hourly wind and solar data rendered it impossible to include Canada in the modelling process.

With Canadian climate data removed from consideration, the most detailed long-term US climate data available is the Solar and Meteorological Surface Observation Network (SAMSON), a three-volume CD-ROM set containing hourly weather observations of varying completeness from 237 stations in the United States, Guam, and Puerto Rico, for the years spanning 1961-1990 inclusive [43]. SAMSON datasets include observations of terrestrial and extraterrestrial solar radiation, sky cover, temperature, relative humidity, atmospheric pressure, wind speed and direction, visibility, ceiling height, present weather, snow depth, and hourly precipitation. The data required for this project are the hourly global horizontal solar radiation and the hourly wind speed for several locations. Locations were chosen primarily for the strength of the solar and wind fluxes available, subject to the completeness of the datasets available. Some low-flux locations were also chosen to provide a comparison to the high-flux sites.

5.1 Solar Data and Technologies

5.1.1 Solar Radiation Data

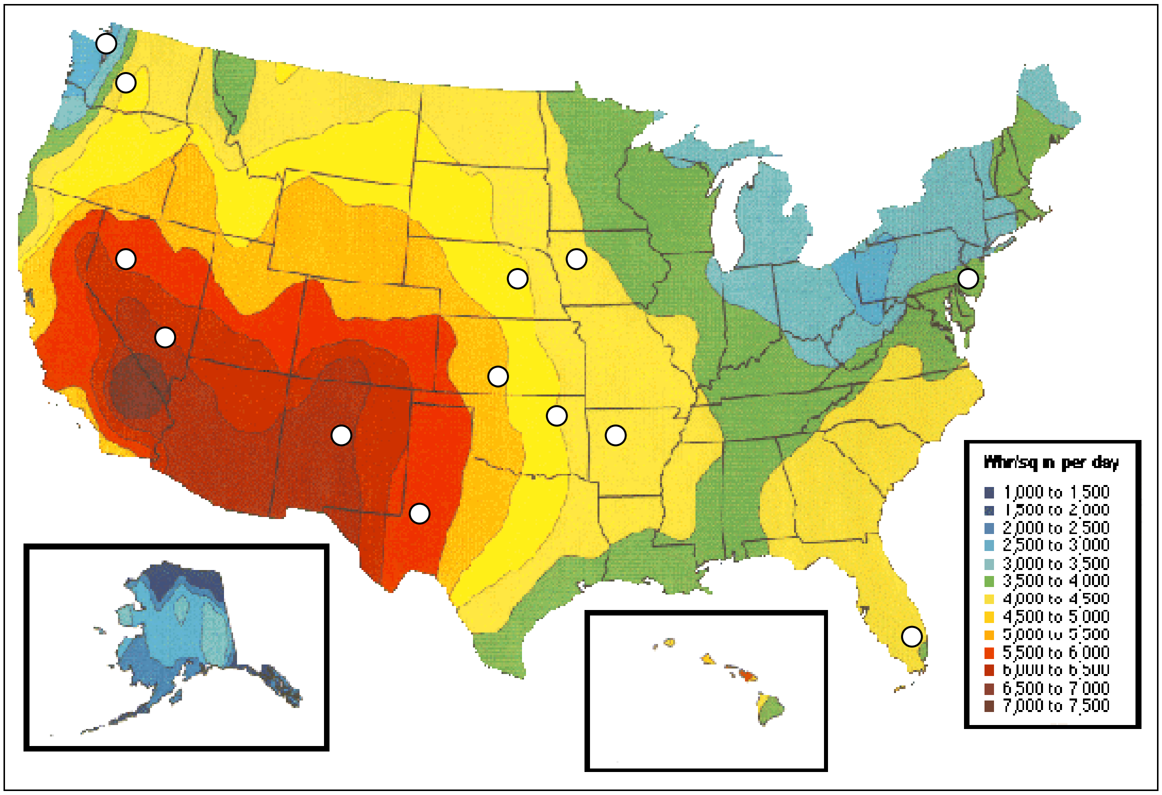


Figure 5: US solar radiation atlas with PV modelling locations shown [44].

The global horizontal insolation is the amount of direct and diffuse solar radiation striking a horizontal surface at ground level, and has SI units of W·m^{-2}. In the SAMSON datasets, the global horizontal radiation figures present the cumulative direct and diffuse insolation over the 60 minutes preceding the hour given, and are in units of Wh·m^{-2}. Solar radiation data in SAMSON is highly complete, in general, although the global horizontal insolation data is more often calculated from direct radiation and sky cover data than measured directly. For the period chosen for this project, 1981-1990, almost every location has complete hourly data in SAMSON, and scarcity of data was not a concern when choosing locations for the modelling of solar photovoltaic technologies.

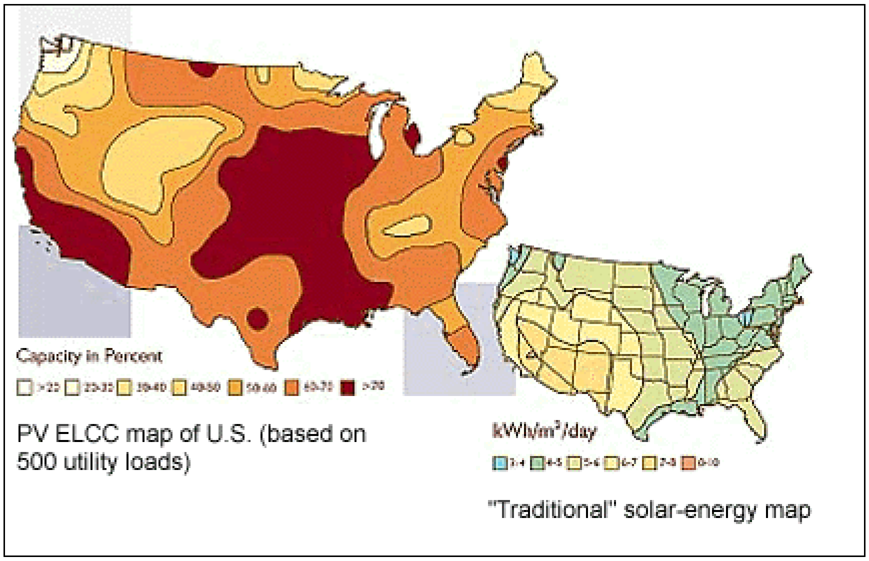


Figure 6: Revised solar atlas based on ELCC data [45].

Thirteen locations were chosen for photovoltaic modelling, as shown on the solar radiation atlas in Figure 5. The four locations in Nevada, New Mexico, and Texas were selected for the high daily insolation characteristics in those regions, based on the information in Figure 5. These are the regions most commonly considered for the siting of large-scale solar power facilities.

The five midwestern locations, Miami, and Philadelphia were chosen based on the information presented in Figure 6, above. A 1996 report prepared for the US Department of Energy contends that absolute insolation levels may be less important than the effective load-carrying capacity (ELCC) of photovoltaic plants [45]. The ELCC measures the ability of an electricity generator to provide power to the utility as needed; it is highest when the generation output is well matched to the load. The authors used hourly demand information from 500 electric utilities to produce the modified solar radiation atlas shown in Figure 6.

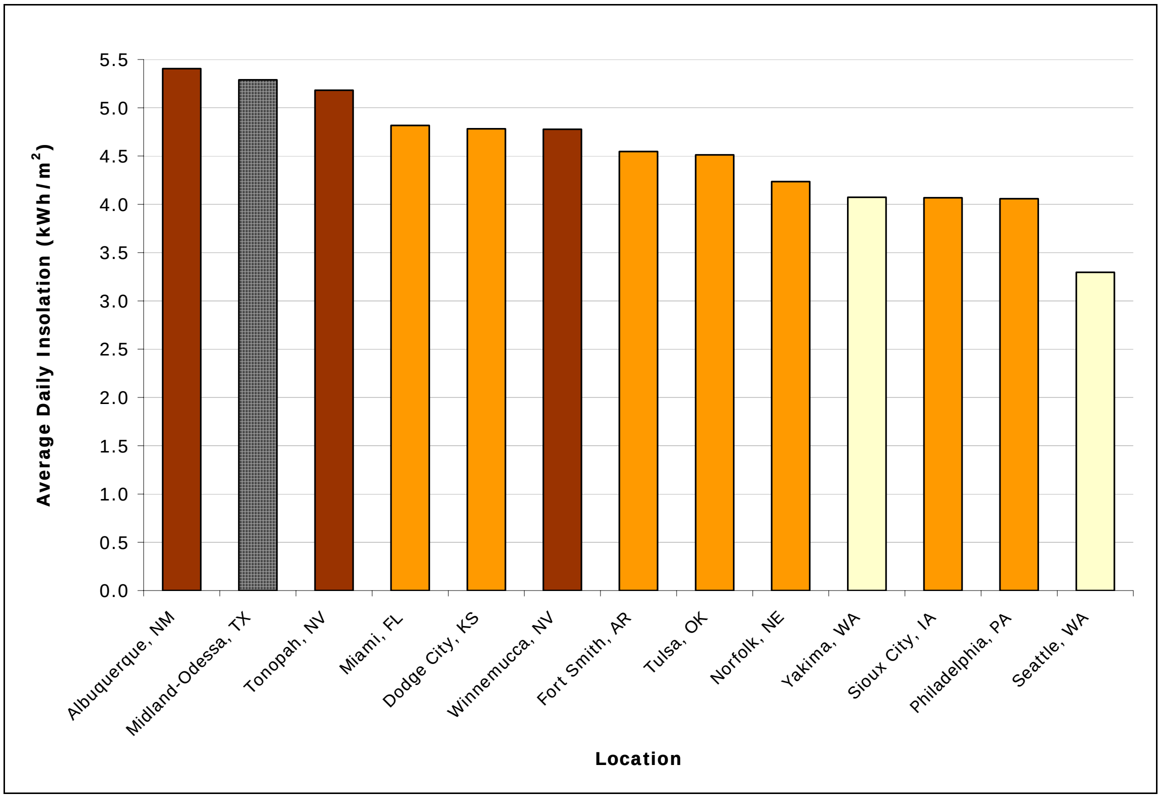


Figure 7: Average daily insolation for modelled locations

According to Figure 6, California and the Midwest may be superior to the high-insolation regions, due to better matching of the solar flux with the local electrical demand. The two Washington state locations, Seattle and Yakima, were modelled to estimate the relative performance of low-insolation, low-ELCC regions. Seattle's performance should be similar to that of photovoltaics in southwestern British Columbia, which has a similar climate and economic mix.

Figure 7 compares the average daily insolation of all 13 solar locations. The high-insolation locations are denoted by the darkest bars, the high-ELCC locations by the medium bars, and the low-insolation, low-ELCC locations by the light-coloured bars. Midland-Odessa, Texas, the only location with both high insolation and high-ELCC characteristics, has an alternating dark/medium pattern on its bar.

5.1.2 Modelling Solar Photovoltaic Technologies

The approach to solar photovoltaic (PV) technologies in this work is essentially unchanged from that used in the Race Rocks project [29]. There were only two significant changes to the ESM's solar photovoltaic module:

1. **The addition of the capability to process an arbitrary number of years of solar resource data.** Earlier versions of the ESM could model only one year at a time [29]. This is not a particular problem for a stand-alone PV system operating in tandem with conventional electrical generators, which can meet demand during prolonged PV outages. It is a problem when (as here) the renewable system must satisfy the entire demand. The PV plant must generate sufficient electricity over an indefinite period to satisfy the total system demand <u>and</u> overcome storage losses. An energy storage system attached to an undersized PV plant will gradually become depleted, leading to system failure. A system modelled over several consecutive historical years avoids this problem: a successful PV/storage combination is one that operates continuously over several years under a wide variety of solar conditions.

2. **The ability to model PV generating plants in different time zones to the demand location.** In this work, the Eastern time zone is the reference location for the US hourly demand; the noon demand in the Eastern time zone is added to the 11am Central demand, the 10am Mountain demand, and the 9am Pacific demand to arrive at an overall "noon" US demand. The thirteen PV locations selected include at least one plant in each time zone. The PV model takes the time zone information as an input

argument in units of hours (west is negative), and adjusts the solar resource information to synchronize the solar plant output with demand.

The photovoltaic panel chosen for all PV modelling in this work is the Shell (formerly Siemens) SP-75, a grid-suitable mono-crystalline panel with a peak power output equivalent to 118 $W \cdot m^{-2}$ [46]. In all the modelling presented here, the panels track around an east-west axis, facing south and following the altitude of the sun each day; that is, the sun remains in the plane normal to the panel surface. The photovoltaic module of the ESM outputs the PV *panel* area required to meet demand, but the PV *plant* area is double the panel area, since PV plants require approximately two square metres of land area for each square metre of panel area, to prevent shading and allow access for maintenance [11].

Photovoltaic panels are represented in the IESVic ESM by a simple technology model. The bulk of the ESM's PV computations are spent calculating the position of the sun in the sky and its angle of incidence to the PV panel; the power output of each panel is simply the computed panel irradiation multiplied by the panel efficiency. For instance, if the solar radiation incident on the PV panel is 500 $W \cdot m^{-2}$, and the panel efficiency is 10%, the panel output will be (500 $W \cdot m^{-2} \times 10\%$ =) 50 $W \cdot m^{-2}$. This approach certainly overestimates the panel output, especially at low levels of irradiation [5, 6]. According to the product information sheet for the SP-75, "The relative reduction of module efficiency at an irradiance of 200 W/m^2 in relation to 1000 W/m^2 both at 25°C cell temperature and AM 1.5 spectrum is 7%" [46]. In other words, the panel efficiency is reduced at lower insolation levels.

A PV panel efficiency of 12% was used throughout this work, remaining constant regardless of insolation levels. The PV modelling results will therefore specify minimum areas for PV plants; if actual efficiency variations were incorporated into the ESM, the PV plant area would certainly increase.

5.2 Modelling Wind Resources and Technologies

5.2.1 Wind Speed Data

In contrast to the hourly solar radiation data, which gives cumulative totals of insolation over the past hour, the hourly wind speed is merely an hourly sample, rather than an average. This doubtless introduces some error into the data—the wind may be blowing unseasonably hard or soft at the moment the data is recorded—but the SAMSON dataset is still the best available at this time.

Ideally, wind locations would be chosen based on the wind characteristics of each site. However, SAMSON's hourly wind data is incomplete or absent for most locations, including many promising wind locations. Of the locations with detailed wind speed data, most did not collect hourly wind speed data until 1982. For this reason, wind data was collected for the period 1982-1990 inclusive.

Despite the relative paucity of complete wind datasets, there were enough to model a number of locations in the highest wind speed regions in the United States, such as the Great Plains states of the Dakotas, Oklahoma, Kansas and Texas. The eleven locations chosen are shown in Figure 8, and ranked by average wind speed in Figure 9. The average wind speed at a 50 m elevation was calculated from anemometer data using the "1/7 power rule" [4], a reasonable approximation for the open surroundings of the airport measurement stations providing most of the SAMSON data [47].

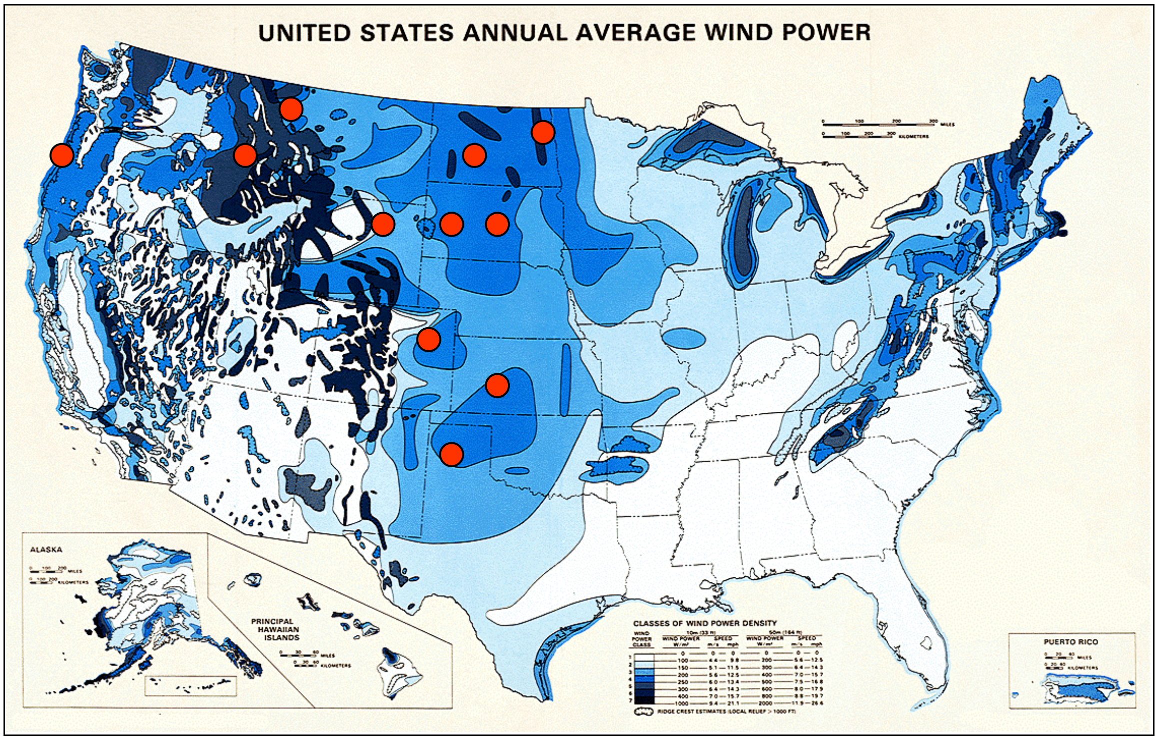


Figure 8: Wind resource atlas of the United States with modelled locations shown [48]. The wind power density table at the bottom of the figure is reproduced in Table 2, below.

	10 m Elevation		50 m Elevation	
Wind Power Class	Wind Power Density (W/m^2)	Wind Speed (m/s)	Wind Power Density (W/m^2)	Wind Speed (m/s)
	0	0	0	0
1				
	100	4.4	200	5.6
2				
	150	5.1	300	6.4
3				
	200	5.6	400	7.0
4				
	250	6.0	500	7.5
5				
	300	6.4	600	8.0
6				
	400	7.0	800	8.8
7				
	1,000	9.4	2,000	11.9

Table 2: Classes of wind power density [47].

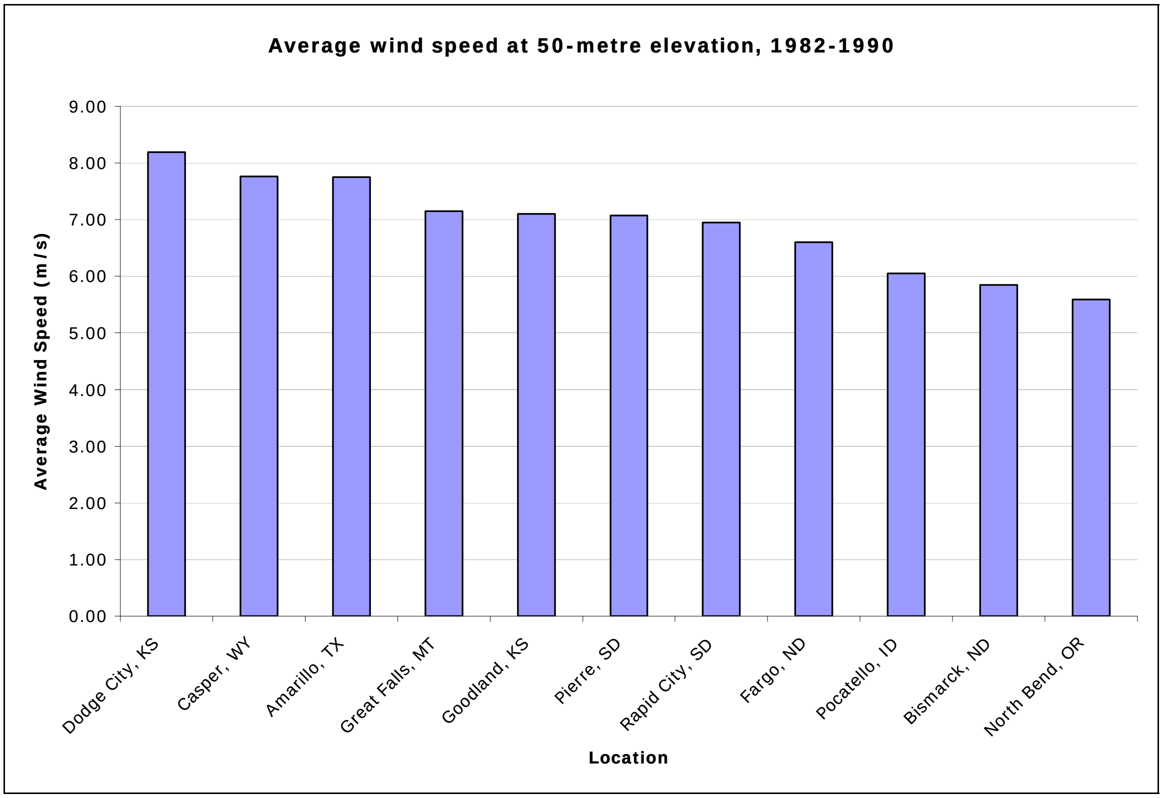


Figure 9: Average wind speeds for modelled locations

One common method of determining the character of a wind regime is to classify it by the average wind power density in that location [15], measured in units of watts per square metre ($W \cdot m^{-2}$) of vertical area exposed to the wind. For example, the wind power passing through a wind turbine's blades would be the wind power density (in $W \cdot m^{-2}$), multiplied by the swept area (in m^2). Locations with average wind speeds exceeding 7.0 m/s are designated as Class 4 wind power density, generally regarded as the minimum power density suitable for wind generation using current technologies [47]. Of the eleven locations modelled in this work, six are Class 4 or higher, while Rapid City, South Dakota—with an average wind speed of 6.95 m/s—is a rounding error short of being a Class 4 site. Table 2 summarizes wind power classes; the leftmost column is offset vertically to indicate that each class spans a range of wind speeds.

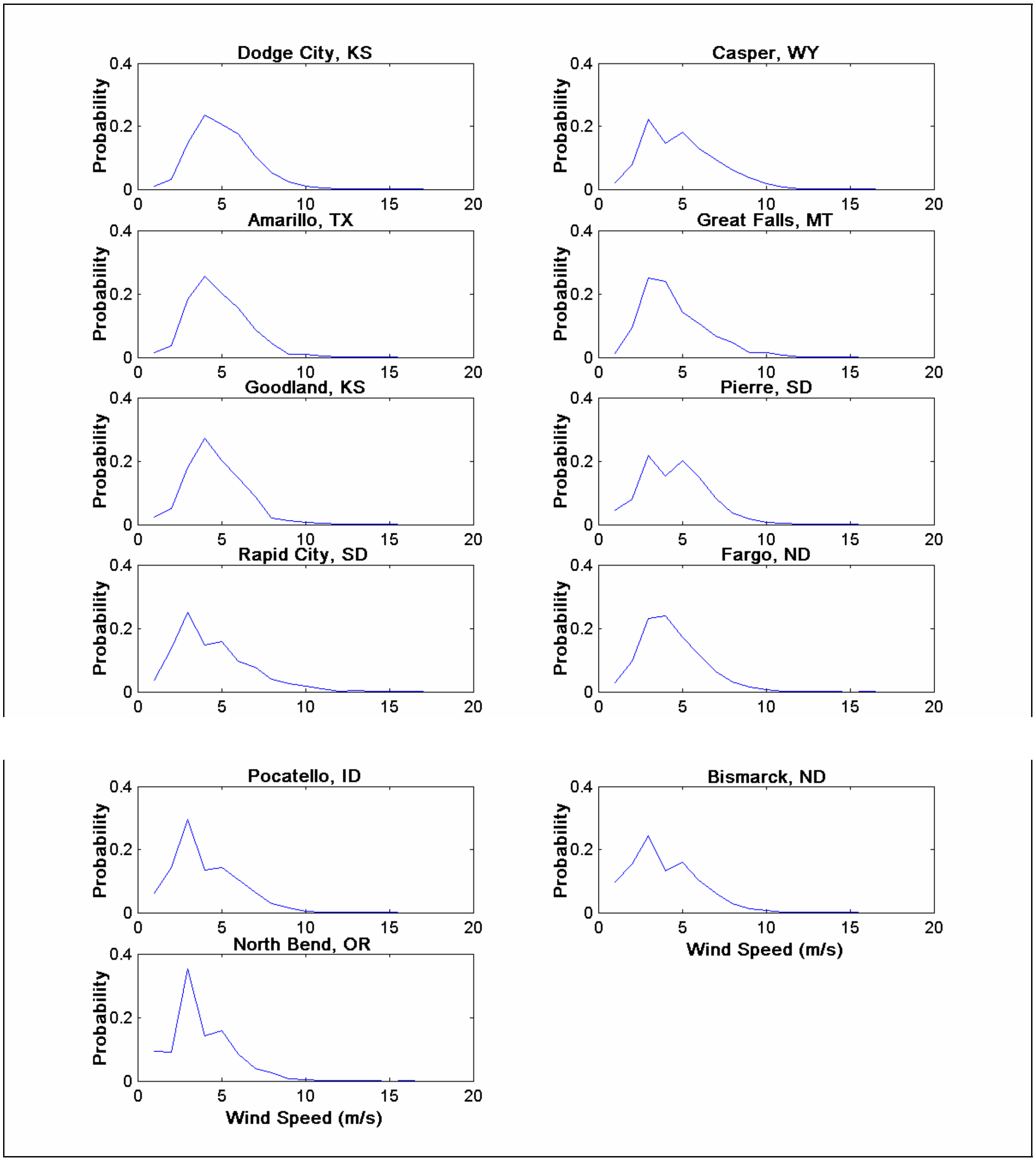


Figure 10: Probability distributions of wind speed for modelled locations, 1982-1990

The average wind speed—while useful—is not the most important measure of the wind resource at a particular site. Wind power density increases proportional to the cube of the wind speed [4], and two sites with similar average wind speeds can have very different wind power characteristics depending on the distributions of wind speeds around the mean. For example, consider the wind speed probability distributions for Amarillo, Texas and Casper, Wyoming shown in Figure 10. The two locations have almost identical average wind speeds, at 7.75 m/s and 7.76 m/s for Amarillo and Casper respectively. However, their wind speed distributions are markedly different, which will lead to quite different modelling results.

Figure 10 is ranked by average wind speed, and stark differences are evident between high and low wind speed locations. In general, the locations with lower average wind speeds feature distributions that peak at low wind speeds, falling off rapidly as the wind speed increases. Since most wind turbines do not begin to operate until the wind speed exceeds 3 m/s, much of the wind energy in these locations will be lost. However, this does not necessarily mean that the low-wind locations have no role to play in generating electricity. The results of the interplay of the various modelling components—wind resources, wind turbines, storage systems, and electricity demand—are sometimes counter-intuitive, and often surprising.

5.2.2 Modelling Wind Power Technologies

Turbine Make and Model	Turbine Diameter (m)	Rated Power (kW)	Cut-in Wind Speed (m/s)	Rated Wind Speed (m/s)	Cut-out Wind Speed (m/s)	Hub Height (m)
GE 3.2s	104.0	3,200	3.5	14.3	25.0	120
GE 1.5s/sl	**70.5**	**1,500**	**3.0**	**12.0**	**25.0**	**100**
GE 900s	53.2	900	3.0	13.0	25.0	59
Vestas V47	47.0	660	4.0	15.0	25.0	55
Vestas V66	66.0	1,750	4.0	16.0	25.0	78
NEG-Micon NM48	48.2	750	4.0	16.0	25.0	70
NEG-Micon NM80	80.0	2,750	3.0	16.0	25.0	80

Table 3: Sample wind turbine specifications [49-51].

The ESM wind turbine module used in this work is almost unchanged from the one used for the Race Rocks project [29]. The same changes were made to the wind turbine module as to the PV module, namely the abilities to model over an arbitrary number of wind resource years, and to locate wind plants in different time zones from the electricity demand.

The ESM's wind turbine module uses the method developed by Chou and Corotis [52], in which manufacturer-specified parameters define the behaviour of the wind turbine at any given wind speed. The parameters include the rated turbine output power; the cut-in wind speed, at which the turbine begins to generate electricity; the rated wind speed, at which the turbine reaches its nominal output power; and the cut-out wind speed, at which the turbine shuts down to avoid damage in high winds. The turbine power curve follows a cubic relation between the cut-in speed to the rated speed, remains constant from the rated speed to the cut-out speed, and drops to zero thereafter. This approach has the advantage of relying solely on readily available manufacturers' specifications and hourly wind speed data to produce wind turbine outputs close to those expected in practice.

A number of grid-suitable wind turbines were considered for modelling in this work, all listed in Table 3, above. All specifications are as given by the manufacturer, and the hub height used for each was the recommended maximum for that turbine. Figure 11 shows the power curve for each turbine as calculated using the method of Chou and Corotis. The turbine chosen for all modelling comparisons in this work was the GE 1.5s, drawn with the bold line in Figure 11. Compared to the other turbines, the 1.5s has a lower rated speed, meaning that the turbine increases its output power more rapidly and reaches its maximum output at a lower wind speed than for the other turbines.

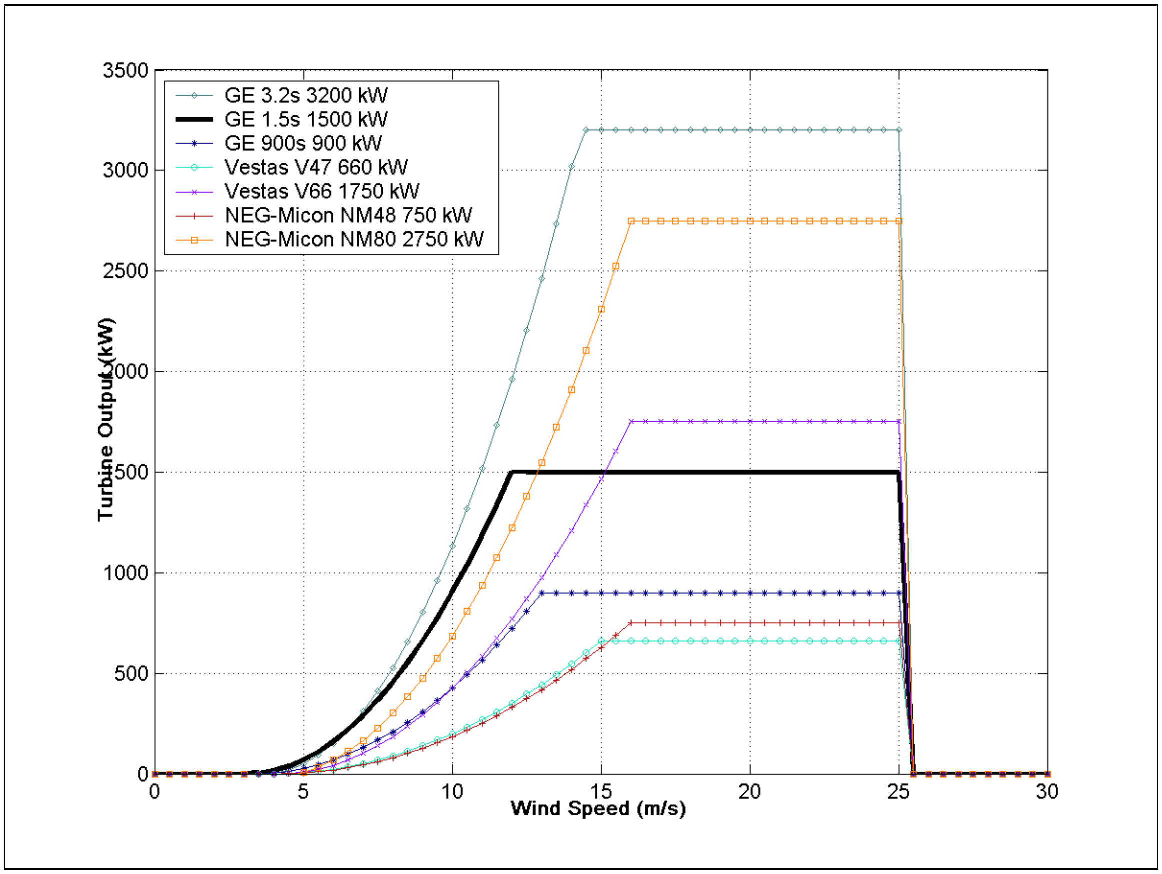


Figure 11: Sample wind turbine power output curves.
The GE 1.5s was chosen for the wind modeling in this work, and its power curve is shown in bold.

The wind plant areas in this work were calculated assuming a rectangular grid formation for all turbines, spaced 5 diameters apart in the crosswind direction (that is, side by side), and 10 diameters apart in the downwind direction. This "10D × 5D" spacing is common for locations where the prevailing winds blow along a single axis; e.g. east-to-west or west-to-east [16]. The higher downwind distance is to allow the wake effects from one turbine to dissipate before the wind reaches the turbine behind it. In multidirectional wind regimes, the crosswind spacing would be increased, and the wind plant areas given in the results of this work should be regarded as minimal.

The ESM's wind module contains a number of implicit assumptions that, if accounted for, would lead to an increase in plant area. The Chou and Corotis model relies on manufacturers' specifications of wind turbine output, and these are given for an altitude of Mean Sea Level (MSL), as defined by the ISO 2533 standard [8]. The air density at MSL is 1.2255 kg/m^3; at higher altitudes, the air density (and therefore the wind power density) is lower, leading to reductions in turbine output. Many of the modelled locations are in the Great Plains or the Rockies, with altitudes ranging from 274 metres in Fargo, North Dakota to 1612 metres in Casper, Wyoming. The average air densities at these locations are 2.2% and 12.3% lower than at MSL, respectively, and it is reasonable to expect corresponding reductions in wind plant output.

Another factor that would be likely to increase the actual wind plant area is the non-homogeneity of the wind resource. The wind measurements used here are made at a point source, usually an airport weather station close to a city. However, it is assumed in this work that the measured wind speed remains constant over the entire area of the wind plant. This is far from being a realistic assumption: the wind plant areas will include regions covered by forests, mountains, cities, lakes, and other geographical features. These areas will doubtless even include some regions where the wind speed is higher than that measured, but it is equally likely that a great portion of the area will be unsuitable—one way or another—for wind energy development [47]. In reality, it is likely that, as the best wind sites are developed or excluded from development, utilities will be forced to exploit ever-diminishing qualities of wind resource, further increasing the land area required [53].

6. Storage Modelling

One of the major insights gained from the Race Rocks project concerns the effects of intermittent renewable fluxes and storage efficiencies on increasing the required capacity of the energy storage system and the area of the renewable plant. For many locations, there may be periods of days or even weeks when the sun does not shine or the wind does not blow. The *minimum* size for a perfectly efficient storage system will therefore correspond to the total energy demand for the longest period where renewable fluxes are absent; if there is no wind generation output for (say) two weeks in a given location, the storage system capacity must be no less than the total demand during that period. Of course, no storage system is perfectly efficient, and the energy conversion losses at the storage outputs will further increase the capacity of the storage system required.

These features of the storage system also help to explain why an hourly time-series analysis (such as that performed by the IESVic ESM) results in a much larger renewable plant size than an aggregate energy balance such as that performed by Turner [11]. An hourly time series analysis reveals that for a stand-alone renewable plant operating in tandem with a storage system, a large fraction of the plant is, in effect, permanently set aside for the purposes of charging the storage system while renewable fluxes are present, in order to carry the system through supply outages. The exact fraction of the plant required to do this depends on a number of factors, including renewable conversion efficiency, and (as mentioned above) the storage efficiencies and the temporal variation of the renewable fluxes, but it is always substantially in excess of the plant size yielded by a simple aggregate energy balance.

6.1 Why is storage required?

Energy storage technologies enable renewable technologies to satisfy the electricity system's requirement for ubiquitous and uninterrupted supply, regardless of climatic conditions. An unbuffered renewable generation system—one in which the renewable generation output goes directly to the grid at all times—gives rise to system instability both when the renewable output fails to meet demand and when it exceeds demand. While the consequences of failing to meet demand are intuitively obvious, those of exceeding demand are less so. A "balanced" system is one in which generation is meeting current demand—there is no sink available for any energy generated in excess of demand. (Such imbalances are often exacerbated by government rules in many locations that force utilities to buy renewable energy whether it is needed or not [9, 22, 26, 54].) In such a situation, a utility is forced to choose between shutting down other generation plants or—where possible—exporting the electricity to sometimes-reluctant neighbouring regions.

If a storage system is used to complement renewable generation, most energy generated in excess of demand can be stored for use later when renewable fluxes are low or demand exceeds what the system can supply at that time. An optimized combination of renewable plants and energy storage facilities could provide, in principle, the responsiveness and ubiquitous service we have come to expect from the conventional energy system.

6.2 Utility-scale energy storage technologies

The current, conventional-dominated electricity system already makes use of energy storage, for applications ranging from power conditioning and regulation, to bulk storage of off-peak baseload electricity for use at peak demand times. The fuels used by conventional power plants—coal, natural gas, uranium, or water behind a dam—are themselves forms of energy storage, able to be converted to electricity on demand. Renewable technologies such as solar and wind power require supplemental storage technologies because their fuels—wind and sunlight—cannot be stored *in situ* for later use. In the current conventionals-dominated electricity system, power conditioning and regulation technologies act on a time scale of seconds to minutes, while bulk storage applications provide energy for hours. A renewables-predominant grid in North America would make extensive use of both types of storage, but simply could not provide high-quality energy services without heavy reliance on large-scale bulk storage facilities.

On the time scale of seconds to minutes, energy storage technologies such as flywheels, supercapacitors, and superconducting magnets are used to smooth out brief fluctuations in the electricity supply and ensure uninterruptible high-quality supply. These technologies typically have high power outputs but low energy densities, and do not have the storage capacity to provide energy for hours or days at a time. Since the IESVic ESM has a resolution of one hour in the time domain, and these technologies typically operate on much shorter time scales, they are not relevant to this work.

Storage technologies that operate on time scales of hours to days are of primary interest for renewable energy systems. With the exception of a significant number of pumped-hydro installations worldwide, there are few utility-scale bulk energy storage facilities in existence. However, as renewable energy technologies' share of the electricity supply system continues to increase, opportunities will arise for large-scale storage facilities to compensate for the randomly intermittent nature of renewable generation. A number of large-scale bulk storage technologies are at or near maturity, as described below.

6.2.1 Pumped Hydro

Pumped-hydro facilities are the most widely used large-scale energy storage facilities in the world today; of the 40 plants worldwide of over 1,000 MW capacity, nine are in the US, with a total nominal capacity of 15,583 MW [55]. Pumped-hydro facilities make use of two reservoirs separated vertically; in times of low demand, surplus energy is used to pump water from the lower to the upper reservoir. The stored energy is then available for use at times of peak demand, with a turnaround efficiency of 70-85%. Like most hydro facilities, pumped-hydro plants have a variety of discharge times depending on the volume of the reservoir, ranging (in US facilities) from 9 - 153 hours, though the majority are in the range of 20 hours [55]. As with conventional hydro facilities, most of the best sites for pumped hydro have already been developed, but it is also possible to use abandoned mines or caverns or even the ocean as the lower reservoir in possible future facilities. However, it is unlikely that there will be many new 1,000 MW-plus pumped-hydro facilities built in the US, given the scarcity of available sites and recent public opposition to large-scale hydroelectric projects.

6.2.2 Compressed-Air Energy Storage

One of the most promising bulk energy storage technologies in development is compressed-air energy storage, or CAES. This technology uses hollowed-out salt caves or other underground cavities as a reservoir into which air is compressed to approximately 7 MPa (~10,000 psi) during times of excess generation [56]. When energy output is required, the high-pressure air is expanded along with methane in a combustion turbine, producing electricity. CAES turbines use only about 40% of the fuel used in conventional gas turbines running on a steady-flow Brayton cycle, because CAES turbines are not required to expend work to compress the incoming air. The compression efficiency of CAES plants is around 75%.

There are two pilot CAES facilities in operation at the time of writing: a 290 MW unit in Hundorf, Germany, and a 100 MW plant in Macintosh, Alabama [56]. In addition, a 2,700 MW CAES plant is planned for construction in Norton, Ohio [57]. The Electric Power Research Institute (EPRI) estimates that almost 85 percent of the contiguous United States has geological characteristics suitable for CAES technologies, meaning that there is great potential for CAES to emerge as a major bulk energy storage technology [58]. The lifetimes of CAES systems are comparable to pumped-hydro at over 10,000 cycles at 80% depth of discharge [55].

6.2.3 Flow Batteries and Hydrogen Fuel Cell/Electrolyzer Combinations

Flow batteries and fuel cell/electrolyzer combinations are grouped together here because they both rely on fuel cells to convert stored chemical energy into electricity. Both technologies feature fast response times, high reliability, and can serve a wide range of power conditioning or energy storage applications. Of the two, flow batteries are nearer to wide-scale use, with a number of grid-connected demonstration plants in service. Hydrogen fuel cells may require a hydrogen infrastructure to be in place before they can serve in a large-scale bulk storage capacity.

Flow batteries are also known as regenerative fuel cells, storing energy in a liquid electrolyte solution (such as polysulfide bromide or vanadium pentoxide), which is charged or discharged by cycling it through a battery stack in a closed cycle [59]. Unlike conventional batteries (and like fuel cells), the power and energy ratings of flow batteries are independent of each other: the former is a function of the number of cells in the stack, the latter of the amount of electrolyte available. Flow batteries have high efficiencies—reportedly in excess of 75%—but low energy densities, comparable to lead-acid batteries. This latter factor may set an upper limit on the output of flow battery installations, since they may require very large tanks of electrolyte. Some demonstration flow battery plants are already operating: a 15 MW, 120 MWh Regenysys polysulfide bromide plant in the UK and a few 500 kW, 5 MWh vanadium redox batteries in Japan [55].

Hydrogen fuel cell/electrolyzer combinations are a widely touted near-term energy storage technology, particularly so in view of the appealing idea of using hydrogen to integrate the electricity system with the transportation system in a zero-emissions nexus. In this vision, a carbon-free electricity system—powered by nuclear, hydroelectric, and renewable generation technologies—would not only supply direct electrical demand but also use excess generation to electrolyze water into hydrogen, which could then be used to provide a variety of energy services [60]. In this vision, bulk energy storage using fuel cell/electrolyzer combinations can serve as a bridging technology towards increasing the penetration of hydrogen into the energy system.

There is a variety of types of hydrogen fuel cell, with typical energy efficiencies of 40-55% [61]. Electrolyzers typically have high efficiencies, up to 80%, although the hydrogen needs to be compressed or liquefied to achieve acceptable storage volumes, lowering the overall energy efficiency of the electrolysis process.

6.3 Modelling storage in the IESVic ESM

The IESVic ESM models storage using a number of generic parameters, designed to allow simulation of a wide variety of energy storage systems. Following is a description of the parameters, and some general discussion of the effects of each on the modelling results.

- The **storage capacity** is the maximum amount of energy that the storage system can hold. This is—along with plant size—one of the two primary outputs of the ESM. There is an inverse relationship between plant size and storage capacity; as plant size increases, storage capacity decreases monotonically, and the objective of the modelling process is to find the narrow range of plant/storage combinations that satisfy the modelling constraints.

- The **storage input and output efficiencies** cause energy losses in the conversion of electrical energy to the storage medium—chemical, potential, or mechanical energy, depending on the type of storage used—and from the storage medium back into electricity. The **storage roundtrip efficiency** is the product of the input and output efficiencies, and indicates the magnitude of total energy losses in the storage process. For instance, a storage system with an input efficiency of 80% and an output efficiency of 75% will have a roundtrip efficiency of (80% × 75% =) 60%, meaning that only 60% of the energy input to storage will ultimately be available to meet demand. The main effect of lower roundtrip efficiencies is to increase the required renewable plant size, regardless of the specific mix of input and output efficiencies chosen. However, the input and output efficiencies differ in their effects on the required storage capacity.

A lower input efficiency should have little effect on the required storage capacity, though it will certainly increase the generating plant size. The storage system is “blind” to energy losses incurred in the input conversion process, since all the heavy lifting is performed by the renewable generation plant. The output efficiency, by comparison, has a much greater effect on storage capacity, since the storage system must contain sufficient energy to overcome losses in the output conversion process. For example, consider the storage system with the 80% input and 75% output efficiencies mentioned above: the renewable plant must be sized to compensate for the 40% loss in all energy that passes through the storage system, but the storage system itself must be sized to overcome only the 25% loss at its output. Both the renewable plant size and storage capacity will therefore rise proportional to the *inverse* of the storage efficiency, the former to the roundtrip efficiency, and the latter to the output efficiency alone.

The default scenario for this work uses an input efficiency of 80% and an output efficiency of 60%, for a roundtrip efficiency of 48%. These figures are intended to represent an aggregation of various energy storage technologies, with none predominating outright. The mix would undoubtedly include existing pumped hydro installations, some compressed air, flow batteries, and fuel cells. It could also be viewed as a rough (and somewhat optimistic) estimate of the efficiencies of a continental electrolyzer/fuel cell system in a hydrogen economy using wind and solar energy for primary generation.

- The **input and output ratings** of the storage system represent the maximum amount of power that the storage system can sink and source respectively, in kWh/h. If the power at the storage input exceeds the input rating, the energy must be dumped. Likewise, if the instantaneous demand exceeds the output rating, the storage system will not be able to satisfy the entire demand. In this work, it is presumed that the storage system will be designed to cope with levels of energy supply and demand comfortably in excess of the maximum expected, and the input and output ratings will have no effect on the results. This is not necessarily a reasonable assumption: renewable generators, as mentioned above, will need to stockpile energy in the "good times" to see the system through climatic "droughts". During the good times, it is conceivable that the renewable input to storage will be many times greater than current demand levels. If so, the storage system may be required to sink electrical energy at rates of several terawatts, rivalling the peak electricity demand for the entire *world* in 2000 [62]. It is worth asking whether such a storage system could even be built. The situation is somewhat better at the storage output, which will never be required to supply energy in excess of peak demand, about 650 GWh/h in 2000. Even so, this implies that the generation capacity of the storage system alone would be comparable to the entire conventional electricity generating system.

- The **hourly loss** accounts for energy storage systems that experience losses in energy over time, such as the boil-off of liquefied-hydrogen, or evaporation of water in dams, or pressure losses in compressed-air storage. This parameter expresses these losses as the percentage degradation in storage capacity per hour, but has been set to zero for the entirety of this work, for the sake of simplicity. If implemented, it would result in marginal increases in the required storage capacity and renewable plant size.

- The **minimum storage level** is the only storage parameter new to this work. Many storage systems suffer damage or loss of function if the storage level drops below a certain level. For example, many lead-acid batteries suffer permanent damage if allowed to drop below 20% capacity. Similarly, many pumped-hydro systems lose effectiveness at low hydraulic heads. It may also be desirable to maintain a certain minimum storage level to cover long outages or other emergencies. This parameter therefore adds another realistic touch to the modelling of storage systems. In this work, the minimum storage level for the continent-wide aggregated storage system was set at 25%.

- The **starting storage level** gives the storage level at the outset of the modelling interval. In this work, the starting storage level was universally set at 50%.

One of the strengths of the IESVic ESM is in its modelling of storage technologies as black boxes with generic parameters. This feature makes it possible to model a wider variety of storage technologies than is possible with models that contain “pre-modelled” storage, and to investigate the effects of varying one or more storage parameters.

7. Modelling Methodology and Constraints

The IESVic ESM's energy balance equations are the core of the modelling process used in this work, but a single set of raw model results is not particularly useful by itself; there must exist a metric by which each set of results can be measured. For each run, the model outputs a number of time-series MATLAB vectors: the raw energy balance given in Equation 2 (*BalanceBeforeStorage*), the final energy balance calculated by Equation 5 and Equation 7 (*Balance*), the storage level (*Storage*), and the renewable plant outputs (*SolarOutput* and *WindOutput*). These model outputs may just as easily describe an infeasible plant as a feasible one, and the results must be constrained to produce only the latter. Not only must the model results be constrained, but they also must provide a means by which disparate technology combinations (under the influence of a variety of input parameters) can be compared. This chapter describes the development of the methodology used to achieve these goals.

7.1 Constraint on Unserved Hours

The objective of the modelling performed in this work is to find the particular combinations of renewable plant size and storage capacity that will satisfy nine or ten consecutive years of US electrical demand, given specific renewable flux inputs. The first step, therefore, is to find the general relationship between plant size and storage; that is, how does storage capacity respond to a change in plant size? In order to answer this question, another must be asked: What is the optimal storage capacity for any given plant size? For the Race Rocks project, Niet developed an optimization process based on the number of unserved hours that the system experiences during the modelled time period [29]. Unserved hours (or "brownout" hours, as Niet called them) are those periods in which the combined output of the renewable plant and storage capacity fail to meet the electrical demand; in unserved hours, the system may continue to satisfy most of the demand (or none of it), but it nonetheless fails to perform adequately. For instance, an unserved hour would occur when the electrical demand was 1,000 MW, and the combined output of the renewable plant and the storage facility was 950 MW. Presumably, conventional backup generation would be available to meet demand during unserved hours.

In the IESVic ESM, unserved hours are those elements of the *Balance* vector that are negative; these occur when the storage drops below its minimum level or when the storage cannot supply energy at the rate demanded. In this work, only the former condition applies, since the storage is presumed to have a sufficient output rating to meet all levels of demand.

For the Race Rocks project, Niet modelled a single year at a time, set the unserved hours constraint to a range of one to five hours, and used an iterative binary search program to run the model until it converged at a result that met the constraint. The basic structure of the program's algorithm is as follows:

- The user inputs initial upper and lower bounds for the storage capacity. The storage capacity input parameter (the initial guess) for the first run of the model is the mean of these bounds.

- At the end of the first run, the program counts the number of unserved hours. If the number of unserved hours exceeds the maximum (i.e. the storage is undersized), the guess becomes the new lower bound. If the number of unserved hours is less than the minimum, storage is oversized, and the guess becomes the new upper bound. Either way, the interval between the new bounds is half the size of that in the previous iteration, and the new guess is the mean of the new bounds.

- If the number of unserved hours falls between the constraints, the program returns the plant size/storage capacity combination and terminates. Otherwise, the model runs again with the new guess as the storage capacity input parameter.

As long as the initial bounds are set such that the correct storage capacity lies somewhere between them, the above algorithm will converge. Figure 12 shows the characteristic relationship between renewable plant size and storage capacity. This particular figure shows the relationships for some wind plants, but the basic shape of the curve is similar for all renewable technologies modelled. At smaller plant sizes, the required storage capacity is very large, often equivalent to several years of electrical demand. As the plant size increases, the storage capacity drops steeply and almost linearly, then transitions to another, much flatter, near-linear regime. Before the “knee” of the curve, a small increase in plant size yields a large decrease in storage capacity; after the knee, the storage capacity drops very slowly as plant size increases.

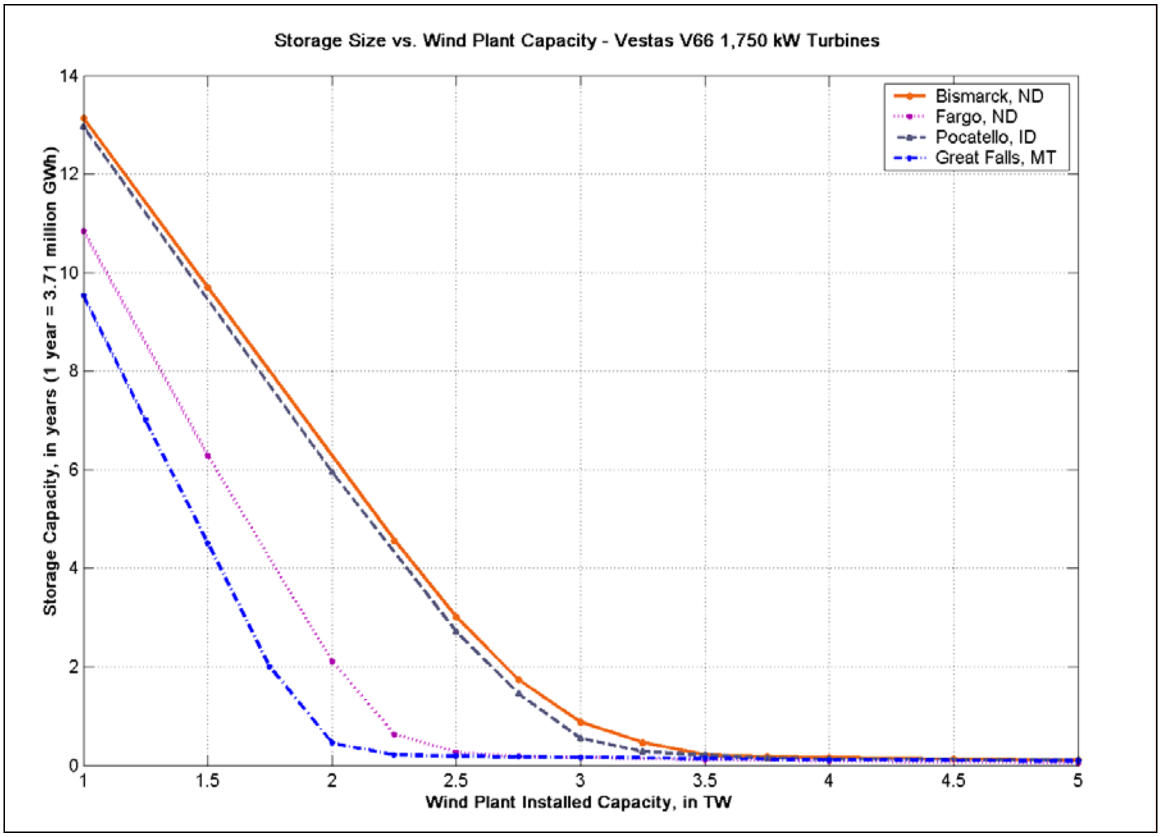


Figure 12: The characteristic relationship between plant size and storage capacity. This relationship is defined by constraining the number of unserved hours.

7.2 *Interpretation of the Plant Size/Storage Capacity Relationship*

It is tempting to use the relationship presented in Figure 12 to find an "optimal" combination of plant size and storage capacity, perhaps based on the relative costs of the technologies involved or on the land area available. This would be a mistake, since not all combinations on any given curve are equally functional—model convergence is no guarantee of satisfactory performance, as we will see. Furthermore, there is the problem of comparing the curves for different technologies, locations, or input parameters: each curve will have a different range, slope and knee, but how to define the relative performance of each? From Figure 12, it is easy to see that Great Falls performs better than Bismarck, but how much better is it? How much of an improvement can be obtained by improving storage efficiencies? What points on the curves are suitable for making comparisons? The answers to these questions form the core of the methodology used to assess results in this work: an extension of Niet's algorithm to one that finds the precise points on the curves where disparate technologies—working under a wide variety of input conditions—have identical performance characteristics.

In order to describe this solution, it is necessary to take a closer look at the relationship between plant size and storage, as output by Niet's binary search algorithm described above. Figure 13 illustrates some features of this relationship, and helps to explain why it is not sufficient to pick an optimal combination based on the curve alone. The curve denotes the set of plant size/storage combinations that meets the unserved hours constraint, but also demarcates between the set of combinations that can satisfy demand—at least for the duration of the period modelled—and the set that fails to do so. The set of failures lies below the curve, and comprises undersized combinations of plant size and storage capacity; that is, they result in unserved hours in excess of the maximum constraint. Above the curve, storage capacities are oversized (that is, the number of unserved hours is less than the minimum constraint) but the extra storage capacity does not affect the combination's ability to meet demand. This work is concerned only with those combinations of plant size and storage capacity that lie **on** the curve, but it is worth pointing out that combinations in the regions above the curve (though oversized) are workable solutions, while those below the curve are not.

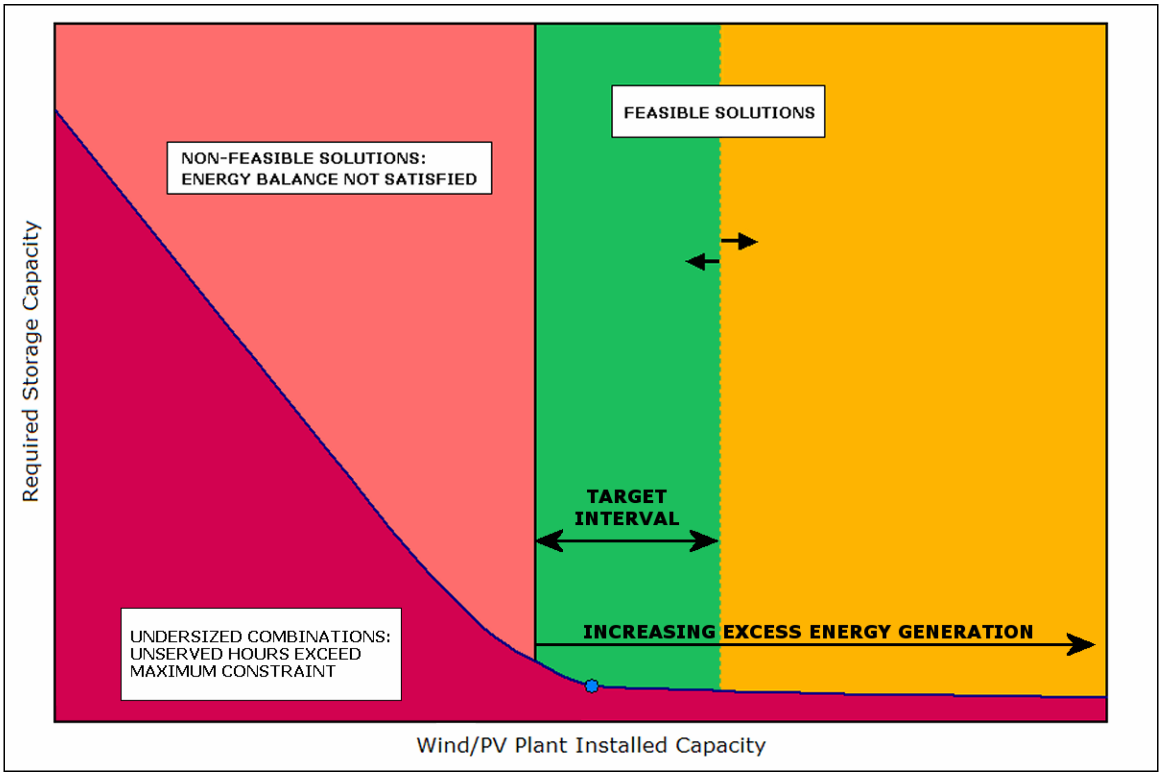


Figure 13: Storage capacity vs. plant size.
The regions in the illustration show the changing behaviour of renewable plant/storage combinations at different points along the "ski-slope" curve of storage size vs. plant capacity.

7.2.1 Energy Balance Relationships

The curve in Figure 13 is divided into two distinct sections: non-feasible solutions, for which the system is not capable of sustained operation beyond the period modelled, and feasible solutions. A feasible solution is one for which the storage level at the end of the modelled period equals or exceeds the storage level at the beginning, leaving enough energy in reserve for the system to continue to function indefinitely. In order to achieve this, the storage system must receive at least as much energy from the renewable plant as it sends out to meet demand. In other words, the renewable plant must be large enough to satisfy the aggregate system energy balance, defined as follows:

Equation 8

$$\sum Demand = \sum \left(DirectRenewableOutput + StorageOutput \right)$$

where:

DirectRenewableOutput is the portion of the renewable plant output that goes directly to satisfying demand without passing through storage;
StorageOutput is the energy output from the storage system required to meet demand when the direct renewable output is insufficient.

To ensure that the storage level at the end of the modelling is at least equal to the beginning storage level, the following inequality must be satisfied:

Equation 9

$$\sum StorageOutput \leq \eta_{STORAGE} \cdot \sum RenewableInputToStorage$$

where:

$\eta_{STORAGE}$ is the roundtrip efficiency of the storage system;
RenewableInputToStorage is the portion of the renewable plant output put into storage when generation exceeds demand.

Substituting Equation 9 into Equation 8, the energy balance becomes an inequality with the right-hand side in terms of renewable energy generation and storage efficiency:

Equation 10

$$\sum Demand \leq \sum \left(DirectRenewableOutput + \eta_{STORAGE} \cdot RenewableInputToStorage \right)$$

Feasible systems will be those that satisfy the inequality in Equation 10. For any given roundtrip storage efficiency, the feasibility of a system (that is, its ability to meet demand without depleting storage) depends primarily on the amount of renewable generation available. Figure 14 illustrates the interactions between renewable supply, electricity demand, and storage.

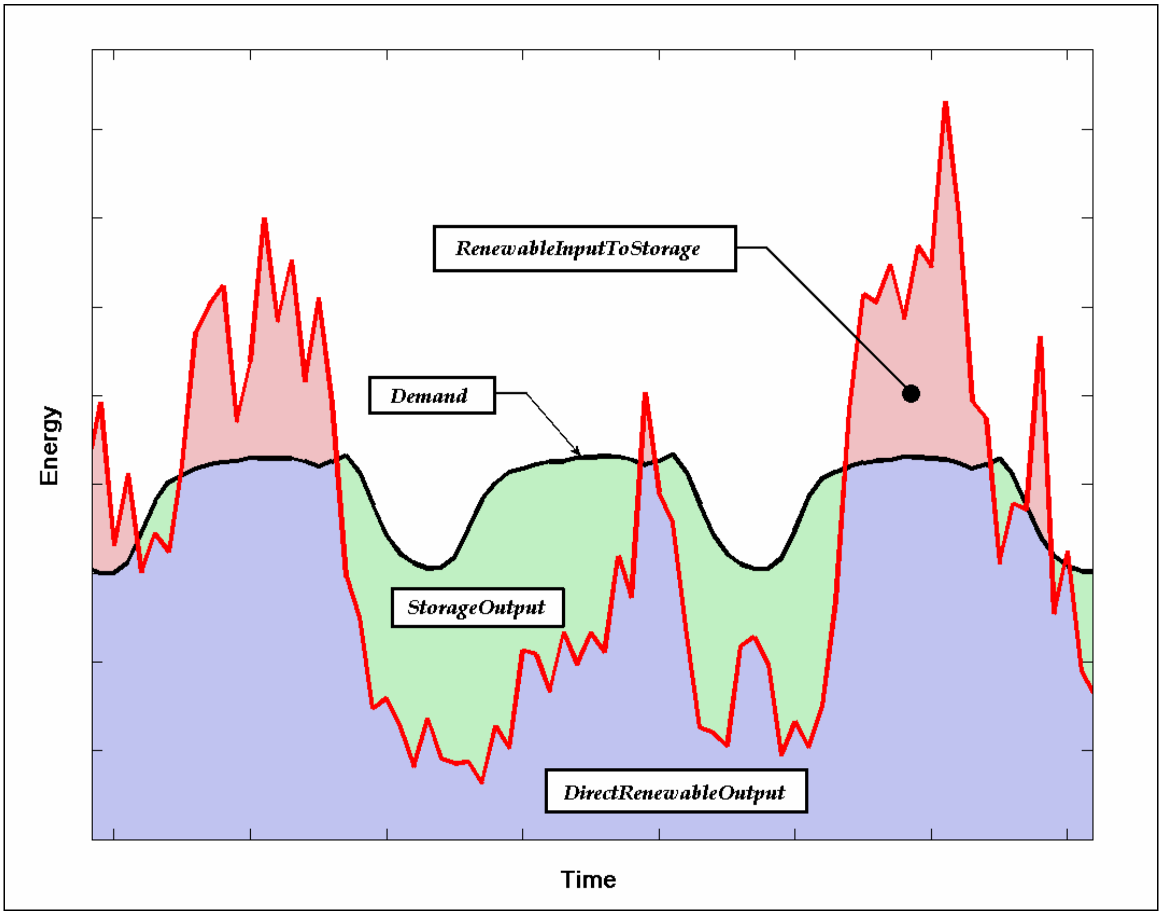


Figure 14: Illustration of the terms of the energy balance equation

7.2.2 Non-Feasible Systems

The distribution of the renewable plant's output between *DirectRenewableOutput* and *RenewableInputToStorage* will, of course, vary according to the situation, but the plant must always be large enough to satisfy the above inequality. A renewable plant too small to satisfy Equation 10 would need to rely on storage to make up for insufficient generation, causing storage levels to fall over the course of the period modelled. Such a combination may "work"—that is, it may satisfy the modelling constraints—but it hardly augurs well for the future if storage is exhausted at the end of the period modelled. This situation occurs in the region labelled **non-feasible**, which encompasses most of the initial, steeply declining section of the curve in Figure 13. In this region, the minimum storage capacities are very large because the storage system is acting as a co-generator (rather than a temporary repository) to make up for inadequately sized renewable generation.

Figure 15 is a typical time-series chart of storage level for the non-feasible region. As shown, the storage declines almost monotonically over the period modelled, with only minor deviations from the downward progression, representing small recharging spells. By the end of the modelled period, the storage system is near depletion. The storage contains an enormous amount of energy in reserve at the beginning, and gradually exhausts it in order to satisfy demand. No systems within this region are sustainable, since the storage will always be near empty by the end. All combinations falling within this region must therefore be excluded from the final set of results, placing an absolute lower bound on the range of acceptable results.

7.2.3 Feasible Systems

The region of **feasible solutions** in Figure 13 is subdivided into two sections: a “target interval” and a region of “excess energy production”, to be defined below. The boundary between these two sections reflects an arbitrary distinction rather than the absolute ones of the preceding sections. By definition, all renewable plants within this region satisfy the energy balance, and the modelling process is guaranteed to yield a “workable” result—a system that will continue to operate indefinitely. However, the basic problem remains: which point to choose on the remaining section of the curve? The non-feasible results have been excluded from the solution set, but the range of possible combinations remaining is still too large to allow precise comparisons between spatially and technologically disparate systems.

As renewable plant size increases, both *RenewableInputToStorage* and *DirectRenewableOutput* will become larger in relation to *Demand*, but the former will increase more rapidly. As a thought experiment, imagine that the renewable generation line in Figure 14 moves upwards (approximating increased renewable output). The areas covered by *DirectRenewableOutput* and *RenewableInputToStorage* would increase, while that of *StorageOutput* would decrease, resulting in a net energy gain to storage. At a certain point (which will vary for each different system), the storage level will reach 100% and the storage system will be unable to accept any more energy from the renewable plant. Any further increases in renewable plant size will result in increasing quantities of energy that cannot be accepted by the storage system.

In large systems such as the ones modelled in this work, the presence of excess energy presents a challenge: in the absence of willing export markets, the excess energy must be dumped (perhaps through resistive heating) or the renewable plant shut down until the storage system can accept energy again.

In terms of the ESM output, the total excess energy generation is the sum of all positive non-zero elements of the *Balance* vector. Recall that *Balance* records each hour's final energy surplus or deficit after the storage calculations have been made, and that the model attempts to drive each hour's balance to zero. In this work, the total excess energy generation is expressed as a fraction of the total electricity demand over the period modelled.

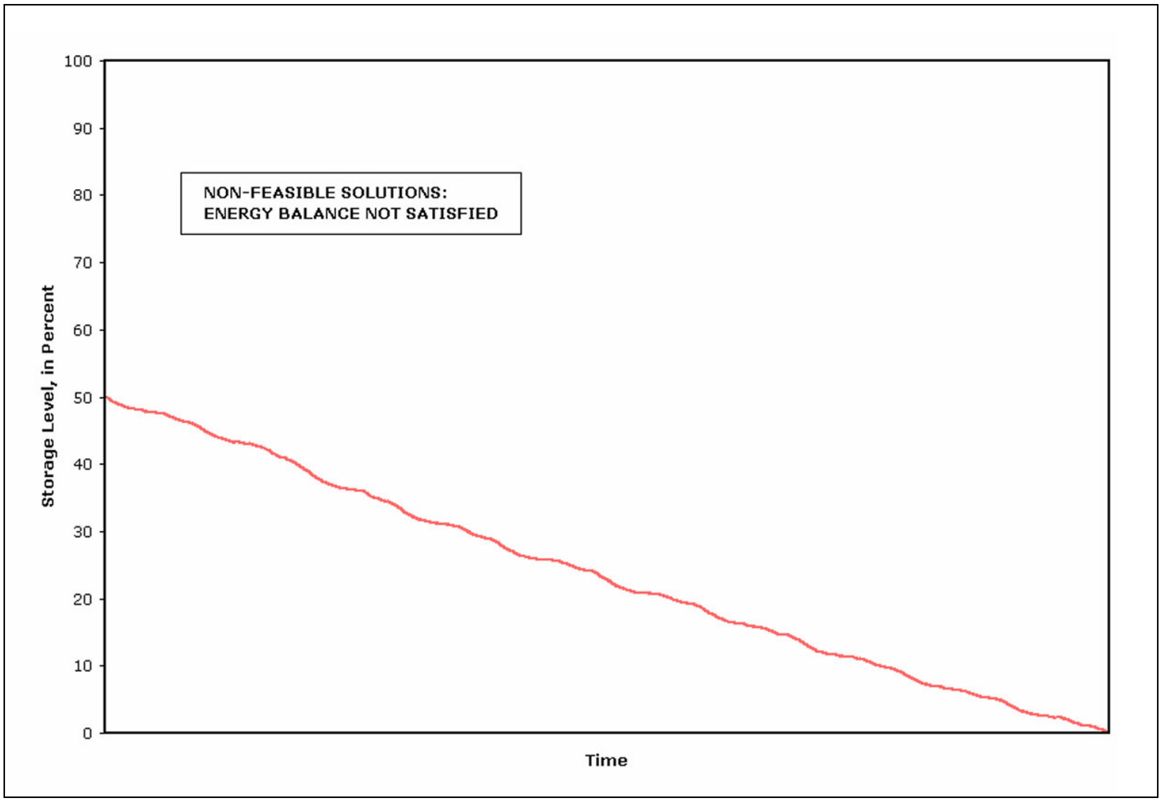


Figure 15: Storage level over time when the energy balance is not satisfied

Figure 13 shows the boundary between feasible and non-feasible systems, and illustrates the growth in excess energy production as the renewable plant size increases beyond the point where the energy balance is satisfied. In the non-feasible region, storage never saturates, and the excess energy production is zero. In the feasible region, the storage system begins to experience saturation shortly after the energy balance is satisfied, and excess energy production grows steadily thereafter. This is an important point for the purposes of this work: excess energy is generated only *within* the feasible region, and it rises steadily as plant size increases. This behaviour is independent of generation technology, storage efficiency, location, or any other parameter used in this modelling.

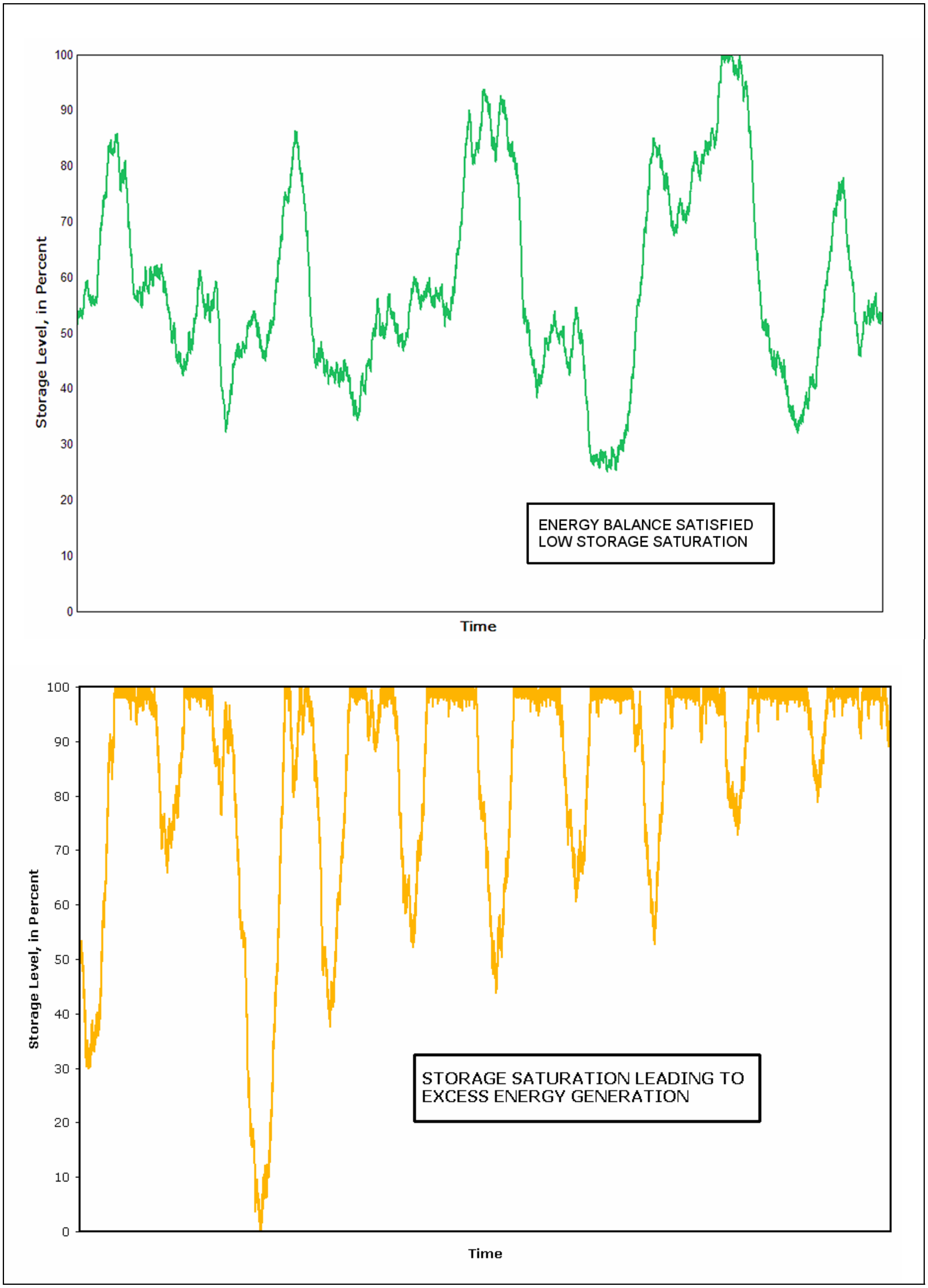


Figure 16: Changes in storage behaviour as plant size increases, leading to excess energy production.

The time series charts of storage levels shown in Figure 16 are characteristic of those systems that experience excess energy production. The storage system saturates early and stays near-full for the bulk of the period modelled.

7.2.4 Constraining Excess Energy Generation

There is no theoretical reason to prefer one particular level of excess energy generation to another; the decision is—for the purposes of the modelling presented here—essentially an arbitrary one. The importance of excess energy lies in its potential to allow comparisons across disparate generating technologies, locations, or input parameters. It is now possible to compare a Kansas wind plant with a Florida PV plant by constraining each to generate the same amount of excess energy. The effects of changes in various input parameters for a given renewable plant/storage combination can likewise be investigated by ensuring that each meets identical excess energy generation criteria.

The algorithm developed by Niet defined the characteristic relationship between renewable plant size and storage capacity by constraining unserved hours; in effect, Niet's binary search algorithm searches *vertically* on the chart in Figure 13, first fixing plant size then finding a storage capacity that yields appropriate results. An algorithm constraining excess energy, by comparison, searches *horizontally* along the curve defined by the first binary search, finding the precise location of the plant that works for a given excess energy constraint (the "target interval" in Figure 13). For each point along the curve, it first uses Niet's binary search to find the minimum storage capacity for a given plant size, then measures the excess energy production as a fraction of aggregate demand.

The structure of this algorithm has many commonalities with Niet's original binary search:

- The user inputs initial upper and lower bounds for the plant size in addition to the storage capacity bounds used in Niet's algorithm. The initial guesses for plant size (that is, the number of wind turbines and/or the PV panel area) and storage capacity parameters are the means of these bounds.

- The first binary search algorithm finds the minimum storage capacity for the given plant size, as described above.

- At the completion of the first binary search, the second algorithm checks the amount of excess energy produced. If the amount produced is less than the minimum constraint, the plant is undersized and the initial guess becomes the new lower bound. If the excess energy exceeds the maximum constraint, the plant size is too large and the initial guess becomes the new upper bound. In either case, the interval between the new bounds is half the size of that in the previous iteration, and the new guess is the mean of the new bounds.

- This new algorithm also makes use of the monotonic decrease in storage capacity as plant size increases. Thus, an excess energy amount above the maximum not only sets an upper bound on plant size but also a lower bound on storage capacity, and the converse also applies. With each iteration of the new algorithm, the ranges of both plant size and storage capacity are reduced, thereby speeding the search.

If the amount of excess energy generation falls between the constraints, the program returns the plant size/storage capacity combination and terminates. Otherwise, the model runs again with the new guesses as the plant size and storage capacity input parameters. The flowchart for this new algorithm is shown in Figure 17.

In Figure 13, the target interval is shown with its lower bound at the boundary between non-feasible and feasible systems; that is, the minimum constraint on excess energy production is zero. This reflects the methodology used in this work, where the constraints on excess energy generation were set between 0 – 1% of aggregate demand. However, there is no reason, in principle, for either of these boundaries to be set where they are; the excess energy constraints could just as easily be set at (say) 20 – 25% of demand, or 63 – 66%. The relative sensitivities of the plant size and storage capacity to increasing levels of excess energy generation will be described in this work.

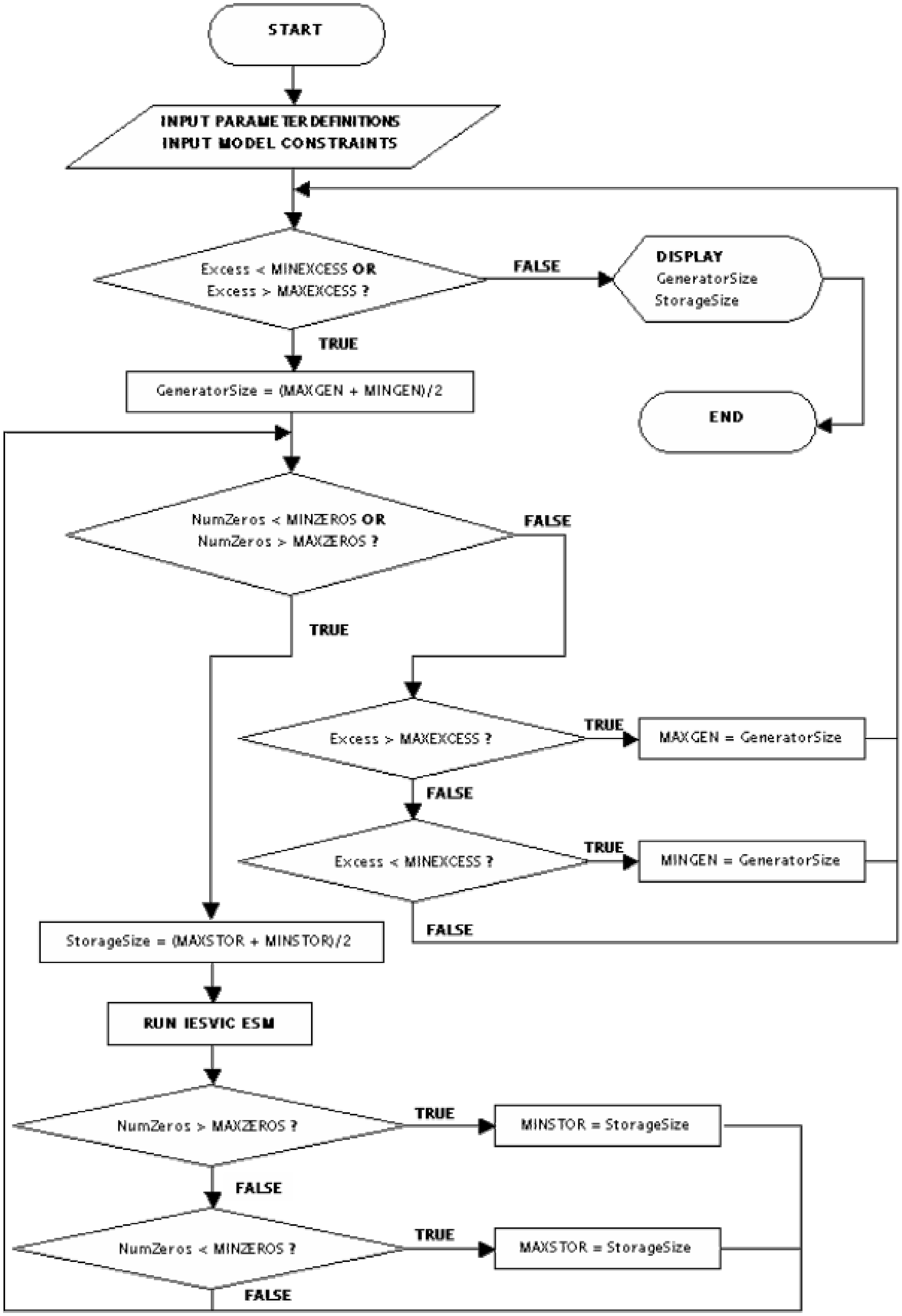


Figure 17: Flow chart of modelling algorithm

8. Results for Solar Photovoltaic Plants

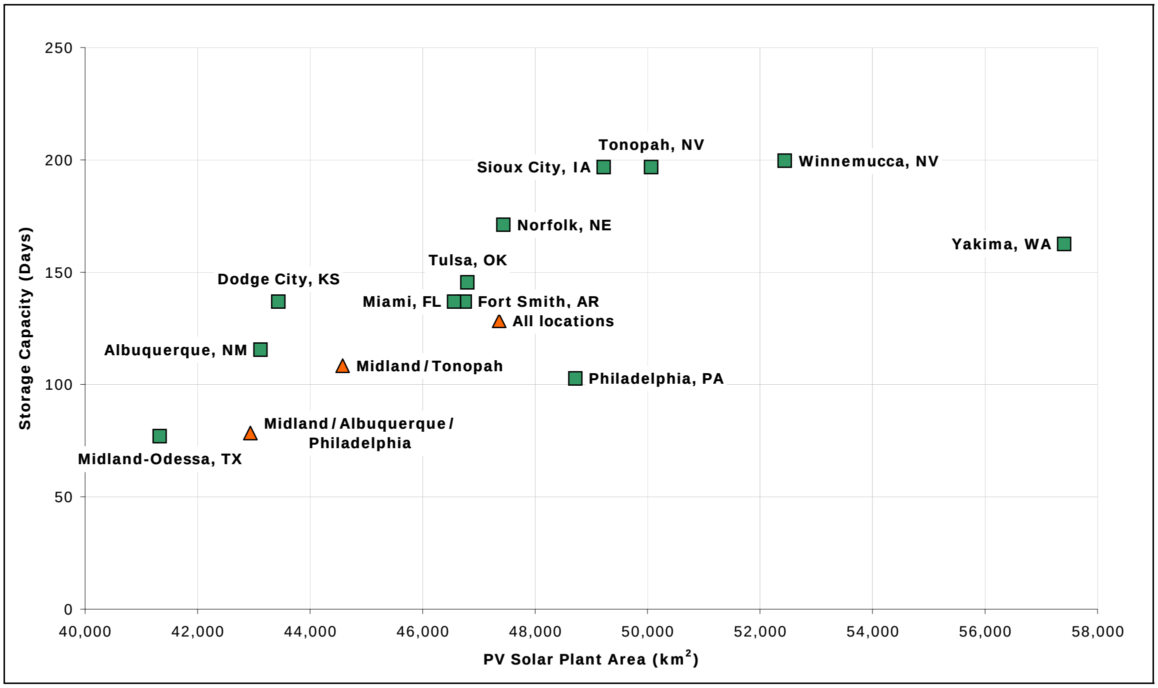


Figure 18: Results for modelling of photovoltaic plants by location.
Combined locations, where generation was shared by two or more locations, are displayed as triangles. Seattle is not shown, due to its large plant size and storage capacity.

The results for the modelling of solar photovoltaic plants are shown in Figure 18 and Table 4. The square data points in Figure 18 represent single locations, while triangles denote combined locations. The storage size is given in days, where one day's storage is equivalent to one day's average US demand (10.04 TWh). To give an idea of the scale of this storage requirement, a one-gigawatt power plant operating continuously generates 0.024 TWh of electricity in one day; more than 418 such plants would be required to generate energy equivalent to one day's storage. None of the modelled PV plants required less than 77 days' storage, and most required much more. The scale of storage required exceeds anything yet devised by several orders of magnitude, but such a system is required in order to meet energy service demands.

	Nominal Capacity (TW)	PV Area (km^2)	Plant Area (km^2)	Storage Capacity (days)
Single Locations				
Midland-Odessa, TX	2.93	20,664	41,328	77
Albuquerque, NM	3.05	21,559	43,117	115
Dodge City, KS	3.08	21,719	43,438	137
Miami, FL	3.30	23,281	46,563	137
Fort Smith, AR	3.31	23,375	46,750	137
Tulsa, OK	3.31	23,398	46,797	145
Norfolk, NE	3.36	23,719	47,438	171
Philadelphia, PA	3.45	24,359	48,719	103
Sioux City, IA	3.48	24,609	49,219	197
Tonopah, NV	3.54	25,031	50,063	197
Winnemucca, NV	3.71	26,219	52,438	200
Yakima, WA	4.06	28,703	57,406	163
Seattle, WA	5.09	35,969	71,938	265
Combined Locations				
Midland/Albuquerque	2.96	20,904	41,808	88
Midland/Albuquerque/Philadelphia	3.04	21,469	42,938	78
Midland/Tonopah	3.16	22,290	44,580	108
All 13 Locations	3.35	23,682	47,363	128

Table 4: PV results for all locations, sorted by plant area requirements

Of the thirteen single PV locations modelled, Midland-Odessa, Texas performed best, with a plant area of 41,328 km^2 (equivalent to a square 203 km on a side) and a required storage size of 77 days. It outperformed Albuquerque decisively, although the latter was the location with the highest average daytime insolation. More surprising is the amount by which Midland's land area requirements are smaller than those of Tonopah and Winnemucca, even though Midland's average insolation is only slightly higher (see Figure 7). The Nevada locations are almost twice the size predicted by Turner [11]: 50,063 km^2 and 52,438 km^2 for Tonopah and Winnemucca respectively. What is more, each requires about 200 days' storage—the highest storage figures among all modelled locations excluding Seattle, and almost three times the storage capacity required for Midland.

On the other hand, Philadelphia's performance was much better than expected. With a plant area of 48,719 km^2 and 103 days' storage, it performs better than the Nevada locations, despite having the second-lowest insolation of the locations modelled.

The nominal plant output capacity is directly proportional to the plant area, but it is worth noting that the smallest single PV plant (Midland) had an output capacity of 2.9 TW, 3.6 times the magnitude of the entire generation capacity of the US electrical system in 2000—to meet the exact same demand. In addition, the average power density of the PV generating plants ranged between 10 – 16 $W \cdot m^{-2}$, well below the 1 – 2 $kW \cdot m^{-2}$ characteristic of coal and nuclear power plants [10]. Compared to conventional electricity generation technologies, photovoltaic plants require several times more power output capacity and land area to produce a given amount of electricity, even before storage requirements are taken into account.

As for the combined locations, it appears that there are few technical gains to be had by producing electricity from more than one PV location simultaneously, although any real-world large-scale solar energy system would require a large degree of decentralization in practice. Midland requires a smaller plant area and storage capacity than any of the combined locations, although the Midland/Albuquerque and Midland/Albuquerque/Philadelphia combinations come close to matching its performance.

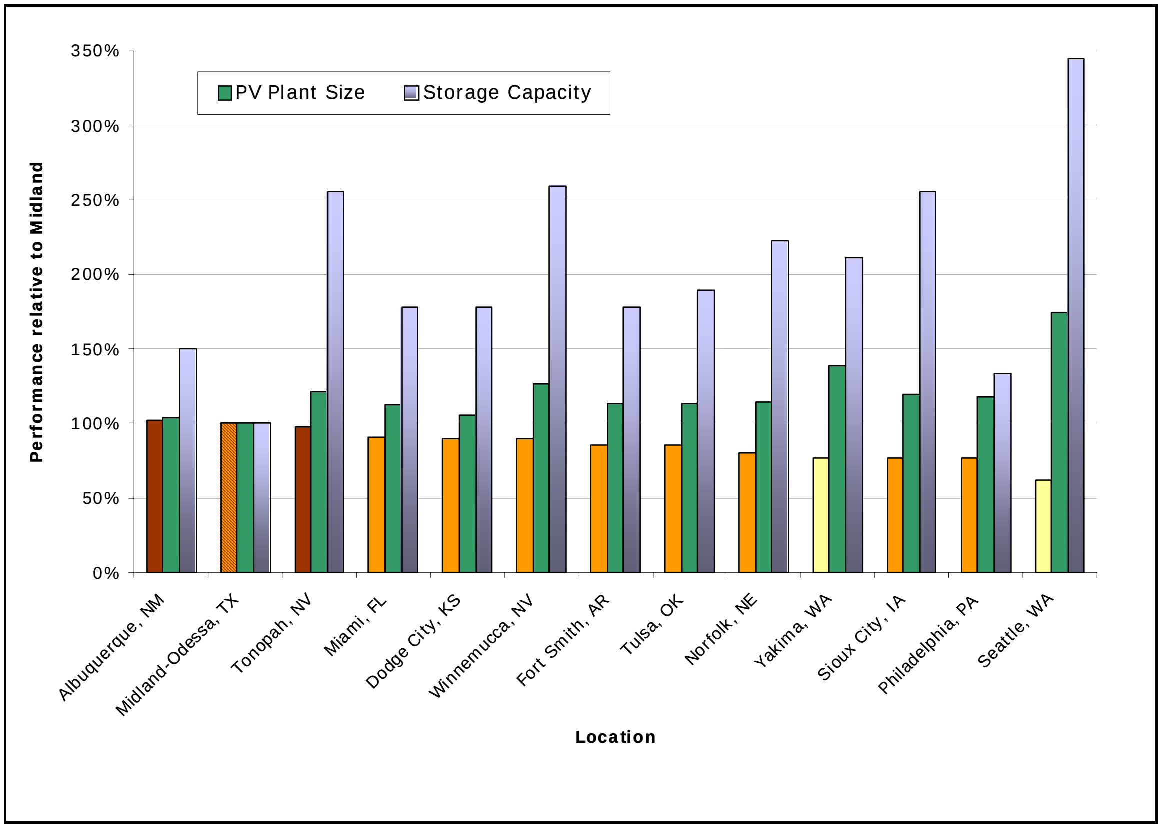


Figure 19: PV results for single locations.
The leftmost bar for each location is its average daytime insolation. All results are normalized to Midland-Odessa = 100%.

Figure 19 compares each location's average daytime insolation, PV plant size, and storage capacity requirement with that for Midland-Odessa, which is set at 100% for all three parameters. The locations are sorted left-to-right in decreasing order of average daytime insolation. There are a number of interesting things to note about Figure 19:

- Storage capacity requirements are far more variable than plant area requirements. The maximum storage capacity required is 200 days (not including Seattle), 160% larger than Midland's 77 days. In comparison, the largest plant area is only 40% larger than the smallest.

- There is no clear tendency for PV plant area to increase with decreasing levels of insolation. Miami, Dodge City, Fort Smith, Tulsa, Norfolk, Sioux

City and Philadelphia all require less plant area than Tonopah, despite its location in the highest insolation region in the United States. Seattle, with the lowest levels of insolation, does have the highest plant area and storage requirements, but Philadelphia—with the second-lowest insolation—outperforms both Nevada locations.

- Storage requirements *do* appear to increase with lower levels of insolation, though this relationship is by no means consistent. Midland has lower insolation than Albuquerque, but requires a smaller plant area and a lower storage capacity. The Nevada locations have high insolation but very large storage requirements. And Philadelphia, as before, has very low insolation but the second lowest storage capacity of all.

- The high-ELCC locations do not, in general, perform noticeably better than the high-insolation locations. However, the ELCC solar atlas in Figure 6 was devised on the basis of *local* electrical demand data for each region, not overall US demand; that is, the Midwestern states were determined to have high ELCC based on data from Midwestern utilities. Using the total US demand (weighted heavily to the East Coast, where the population and industrial density is highest) may shift the location of daily demand peaks, perhaps lowering the ELCC for those locations situated further from demand concentrations. This may help to explain Philadelphia's surprisingly good performance. The low-insolation city is a high-ELCC location in the midst of the highest population and industrial density in the United States, and its high performance may reflect the weighting of the demand.

	Storage Capacity (days)	Storage Output Utilization (%)	Peak Storage Output (GW)
Single Locations			
Midland-Odessa, TX	77	61.7%	597.2
Albuquerque, NM	115	65.1%	616.8
Dodge City, KS	137	61.7%	597.2
Miami, FL	137	58.9%	616.8
Fort Smith, AR	137	61.1%	616.8
Tulsa, OK	145	61.2%	600.4
Norfolk, NE	171	61.6%	597.2
Philadelphia, PA	103	59.0%	616.8
Sioux City, IA	197	61.7%	597.2
Tonopah, NV	197	68.6%	616.8
Winnemucca, NV	200	68.6%	616.8
Yakima, WA	163	68.9%	597.2
Seattle, WA	265	70.1%	597.2
Combined Locations			
Midland/Albuquerque	88	62.5%	597.2
Midland/Albuquerque/Philadelphia	78	59.7%	597.2
Midland/Tonopah	108	63.4%	597.2
All 13 Locations, evenly allocated	128	61.1%	597.2

Table 5: Selected storage characteristics for modelled PV locations

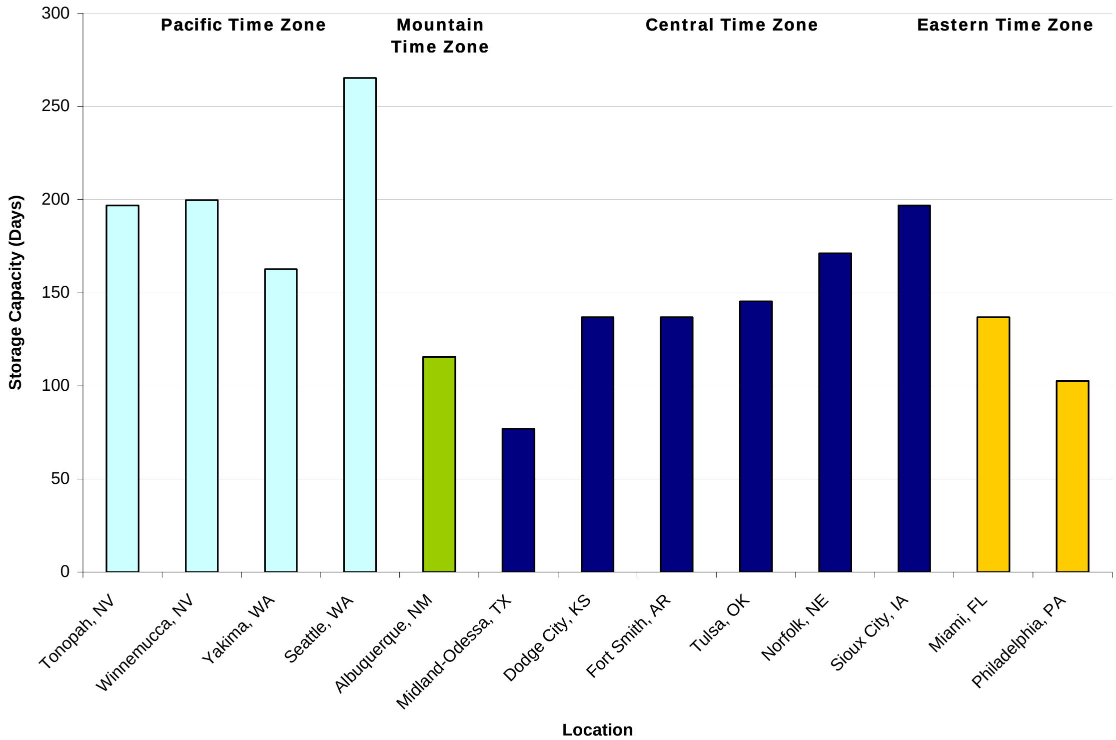
The storage capacities given in Table 4 are not the only measure of the size of the storage system. Table 5 displays some of the storage output characteristics for each modelled location. The storage utilization is the fraction of the total modelled time interval that the storage system must supply energy; in other words, the fraction of time that the PV system's output must be supplemented by energy drawn from storage. A location with a poor match between solar supply and electricity demand would make more use of storage than one with a good match, increasing its utilization percentage. All the modelled locations require storage at least 59% of the time, due to the absence of PV generation during the night hours. The peak storage output is the maximum power output required of the storage system over the period modelled, and will be described in more detail below.

Figure 20 provides further support for the hypothesis that PV plant performance is more dependent on load matching than on insolation levels. The locations are sorted into time zones: four Pacific Time (Tonopah, Winnemucca, Yakima, Seattle), one Mountain Time (Albuquerque), six Central Time (Midland-Odessa, Dodge City, Fort Smith, Tulsa, Norfolk, Sioux City), and two Eastern Time (Philadelphia and Miami). Within each time zone, the locations are sorted left to right from the highest insolation to the lowest. Two things stand out in the data presented in Figure 20:

- Within each time zone, there is a clear tendency for plant area and storage capacity to increase as average insolation decreases. Plant area increases monotonically with decreasing insolation. Storage also tends to increase, although Yakima and Philadelphia are exceptions. There are too few locations in the Mountain and Eastern time zones to draw any firm conclusions, but the trends are quite clear in the Pacific and Central time zones.

- Both plant areas and storage capacities appear to vary more across time zones than within them. The Pacific locations are almost uniformly larger than the Central locations, both in plant area and storage capacity, and these are in turn predominantly larger than the Eastern locations.

The storage output utilization is shown in Figure 21, below. The Eastern locations make the least use of storage, and the Pacific locations the most, with the Mountain and Central time zones in between. Within each time zone the storage utilization is relatively uniform, and there is little correlation between storage utilization and insolation levels. Once more, there is more variation across time zones than within them.



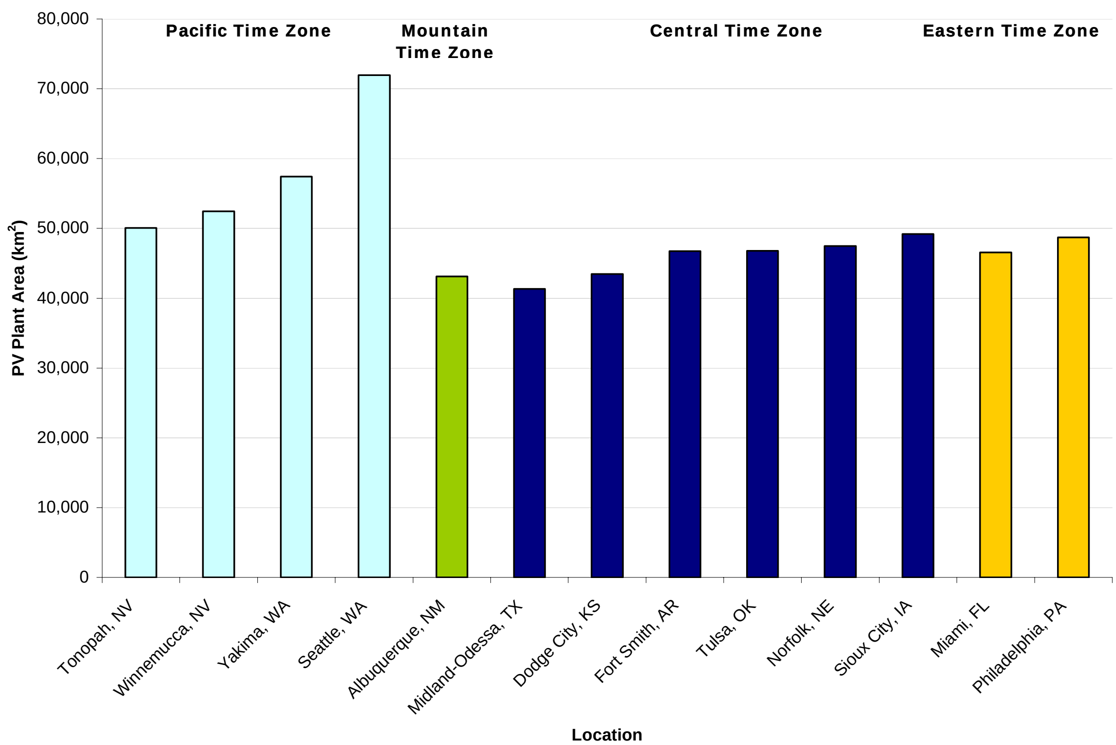


Figure 20: PV Plant area and storage capacity results.
The charts are ordered left to right, first by time zone (with a different bar colour for each zone), then by declining average solar insolation.

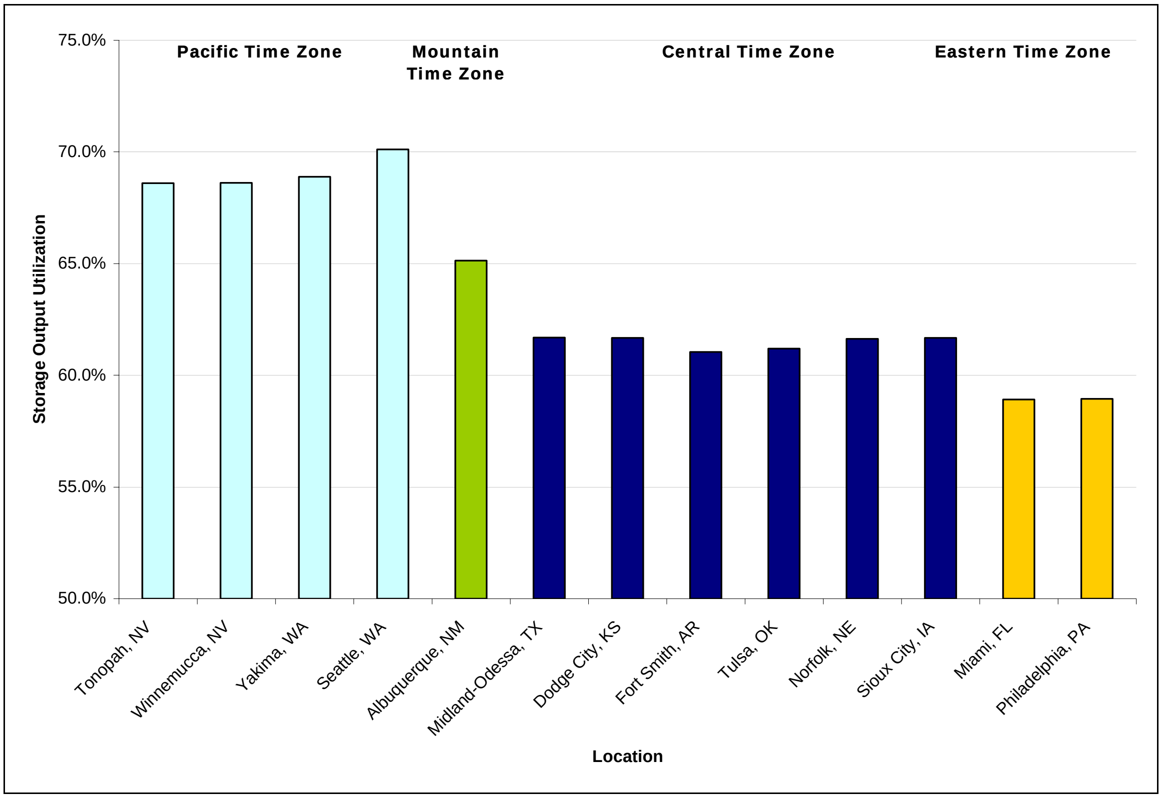


Figure 21: Storage output utilization, ordered by time zone, then by average insolation levels.

It appears, then, that load matching is indeed a crucial consideration to take into account when designing a solar plant. However, it would be useful to model other locations in the Mountain and Eastern time zones before drawing firmer conclusions. It would also be interesting to model the Pacific, Mountain, and Central locations using local (non-time shifted) demands. Nevertheless, it appears that in choosing a location for a photovoltaic plant, load matching is more important than absolute insolation levels.

Figure 22: PV plant area required at 9 modelled locations to meet 2000 US electricity demand

Figure 22, above, is an illustration of the PV plant areas required at nine of the modelled locations. Although the plant areas are themselves very large, they are merely the most visible component of the system that must be put in place in order to meet the electricity service demands of the United States. There is also a very large storage system capable of providing electricity equivalent to between 77 and 265 days of total United States demand. How large would such a storage system be? Without knowing the specific mix of storage technologies to be used, it is impossible to say precisely, but some light can be shed on the question by investigating the output characteristics of the aggregated storage system.

An energy storage technology's storage capacity is analogous to a car's gas tank; its size determines the amount of energy that can be stored. By contrast, the storage system's power output capacity is analogous to a car's engine rating. If a car's engine output is insufficient, it doesn't matter how large the tank is; similarly, an energy storage system must be able to supply enough power to carry the system through the largest supply/demand imbalances it will encounter. Since the storage system will act as a supplemental (and parallel) generation system to the renewable technologies, it is worth investigating how much generation capacity will be required in addition to the renewables. This approach could also be used as a tentative measure of the conventional generation displaced by a given amount of renewable generation, or to optimize the mix of storage technologies used in a given renewables-based system. Less expensive storage technologies (such as pumped hydro or perhaps compressed-air) may be suited to "baseload" use, reserving the higher-cost technologies (perhaps flow batteries) for "peaking" operations.

Figure 23 shows a week's demand in late April 2000, along with the output of the Midland-Odessa PV plant (using climate data from late April, 1981) and the storage level. The figure illuminates the almost binary nature of solar energy-based generation technologies; when the sun is shining, the PV generation output can exceed demand by a factor of five or more, in order to fill storage to carry the system through the night hours. Note that the peak power output of the PV plant is often more than 2 TW in excess of demand, and that the storage system will therefore be required daily to sink an amount of electricity comparable to the peak electricity generation of the entire world in 2000.

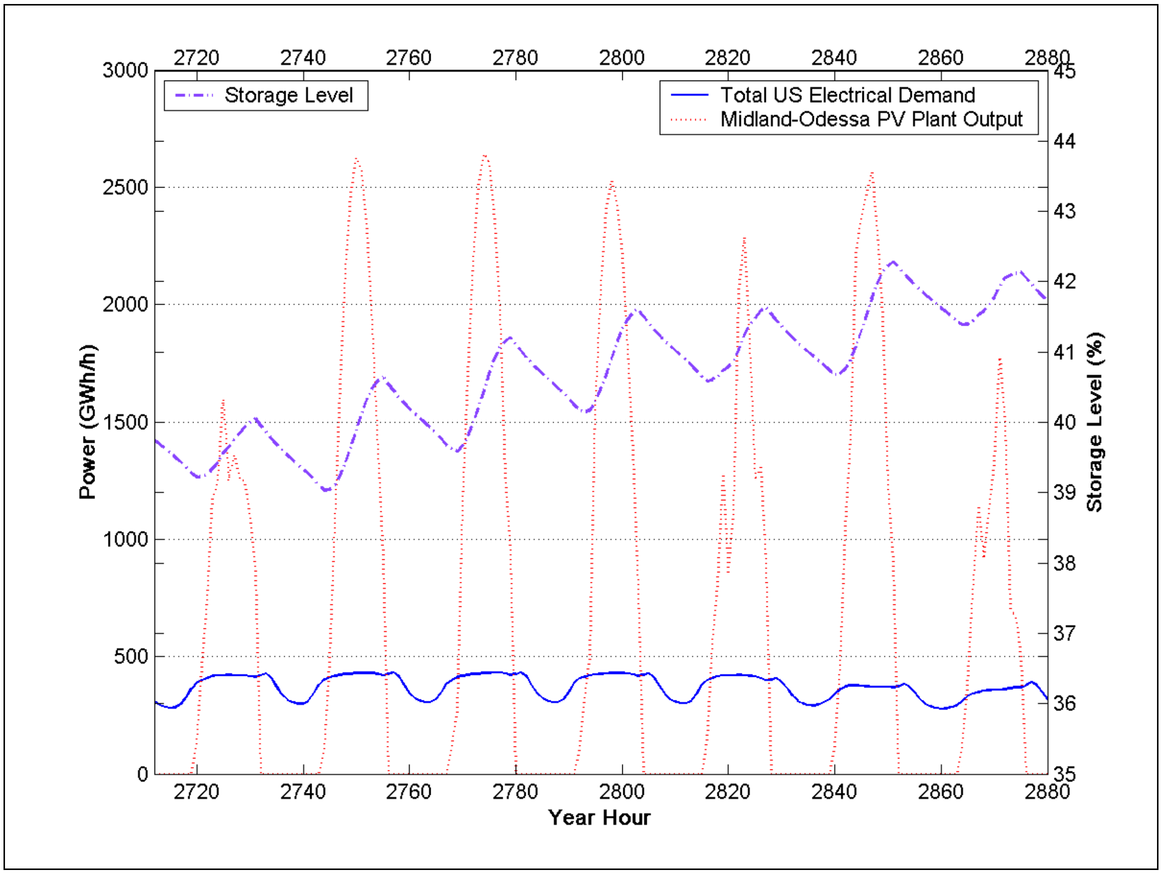


Figure 23: Midland generation, total US demand, and storage levels, 24-30 April 2000

Figure 24 shows the probability distributions of the storage output power that will be required for the modelled PV locations. The probability given on the vertical axis is the fraction of the total modelled time interval that the storage system will be required to supply energy at a given rate; for example, the storage system for Midland/Tonopah outputs at ~350 GWh/h for 0.09 of the modelled interval, or 7,884 hours. The peak output for each location is between 597-618 GWh/h; this magnitude of output is required only a few hours in each year, on average, but the storage system must be able to supply this amount of energy when required. In total, then, the storage system for a PV-based electricity system must be capable of outputting over 600 GW. This is about 74% of the generating capacity of the entire 2000 US electricity system (811 GW), in addition to the 3-5 TW (3,000-5,000 GW) of photovoltaic generating capacity required.

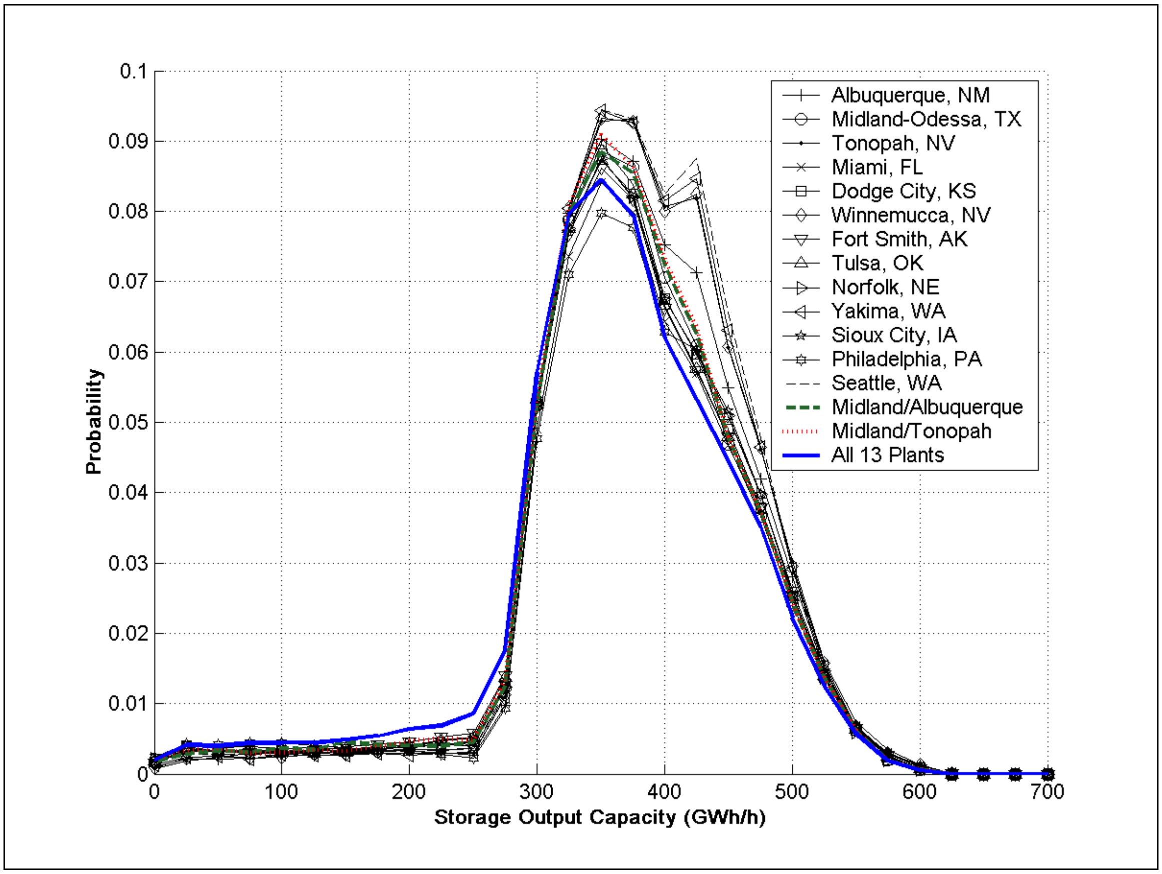


Figure 24: Probability distribution of storage capacity requirements for modelled PV locations

The distributions for the combined locations offer no substantial improvement over the single locations. Only the distribution for all 13 plants shows any improvement over the single locations, and that is a very small shift to the left of the distribution, effectively lowering the mean output power required. This effect can be more clearly seen in the survivor distribution shown in Figure 25, below.

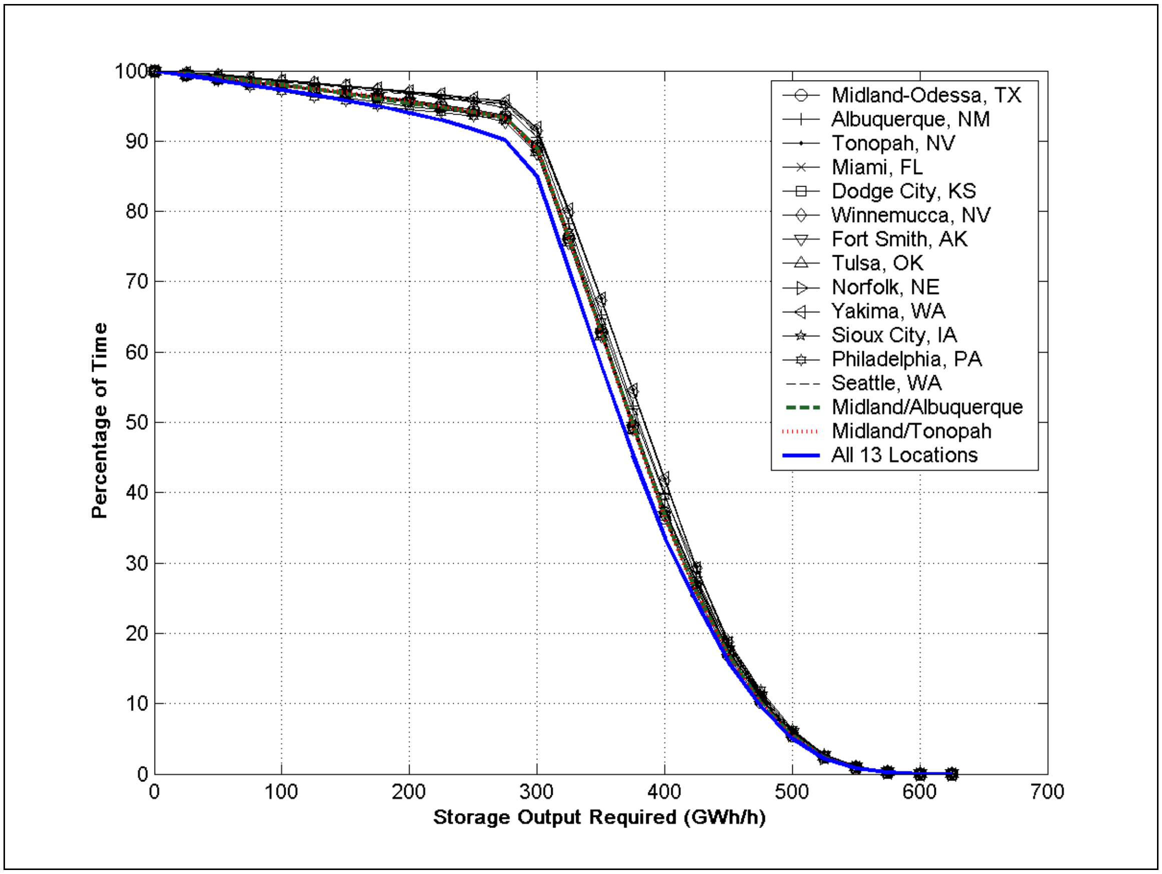


Figure 25: Survivor distribution for modelled PV locations

The survivor distribution assists in clarifying some characteristics of the power output required of the storage system. It shows the percentage of time that generation above a given level of storage output will be required; for the combination of all 13 locations, 90% of the storage output will be above 275 GWh/h. For all modelled PV locations, between 85 – 92% of the storage outputs will be in excess of 300 GWh/h, and 6 – 7% will be above 500 GWh/h. The great majority of the storage output will therefore be between these two figures, requiring a nighttime generation capacity roughly half the size of the conventional generating system in the year 2000. All other things being equal, a smaller average generation output requires smaller (or fewer) facilities and is less expensive than a larger output.

9. Results for Wind Plants

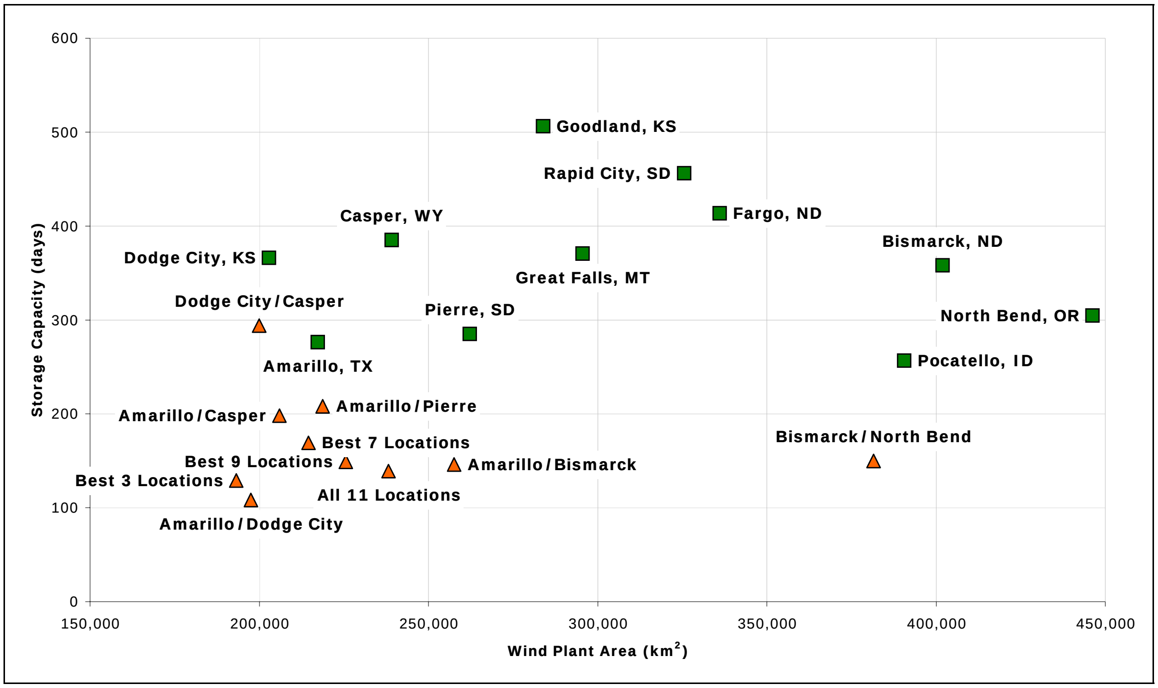


Figure 26: Results for modelling of wind plants by location

Figure 26, Figure 27, and Table 6 present the results for the modelling of a variety of single and combined wind locations. Figure 26 is similar to Figure 18, with the major exception that wind plants require approximately five times as much land area as PV plants to satisfy the US demand. PV plant areas ranged from 41,328 – 71,938 km^2, while single wind plant locations start at 202,887 km^2 and go up to 446,222 km^2. By way of comparison, the entire urbanized area of the contiguous United States in 2000 was about 241,000 km^2 [63]*. That is, the average wind plant modelled here would require a greater land area than all of the cities, suburbs, and towns in the lower 48 states. And as mentioned above, the wind plant areas given here are *minimum* figures.

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* This area includes the US Census Bureau classifications of Urban Areas and Urban Clusters, consisting of a core "block" with population densities of at least 1,000 people per square mile, and surrounding "blocks" with population densities exceeding 500 people per square mile.

	Nominal Capacity (TW)	Number of Wind Turbines	Plant Area (km2)	Storage Capacity (days)
Single Locations				
Dodge City, KS	1.27	816,406	202,887	366
Amarillo, TX	1.31	874,349	217,287	276
Casper, WY	1.44	962,240	239,129	385
Pierre, SD	1.58	1,055,013	262,184	285
Goodland, KS	1.71	1,142,293	283,874	506
Great Falls, MT	1.78	1,189,372	295,574	371
Rapid City, SD	1.97	1,309,977	325,546	456
Fargo, ND	2.03	1,352,295	336,062	413
Pocatello, ID	2.37	1,571,615	390,566	257
Bismarck, ND	2.43	1,617,188	401,891	358
North Bend, OR	2.69	1,795,573	446,222	305
Combined Locations				
Best 3 Locations	1.17	777,344	193,180	129
Amarillo/Dodge City	1.19	794,792	197,516	108
Dodge City/Casper	1.21	804,688	199,975	294
Best 5 Locations	1.24	825,521	205,152	133
Amarillo/Casper	1.24	828,776	205,961	198
Best 7 Locations	1.29	863,281	214,536	169
Amarillo/Pierre	1.32	880,208	218,743	208
Amarillo/Great Falls	1.36	906,250	225,214	121
Best 9 Locations	1.36	907,552	225,538	149
All 11 Locations	1.44	958,333	238,158	139
Amarillo/Pocatello	1.54	1,026,042	254,984	207
Amarillo/Bismarck	1.55	1,036,458	257,573	146
Amarillo/North Bend	1.62	1,079,427	268,251	198
Bismarck/North Bend	2.30	1,535,156	381,506	150

Table 6: Wind results for all locations, sorted by plant area requirements

Clearly, such sizes are infeasible for single wind farms; not only would these wind plants encroach upon cities, highways, wilderness areas, and agriculture, but it is unlikely that the wind regime would remain constant over the entire area of each plant. The assumption made here that the entire wind plant area experiences the wind regime measured at the local airport—ofte one of the more exposed places in any region—will tend to underestimate the plant area required, possibly by a very substantial amount.

Not only do all wind plants require greater land areas than their PV counterparts, but the single locations also require much larger storage capacities, ranging from 257-506 days, in contrast to the 77-265 days required for PV locations. Unlike sunlight, which is reliably present—if attenuated—even on cloudy days, wind can be very low or absent for periods of days or even weeks, placing greater demands on the storage system. Wind turbines perform poorly in low wind levels for two reasons: first, the turbine generates no power at all when the local wind speed is below the turbine's cut-in speed (3 m/s for the GE 1.5s turbine used in the modelling). Second, when the wind speed is between the cut-in speed and the rated speed (12 m/s for the 1.5s), turbine output is proportional to the cube of the wind speed, meaning that the turbine generates one-eighth as much power at, for example, 4 m/s as it does at 8 m/s. Since even the best wind locations experience prolonged periods of relatively low wind, the high storage capacities required are not surprising.

However, it turns out that there are substantial advantages to combining wind locations. In every case where two or more wind locations were combined, the storage capacity requirements for the combined locations were lower than for the locations by themselves. This can be seen in Figure 26, in which the lower portion (representing lower storage requirements) of the chart is entirely populated by combined locations, represented by triangular data points. Some combined locations, such as Amarillo/Dodge City, outperform their constituent locations in both plant area and storage capacity requirements. There are even advantages to pairing high-wind locations such as Amarillo (Class 5 winds) with individually unsuitable locations such as North Bend (Class 2); the resulting combination reduces North Bend's required storage capacity by 107 days, while lowering its area requirements by 40%.

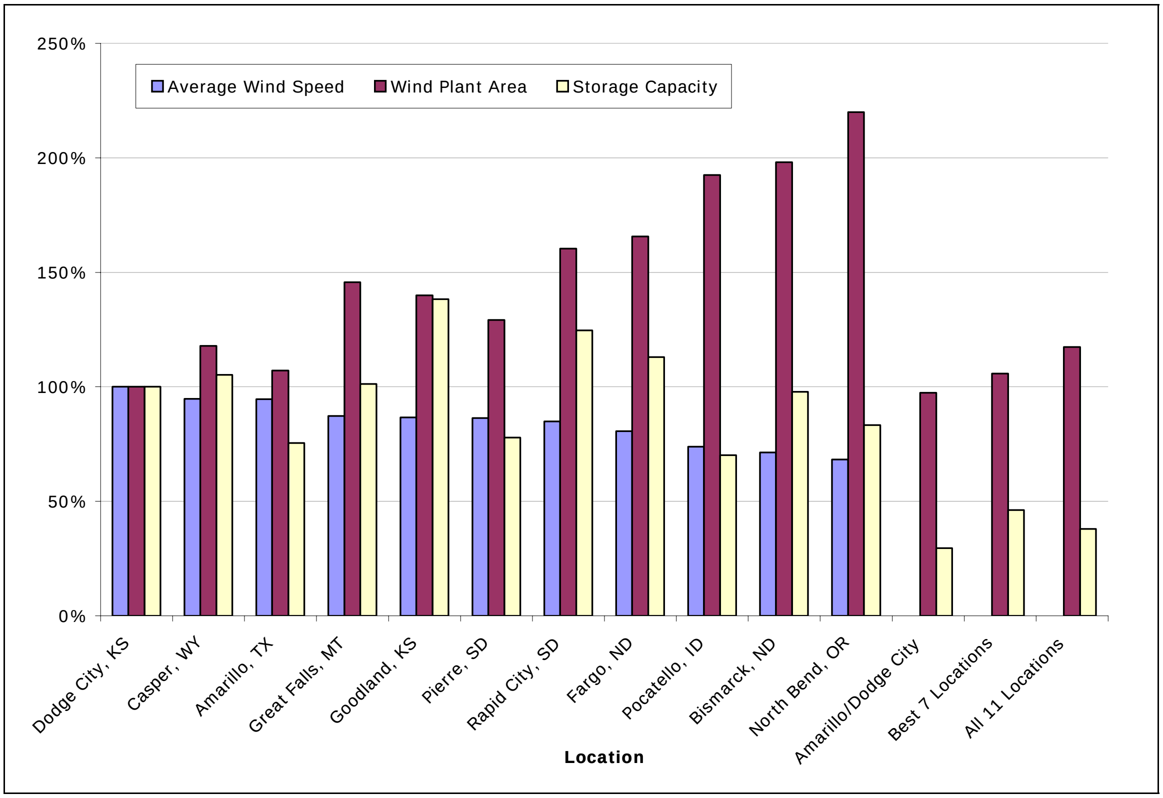

Figure 27: Wind results ordered by average wind speed.
Normalized to Dodge City = 100%.

Another notable advantage of wind systems compared with PV systems is their much lower power output capacities. The average rated output of the modelled wind plants was 1.62 TW which—while still twice the total generating capacity of the US in 2000—is less than half the size of the average PV installed capacity of 3.42 TW. At the time of writing, the capital cost of a photovoltaic plant of a given capacity was several times greater than that of an equivalent wind plant [62]. This implies a potential trade-off between the larger land area requirements and the lower capital costs of wind plants compared to those of PV plants.

If all 11 wind locations are modelled as a single combined plant, with each location bearing an equal share of land area given over to the wind farm, the result is still an improvement over most wind locations modelled alone, but is not the best performing combination. This result hints at an interesting optimization problem, albeit one (unfortunately) outside the scope of this thesis. There are thousands of combinations of wind locations to choose from, and an effectively unlimited number of ways to distribute wind turbines for each combination. For the combination of the "Best 3" locations, for instance—that is, the three wind plants with the lowest areas: Amarillo, Dodge City and Casper—what is the optimal distribution of plant area? All the modelled results for combined locations assume an evenly divided area—in this example, Amarillo 33%/Dodge 33%/Casper 33%—but there is no reason to favour this particular distribution other than modelling convenience.

Figure 28 illustrates the benefits of using combined wind locations. Amarillo and Dodge City are two of the best-performing single locations, but when the two locations are combined, with each allocated an equal plant area, the result is the lowest storage capacity of all modelled combinations and a total plant area 2.6% and 9.1% lower than those of Dodge City and Amarillo by themselves. The reasons for this improvement can be seen in Figure 28, which uses 2000 electricity demand and 1981 wind data for the week of 24 – 30 April. The two sets of dotted lines closest to the bottom of the figure represent the outputs of the Dodge City and Amarillo halves of the combined plant; the thick dashed line, peaking at 1200 GWh/h, represents the combined output of the two plants. Taken alone, each location experiences several periods of zero output in the week illustrated. Taken together, however, low-output intervals are reduced in number and duration (though not eliminated); each location "fills in" for the other, reducing the amount of time that the system needs to draw energy from storage.

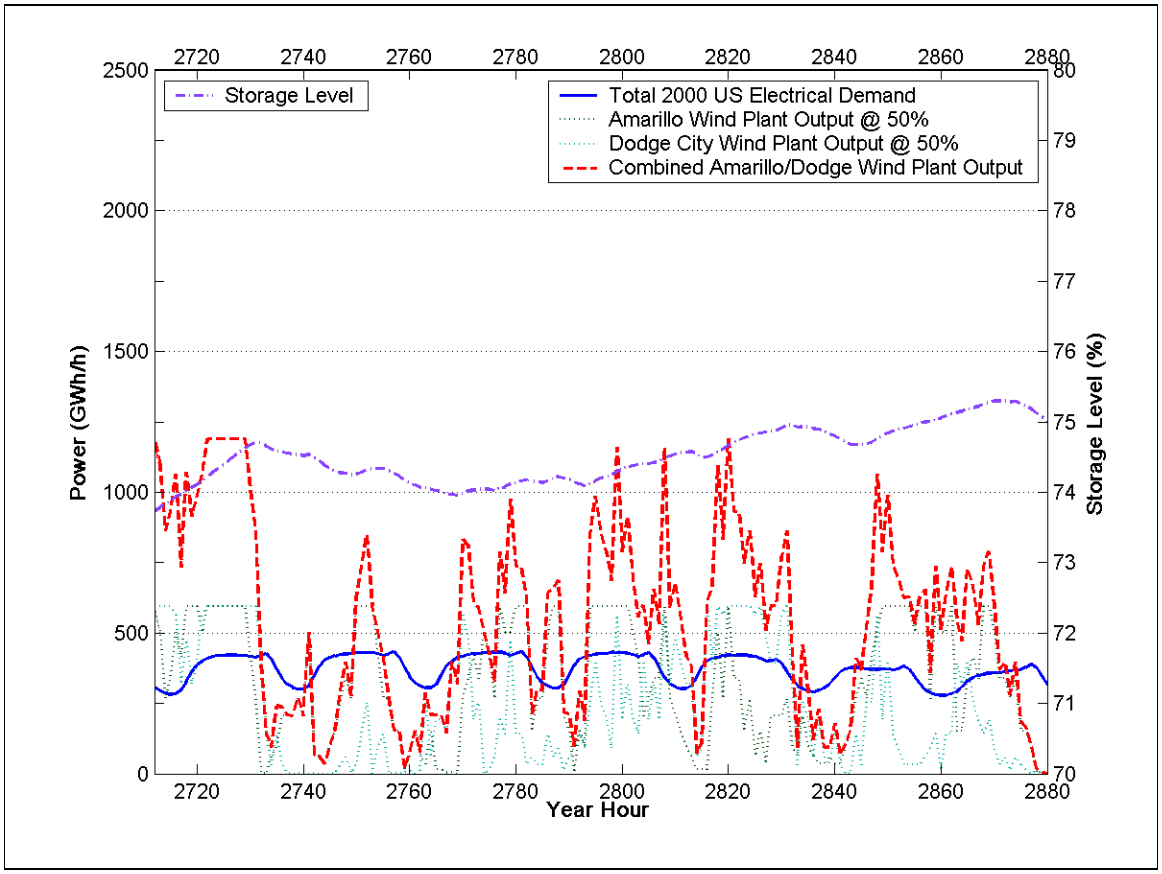

Figure 28: Amarillo/Dodge City generation, total US demand, and storage levels, 24-30 April.

The storage level shown in Figure 28 remains quite constant, varying far less than its PV system counterpart in Figure 23. The regular diurnal fluctuations in storage characteristic of the PV system are absent here. Why, then, do wind plant systems require greater storage capacities than PV systems? The answer is shown in Figure 29, which displays another week's electricity demand vs. wind plant output, this time using wind speed information for the dates December 17 – 24, 1984. The wind output exceeds demand only twice during the entire week, and does so only briefly. The bulk of the remaining electricity supply during this interval comes from storage, drawing down the storage capacity more than 10% over the time shown.

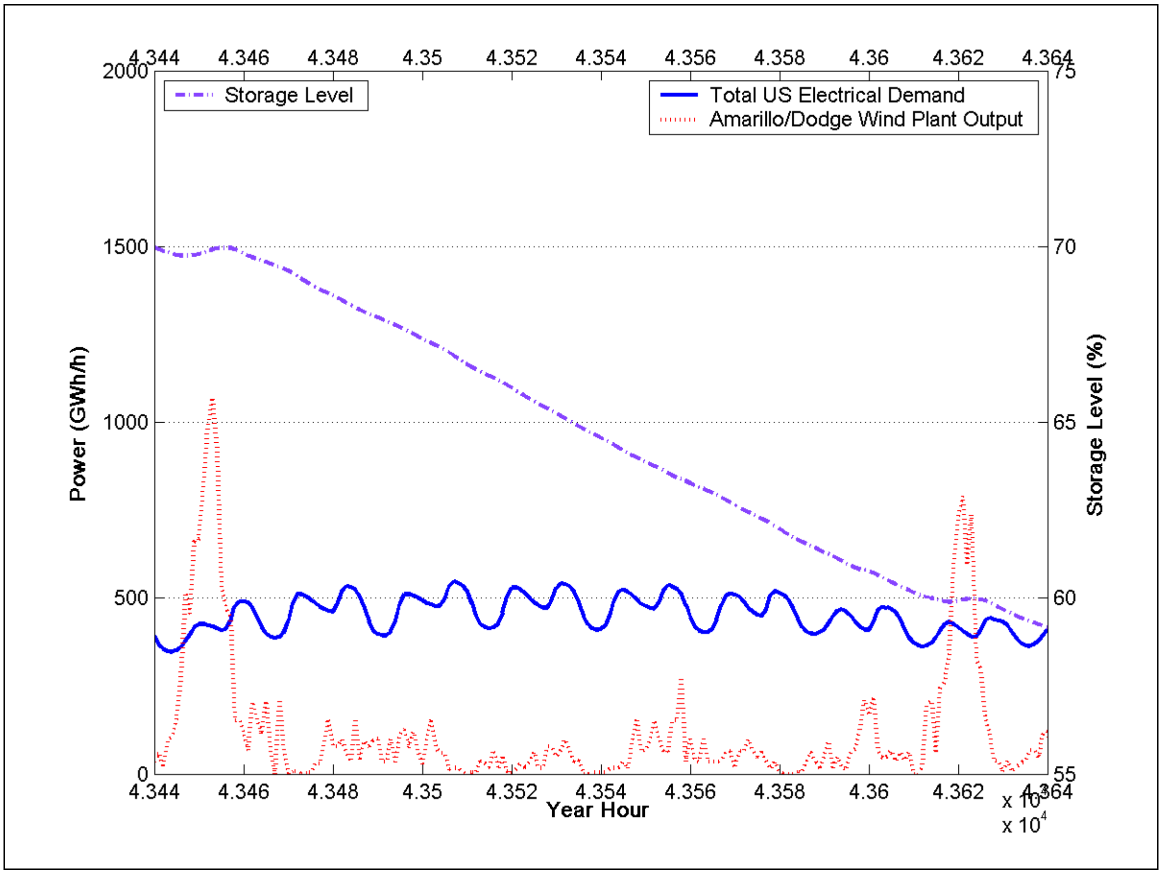

Figure 29: Effects of a long wind outage on storage, December 17 – 24.

This is one of the longest extended wind outages during the period modelled, but there are many other examples. The PV systems modelled, by comparison, never experienced extended intervals without sunlight; Seattle, the poorest-performing PV location, generated energy in excess of peak demand almost every day in ten years, replenishing storage by a small amount each time.

Figure 28 also shows the maximum power output of the Amarillo/Dodge wind plant, at about 1.2 TW. Unlike the PV plant shown in Figure 23, which required a storage system capable of sinking more than 2 TW, the wind plant shown here will only require about 0.9 TW of storage input capacity. This amount of energy is still much larger than peak US demand, and there are no storage technologies in existence capable of sinking such large energy fluxes.

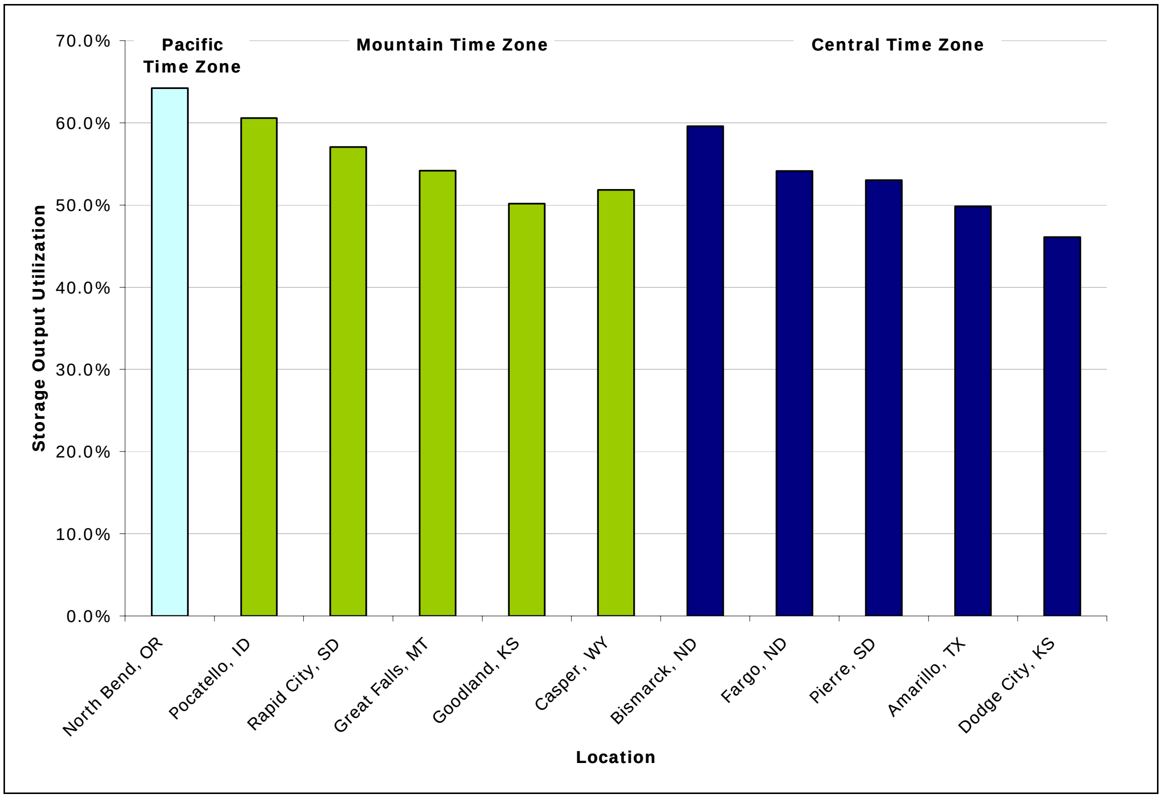

Figure 30: Storage output utilization for wind plants ordered by time zone, then left to right by average wind speed

In contrast to the PV results, a wind plant's location in relation to electricity demand does not have any noticeable influence on its performance. Wind plants do not produce reliable peak output coincident with demand; there is a slight tendency for wind speeds to increase during daylight hours (this can be seen in Figure 28), but the effect is small. Recall that the modelled PV plants experienced greater differences in storage utilization between time zones than within them, almost regardless of insolation levels. But according to the corresponding wind results shown in Figure 30, there is more variation within the Mountain and Central time zones than there is between them. In fact, there is a tendency within each time zone for the storage utilization to increase as average wind speed decreases.

	Storage Capacity (days)	Storage Utilization	Peak Storage Output (GW)
Single Locations			
Dodge City, KS	366	46.1%	647.8
Amarillo, TX	276	49.8%	647.7
Casper, WY	385	51.8%	647.9
Pierre, SD	285	53.0%	635.1
Goodland, KS	506	50.2%	644.2
Great Falls, MT	371	54.2%	644.4
Rapid City, SD	456	57.0%	634.9
Fargo, ND	413	54.1%	647.7
Pocatello, ID	257	60.6%	647.1
Bismarck, ND	358	59.6%	647.2
North Bend, OR	305	64.2%	627.2
Combined Locations			
Best 3 Locations	129	41.9%	619.6
Amarillo/Dodge City	108	45.4%	615.0
Dodge City/Casper	294	40.3%	647.8
Best 5 Locations	133	42.5%	580.9
Amarillo/Casper	198	42.3%	629.4
Best 7 Locations	169	41.2%	579.3
Amarillo/Pierre	208	45.2%	619.6
Amarillo/Great Falls	121	43.4%	628.6
Best 9 Locations	149	41.7%	533.9
All 11 Locations	139	42.4%	512.8
Amarillo/Pocatello	207	46.5%	612.1
Amarillo/Bismarck	146	46.4%	628.6
Amarillo/North Bend	198	46.9%	611.8
Bismarck/North Bend	150	52.6%	605.0

Table 7: Storage output characteristics for modelled wind locations

The storage output utilizations for the modelled single wind locations range from 46% in Dodge City to 64% in North Bend, compared to the 59 – 70% range for single PV locations. For combined wind locations, the storage utilization drops to between 40% and 53%, compared to a range of 60 – 63% for combined PV locations. Most wind systems make less use of storage than PV systems, since they do not experience regular outages, as PV systems do at night. However, the peak storage output for wind systems is slightly higher than for their PV counterparts, because solar outages occur during periods of low electricity demand, while wind outages can occur at any time. Since many wind outages will inevitably take place during times of peak electricity demand, the peak storage output for wind systems will be higher.

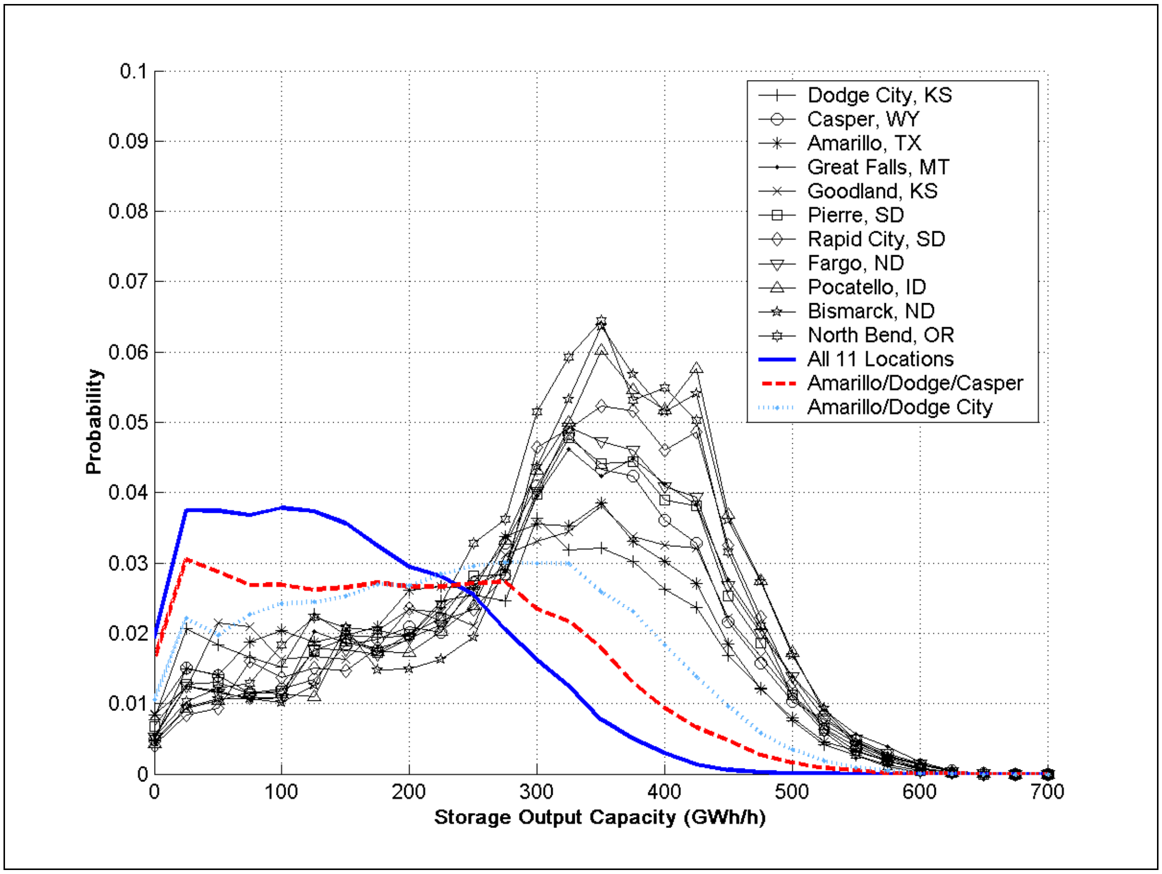

Figure 31: Probability distribution of wind storage output

Note, however, that the peak storage output for all eleven locations is almost 100 GW lower than for most other combined locations, and about 130 GW lower than for any single location. In fact, for the combination of all eleven locations there are no complete outages whatsoever over the entire nine years modelled; at least one location is generating electricity at all times, with a minimum power output of 3.25 GW.

The distribution of storage output shown in Figure 31 is even more revealing. Not only are there large differences between the distributions of single locations, but also the advantages of combined locations are strikingly apparent. In contrast to the PV storage output distribution shown in Figure 24, in which there are minimal differences between single and combined locations, the distributions of the combined wind locations are shifted down and to the left.

Compared to single locations, the storage systems for combined locations are both smaller in storage capacity and operate at a lower average power output. Furthermore, the wind distribution has a "tail" at lower storage outputs that is almost nonexistent for the PV distribution; the wind storage system spends a substantial fraction of the total time operating at a lower output level.

The PV storage system occupies an almost entirely separate domain from the primary PV generating system, coming online at full output when the sun goes down and going offline shortly after sunrise; in other words, it is *complementary* to the generating system. By contrast, the wind storage system frequently operates in parallel with the wind plant; it is *supplementary* to the generating system.

The survivor distribution in Figure 32 shows even more clearly the power output characteristics of the storage systems for the various single and combined wind locations. For the combination of all eleven locations, only 9% of generation output exceeds 300 GWh/h; fully 85% of the storage output was above this level for the equivalent PV combination. The bulk of the storage output for the single wind locations is also lower than for single PV locations; only 45 – 68% of the wind systems' storage output is above 300 GWh/h, compared to 85 – 92% for the PV systems. While the total generation capacity for most wind storage systems is similar to that for the PV storage system at about 650 GW, the wind storage systems will require a smaller portion of this capacity to be in use at any given time, on average. This implies that the operations and maintenance cost of the wind storage system may be substantially below that of the PV storage system.

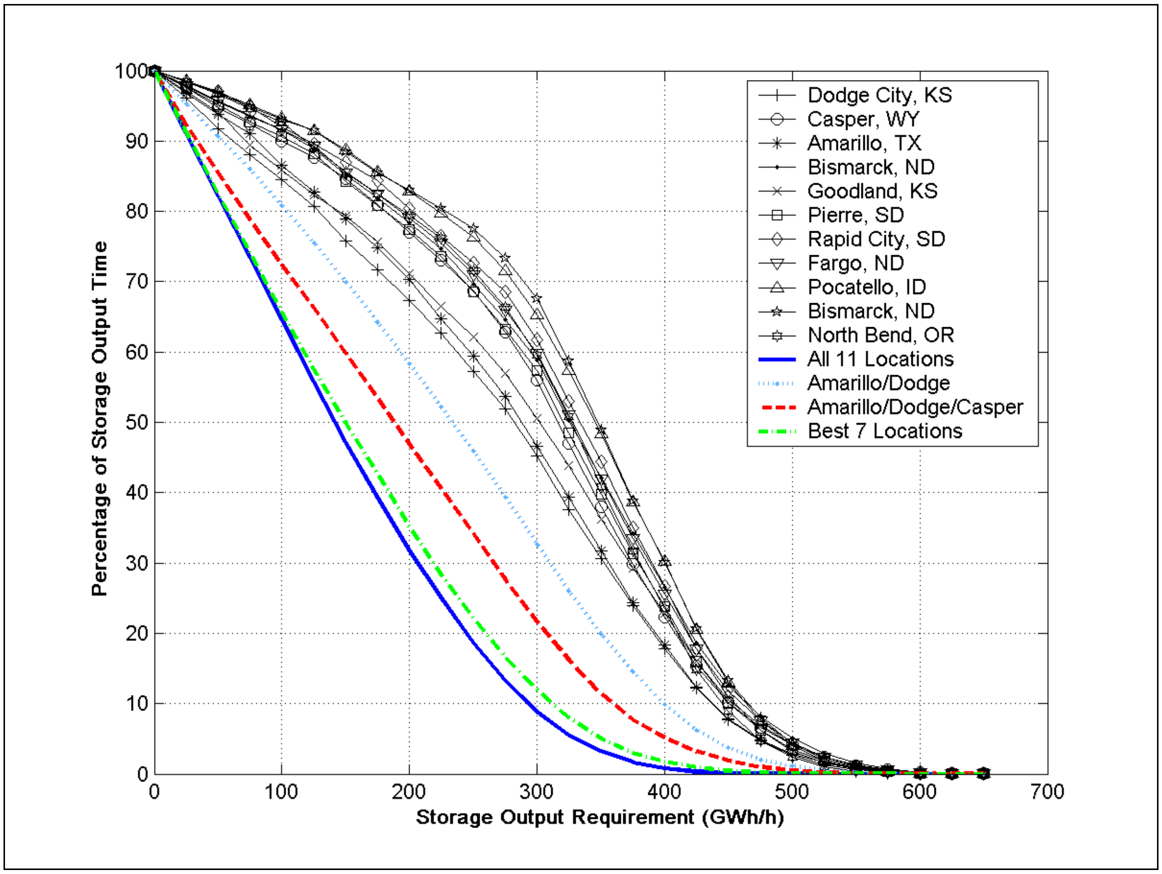

Figure 32: Survivor distribution for wind storage output

Wind-based electricity systems require several times more land area but lower installed capacities than PV systems, and require comparable storage capacities if combined wind locations are used. The energy storage power output levels for wind-based systems are also much lower than those of PV-based systems, on average. However, wind plants have much lower power densities than even PV plants, coming in at between 1 – 3 W·m^{-2}, three orders of magnitude below the power densities of conventional thermal power plants. The exact trade-off between plant capital costs, land area, storage capacity, and storage power output rating requires a full techno-economic analysis that is beyond the scope of this work, but the results presented here indicate interesting avenues for further research.

10. Wind/PV Hybrid Systems Results

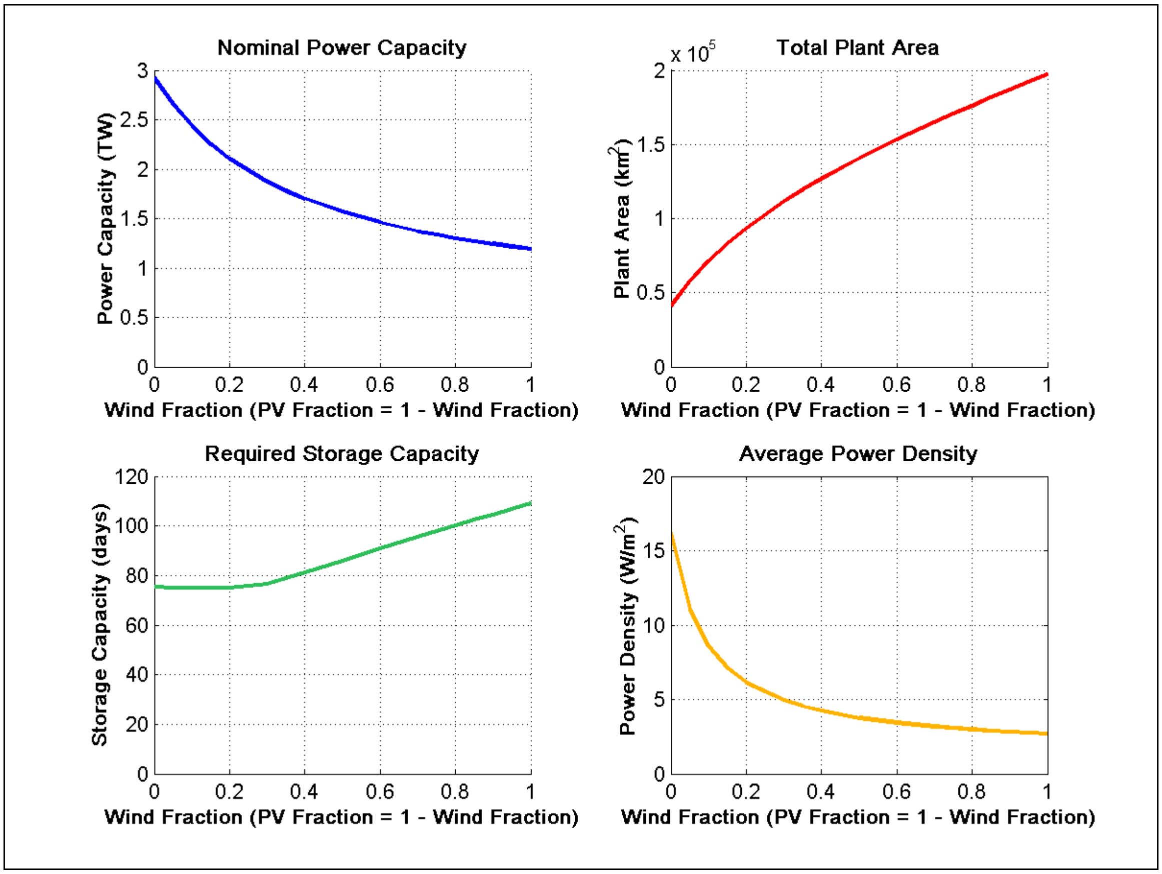

Figure 33: Results for modelling of wind/PV hybrid plants.

In addition to the pure PV and wind modelling presented above, a number of hybrid wind/PV systems were evaluated. The locations chosen were the best performing from each renewable technology: Midland-Odessa for PV, and Amarillo/Dodge for the wind component. The wind and PV locations were allocated a varying fraction of the total plant size, with Amarillo and Dodge City each sharing half of the wind turbines. The modelling was performed using wind and solar data for the nine-year interval 1982-1990, since complete wind data was not available for 1981. All other input parameters were identical to those used for the pure systems.

The results are presented in Figure 33 and Table 8. In Figure 33, the horizontal axes represent increasing penetration of wind into the system. As the proportion of wind generation increases, nominal plant output capacity decreases, while total plant area increases, as expected. However, the results for storage capacity were more surprising: the wind fraction in a hybrid system can approach 30% before the required storage capacity begins to increase. Below this penetration level, the required storage capacity remains close to the pure PV figure of 77 days.

Wind Fraction	PV Fraction	No. of Wind Turbines	PV Area (km^2)	Nominal Cap. (TW)	Total Area (km^2)	Storage Cap. (days)
100%	0%	794,792	0	1.19	197,516	108
90%	10%	745,968	878	1.24	187,138	106
85%	15%	720,596	1,347	1.27	181,771	104
80%	20%	694,580	1,840	1.30	176,291	101
70%	30%	640,428	2,908	1.37	164,970	96
60%	40%	583,492	4,121	1.46	153,247	92
50%	50%	522,140	5,531	1.57	140,821	85
40%	60%	453,240	7,202	1.70	127,040	82
30%	70%	374,218	9,250	1.87	111,498	77
20%	80%	280,420	11,882	2.10	93,452	76
15%	85%	225,340	13,527	2.25	83,054	76
10%	90%	162,532	15,496	2.44	71,383	77
5%	95%	88,606	17,834	2.66	57,688	76
0%	100%	0	20,664	2.93	41,328	77

Table 8: Modelling results for wind/PV hybrid systems

The implications of this result may be important for the design of hybrid systems. On one hand, pure wind generation systems require much larger land areas and higher storage capacities than PV systems to meet the same electrical demand; on the other, the wind systems require lower installed nameplate capacities, an important factor when PV systems are many times more expensive per installed kilowatt than wind. These results suggest that, if extra land is available, the total power output capacity can be reduced by introducing wind generation into a PV system, without requiring any extra storage capacity.

Wind Fraction	PV Fraction	Storage Capacity (days)	Storage Utilization	Peak Storage Output (GW)
100%	0%	108	45.4%	615.0
90%	10%	106	45.6%	581.9
85%	15%	104	45.6%	582.1
80%	20%	101	45.6%	582.3
70%	30%	96	45.1%	582.8
60%	40%	92	44.7%	583.2
50%	50%	85	45.5%	583.7
40%	60%	82	47.9%	584.3
35%	65%	80	49.6%	584.6
30%	70%	77	51.6%	584.9
20%	80%	76	57.5%	585.7
15%	85%	76	60.5%	586.2
10%	90%	77	61.7%	586.7
5%	95%	76	61.6%	589.8
0%	100%	77	61.7%	597.2

Table 9: Storage output characteristics for wind/PV hybrid locations

That may not be the only advantage to a wind/PV system. The combination of wind and PV generation also reduces both storage utilization and peak storage output over what a PV system can achieve on its own. Table 9 shows the storage output characteristics of the hybrid systems modelled. As the wind fraction exceeds 10% above the 100% PV baseline (moving upward from the bottom of the table), the storage utilization decreases until the wind fraction reaches 50%, after which it stays constant at around 45.5%; the increasing proportion of wind generation reduces the workload of the storage system.

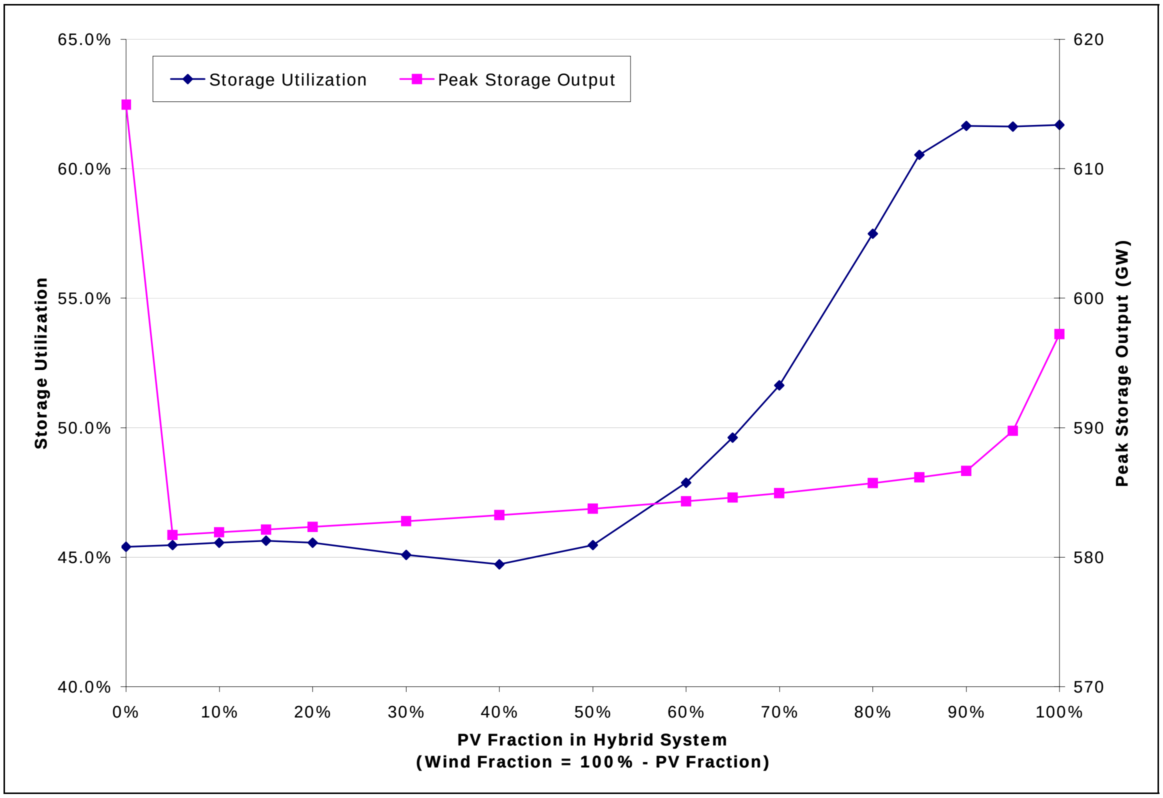

Figure 34: Storage utilization and peak storage output for wind/PV hybrid systems

Introducing even a small fraction of wind generation into a PV system (or vice versa) causes a sharp drop in the peak storage output power. The effect is even greater for the introduction of a small amount of PV generation in to a wind-dominated system, as Figure 34 indicates. This is a welcome development, other things being equal, since it reduces the amount of standby generation required. The reason for the sharp drops at either end of the hybrid spectrum is that the wind and solar fluxes usually complement each other to some extent. If the wind dies entirely during the day, there is always some solar flux to reduce the storage output required; similarly, there is most often some wind at night time, although there will inevitably be complete night time outages under a wind-dominated system. However, such outages will be lower in magnitude since nighttime demand is substantially lower than in daytime.

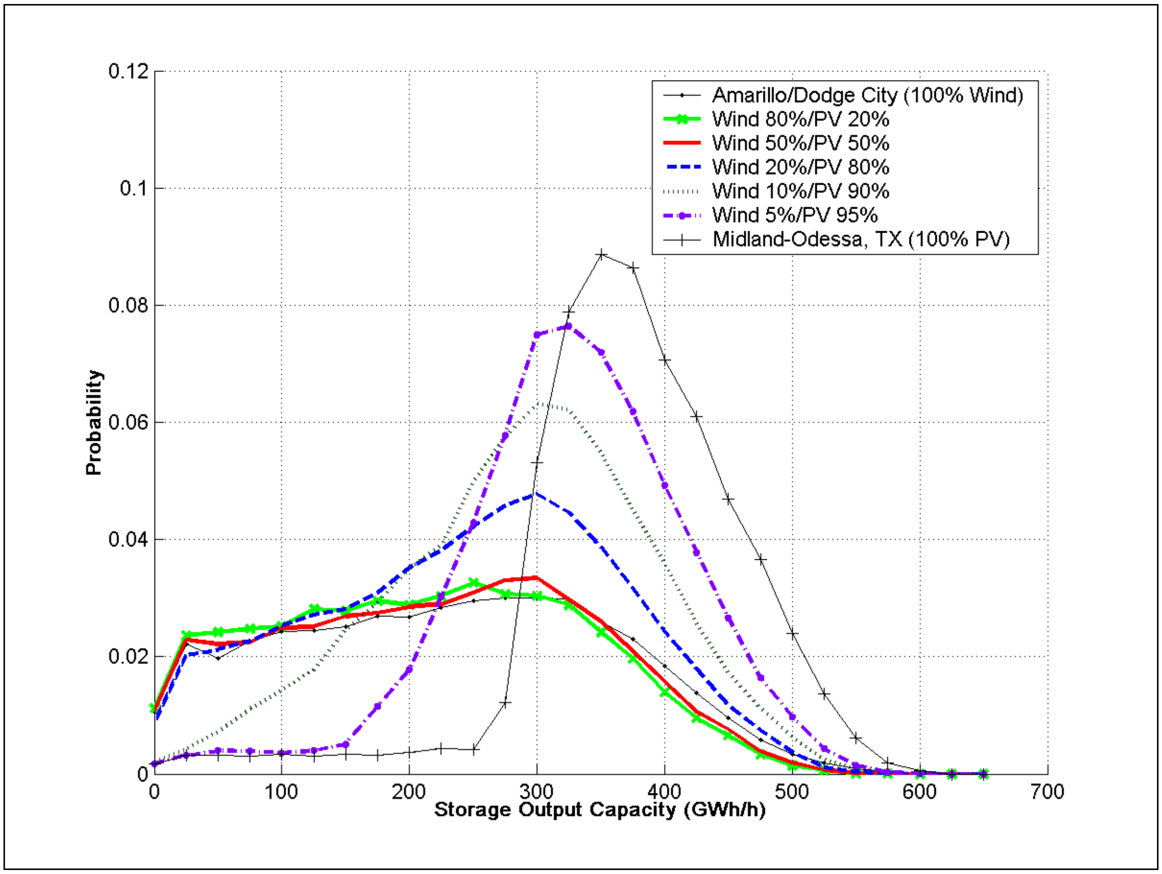

Figure 35: Storage output probability distribution for hybrid systems

The distributions in Figure 35 and Figure 36 further illustrate the advantages of a wind/PV hybrid system. Introducing wind into a PV-dominated system not only reduces the installed generation capacity without sacrificing storage capacity, it also substantially reduces the storage output requirements. The probability distribution in Figure 35 shows a select few of the hybrid combinations modelled, along with the distributions for pure wind and PV systems. Even a 5% wind fraction moves the distribution downwards and to the left, reducing the average storage power output requirement. At a 20% wind fraction, the distribution is approaching the shape of the pure wind distribution, and by the time wind makes up 50% of the system, the distribution curve is essentially indistinguishable from the pure wind scenario.

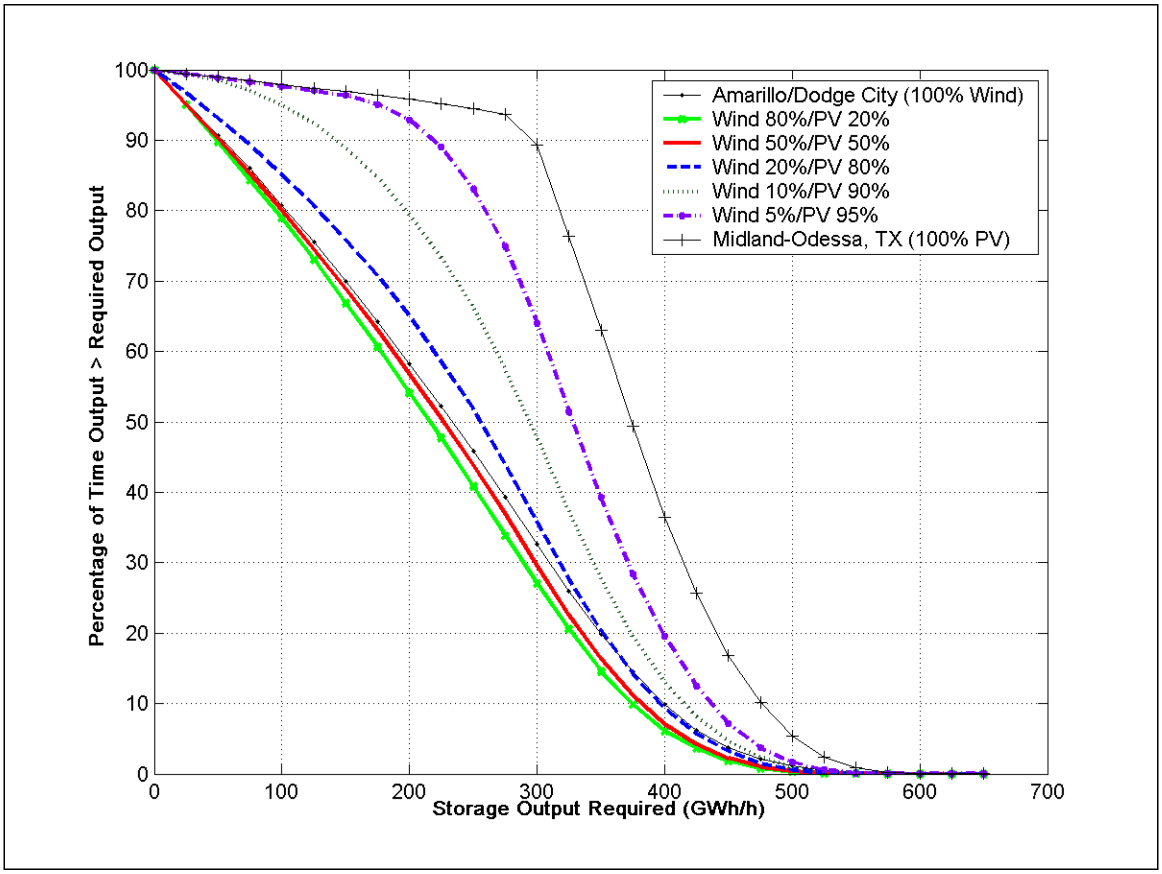

Figure 36: Survivor distribution for modelled wind/PV hybrid locations

One trade-off of the lower, flatter distribution characteristic of wind-dominated systems is a less predictable storage output. The output power is lower, on average, but the range of possible outputs is greater. The pure PV system requires higher storage output but within a narrower range. When the sun goes down, the storage comes online and follows a predictable nighttime demand. The storage for a wind-dominated system is required to come online at all times of the day at varying output levels. As with all the trade-offs discussed in this work, this is not amenable to resolution by a pure technical analysis.

The survivor distribution in Figure 36 gives a more precise picture of the storage output requirements of the hybrid wind/PV systems. For the pure PV system, 90% of the storage output is at levels exceeding 300 GWh/h; at a 5% wind fraction, 64% of output exceeds this level, and by the time the wind fraction reaches 50%, only 35% of generation exceeds 300 GWh/h. As in the previous figure, the distribution rapidly converges on the pure wind curve as the wind fraction increases. In fact, the 50% and 80% wind fraction actually drop slightly more steeply than the pure wind distribution, indicating that these systems require even lower storage output power.

Which hybrid system is best? Unfortunately, there is no easy way to choose, and the answer (under some circumstances) may even be "none of the above". For instance, if land area is the most important factor, the pure PV system has the smallest footprint. If it is necessary to minimize nameplate generation capacity, the pure wind system has the lowest rating. However, if storage capacity and output characteristics are important factors (as they almost certainly would be), a hybrid combination may offer the best technical solution. Up to about a 40% wind fraction, the storage capacity barely increases over the pure PV minimum. This comes at a cost in land area and power density, but both the peak storage output and the output distribution are improvements over the pure PV system. On average, a hybrid system with even a small wind fraction will require a significantly smaller level of storage output than a system completely dominated by PV generation.

11. Sensitivity Analyses

A number of assumptions are made in this work to allow comparisons of disparate technologies under a variety of conditions. Perhaps the most notable is the use of a "black box" storage system with overall system input and output efficiencies of 80% and 60%, respectively. The photovoltaic panel efficiency of 12%—held constant over all modelling activities—is perhaps overly generous at this stage of PV technology development. A number of other assumptions are less obvious: why, for instance, allow all renewable systems to produce no more than 1% energy in excess of demand? Why not 5%, 10%, or 25%? Similarly, for the Amarillo/Dodge combined wind locations, why choose a 50/50 division of labour, when a different distribution of turbines may result in improved performance? How do high-performing locations perform when artificially "moved" to different time zones? This chapter comprises sensitivity analyses of all the above assumptions.

All sensitivity analyses are performed on the locations used for the modelling of hybrid wind/PV systems (itself a sensitivity analysis of a sort): Midland-Odessa, Texas, for PV and the combination of Amarillo, Texas and Dodge City, Kansas, for wind. The choice of these locations contains in itself the assumption that the particular results of these sensitivity analyses can be generalized to all wind and PV locations, making it a candidate for yet another sensitivity analysis. However desirable such an analysis may be, it opens the door to an essentially limitless proliferation of sensitivity analyses, given the myriad permutations of wind and PV systems.

11.1 PV Panel Efficiency

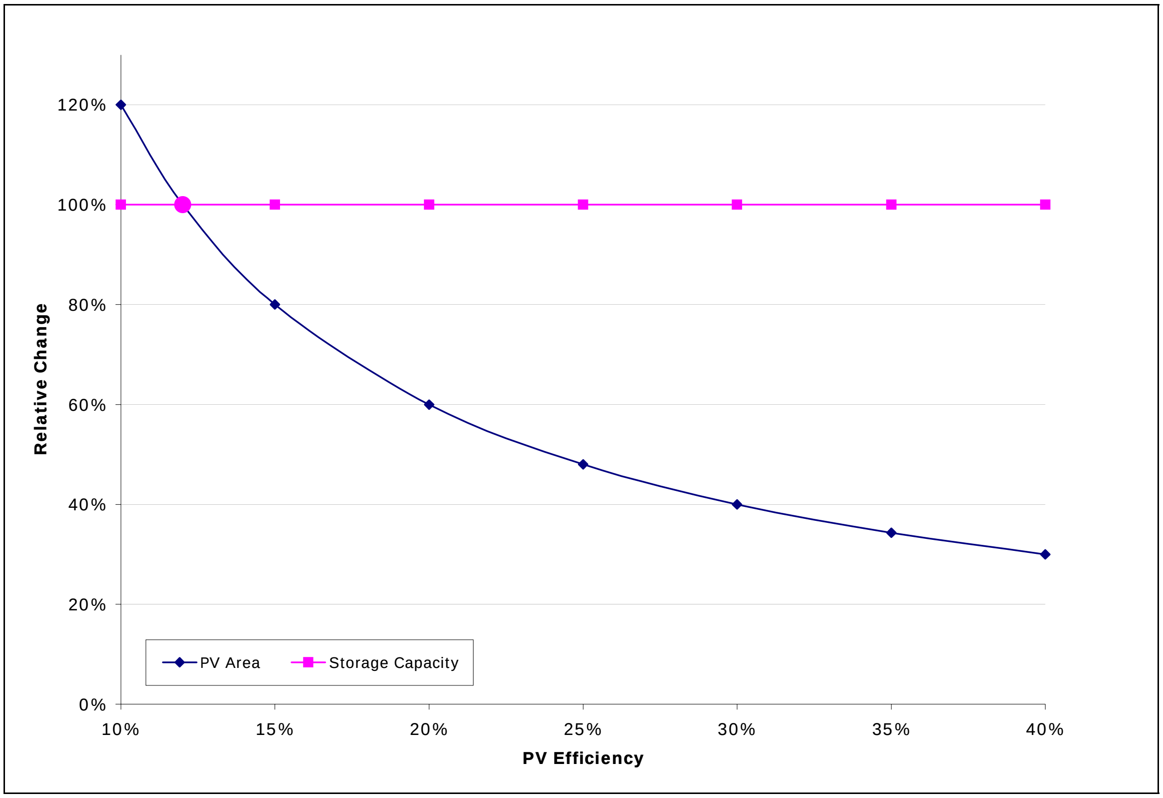

Figure 37: Sensitivity of storage capacity and PV area to PV efficiency, normalized to results at 12% PV panel efficiency.

Figure 37 shows the sensitivity of the Midland-Odessa PV plant to PV panel efficiency. The default PV efficiency for the modelling exercises was 12%, and other efficiencies were evaluated relative to this figure. An efficiency of 10% is, in fact, more realistic for the Shell Solar SP-75 panels used in the modelling [46], and the default modelling results should therefore be regarded as optimistic relative to the current state of photovoltaic panel technology. However, the National Renewable Energy Laboratory is sponsoring research aimed at achieving photovoltaic efficiencies exceeding 20% in the near-to-medium term [64], and the 12% default assumption may be more realistic within a few years.

At a PV efficiency of 10%, the total Midland plant area increases by 20%, for a total plant area of 49,648 km^2, or a square 223 km on a side. As the PV efficiency increases, the PV area drops, until it is 30% of the original area at an efficiency of 40%. For Midland-Odessa, this would result in a plant area of 12,398 km^2, or a square 111 km on a side. The storage size requirements do not change at all over the range of PV efficiencies, which is to be expected; all the storage system "sees" is an energy flow, regardless of the plant producing it. A PV plant with 30% panel efficiency would produce the same amount of energy as one with 12% panel efficiency, but would require only 40% of the land area to do so. Of course, this requires the implicit—and rather questionable—assumption that solar fluxes are constant over both panel areas.

11.2 Storage Efficiency

In this work, the storage system is modelled as a "black box" for which only aggregated parameters are available: storage capacity, input and output efficiencies, minimum storage capacity, and the storage level at the beginning of the modelling period. A continental energy storage system will consist of a variety of technologies, each with its own characteristics, but with none dominating. The storage capacity is, along with plant size, one of the two primary outputs of the optimization used in this version of the ESM, and the minimum storage level and starting storage are held constant throughout this work.

The storage input and output efficiencies are important input parameters to the model, and are key factors in determining the renewable plant area and storage capacity required. The default input and output efficiencies used in the modelling for this work are 80% and 60% respectively, for a roundtrip efficiency of 48%; that is, just under half the energy that the renewable plant puts into storage is available to satisfy demand, due to conversion losses at the inputs and outputs of the storage technologies.

There is an infinite number of combinations of storage input and output efficiencies to produce any given roundtrip efficiency; for instance, a 48% roundtrip efficiency can be satisfied with input and output efficiencies of 60%/80%, 95%/51%, 75%/64%, or 55%/87%, to mention a few alternatives to the 80%/60% default used in the modelling. It is obviously impractical to test more than a few of these, let alone do the same for a range of other roundtrip efficiencies, so a different approach was taken. First, the model was run with the output efficiency held constant at 100% while the input efficiency was varied from 100% down to 40%; then the input efficiency was held constant at unity while the output efficiency was varied over the same range. The aim was twofold: to measure the response of the plant area and storage capacity requirements to changes in storage efficiency, and to determine whether the input and output efficiencies had different effects on the system's response; that is, whether an 80%/60% input/output efficiency is equivalent in effect to a 60%/80% input/output efficiency.

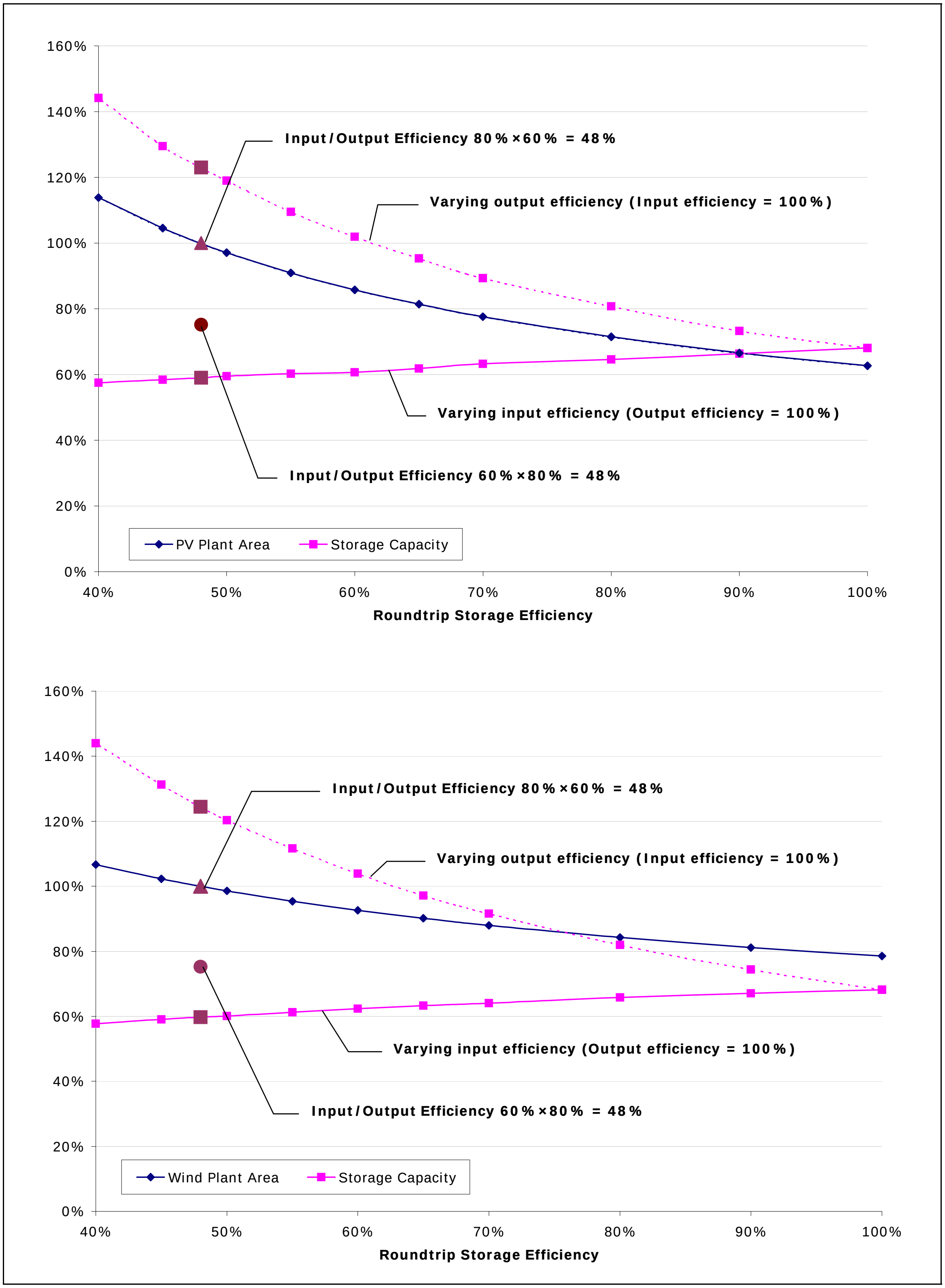

Figure 38: Sensitivity to storage efficiency for PV plants (above) and wind plants (below), normalized to an 80% input/60% output storage efficiency.

Figure 38 shows the results of the sensitivity analysis of storage efficiencies for PV and wind systems. The default situation, of an 80%/60% input/output efficiency combination, is represented by the triangle at the coordinates of (48%, 100%), and all other measurements are relative to this point. The other single point, the circle directly below the triangle, is the relative storage size for the situation where the input and output efficiencies were reversed; that is, an input efficiency of 60% and an output efficiency of 80%. The large squares above and below the two single points give the relative storage capacities for input/output efficiencies of 100%/48% and 48%/100%, respectively.

For a storage efficiency of 40%, the PV plant area required is 114% of that required for the default scenario, dropping smoothly to 63% at a roundtrip storage efficiency of 100%. Wind plant area is less sensitive to storage efficiency, ranging from 107% of the default area at a roundtrip storage efficiency of 40% to 79% of the area at an efficiency of 100%. This is probably the result of wind systems' lower storage utilization relative to PV systems; since a greater proportion of the wind plant's output bypasses storage and goes directly to meeting demand, it is not as sensitive to changes in storage parameters.

As expected, the plant area required is identical for any given roundtrip efficiency for both PV and wind systems; the lines for constant input efficiency and constant output efficiency are superimposed. The generating plant sees only the energy penalty associated with the storage roundtrip efficiency; the specific input/output mix does not matter.

In contrast, storage capacity depends strongly on the storage output efficiency, while the storage input efficiency has little effect. Figure 38 indicates that any given change in the storage output efficiency has a far greater influence

on the storage capacity than the same change in the input efficiency.
For any given roundtrip efficiency, the required storage capacity can be minimized by maximizing the storage output efficiency. As further confirmation of the advantages of a higher output efficiency, consider the case where the default storage efficiency is reversed, so that the input efficiency is 60% and the output efficiency 80%. Once more, the roundtrip efficiency is 48%, but for both PV and wind systems, the reversal of the storage efficiencies resulted in a storage capacity 75% the size of the default capacity.

These results—with the exception of the effects of the storage input efficiency on storage capacity—are not surprising. The renewable plant increases in area to overcome the storage roundtrip efficiency, and the storage capacity rises to overcome efficiency losses in the output conversion stage. Both the renewable plant and the storage tank must, in effect, be large enough to be able to waste energy in the storage conversion losses, although the tank does not "see" the energy wasted in the input conversion. These are unavoidable characteristics of stand-alone renewable/storage systems of any size.

The one unexpected result in this analysis is that a lower storage input efficiency *reduces* the storage capacity slightly, for both wind and PV systems. The input efficiency was expected to have little effect on the storage capacity. The probable explanation is related to the excess energy constraint: a storage input efficiency of 100%, for example, allows all energy input to storage to increase the storage level. Under these circumstances, storage will saturate more quickly than in a system with a lower storage input efficiency, producing excess energy. Once the amount of excess energy exceeds the constraint (1 – 2% in excess of demand, in this work), the binary search algorithm iterates with larger storage capacities until the constraint is met. Lower input efficiencies would fill storage less effectively, and thus delay saturation.

The storage capacity sensitivity for both PV and wind systems were nearly identical, the differences between the two amounting to a few tenths of percentage points. The storage system simply performs energy transactions, and cannot distinguish one energy source from another.

11.3 Sensitivity to Time Zone

As mentioned above, a PV plant's time zone appears to be key in determining the plant area and storage capacity it requires. In this work, with an aggregated US demand weighted towards the highly populated eastern regions of the country, the locations in the Eastern time zone (Philadelphia and Miami) outperformed locations with much higher insolation levels in the Pacific time zone (Tonopah and Winnemucca). Although it was intuitively obvious that load matching would be an important factor in minimizing PV plant area and storage capacity, it affected the modelling outcome to an unexpected degree.

In this sensitivity analysis, the effect of time zone on PV systems was investigated by artificially changing Midland's time zone from -3 hours to zero hours relative to the Eastern time zone, progressively moving its insolation characteristics eastward from Pacific Time to Eastern Time, one time zone at a time. The same was done for wind systems, moving Amarillo/Dodge (also located in the Central time zone, in reality) across the same range. The results are shown in Figure 39, below, with the large markers at (-1, 100%) corresponding to the actual locations in the Central time zone. There are a number of interesting things about the results:

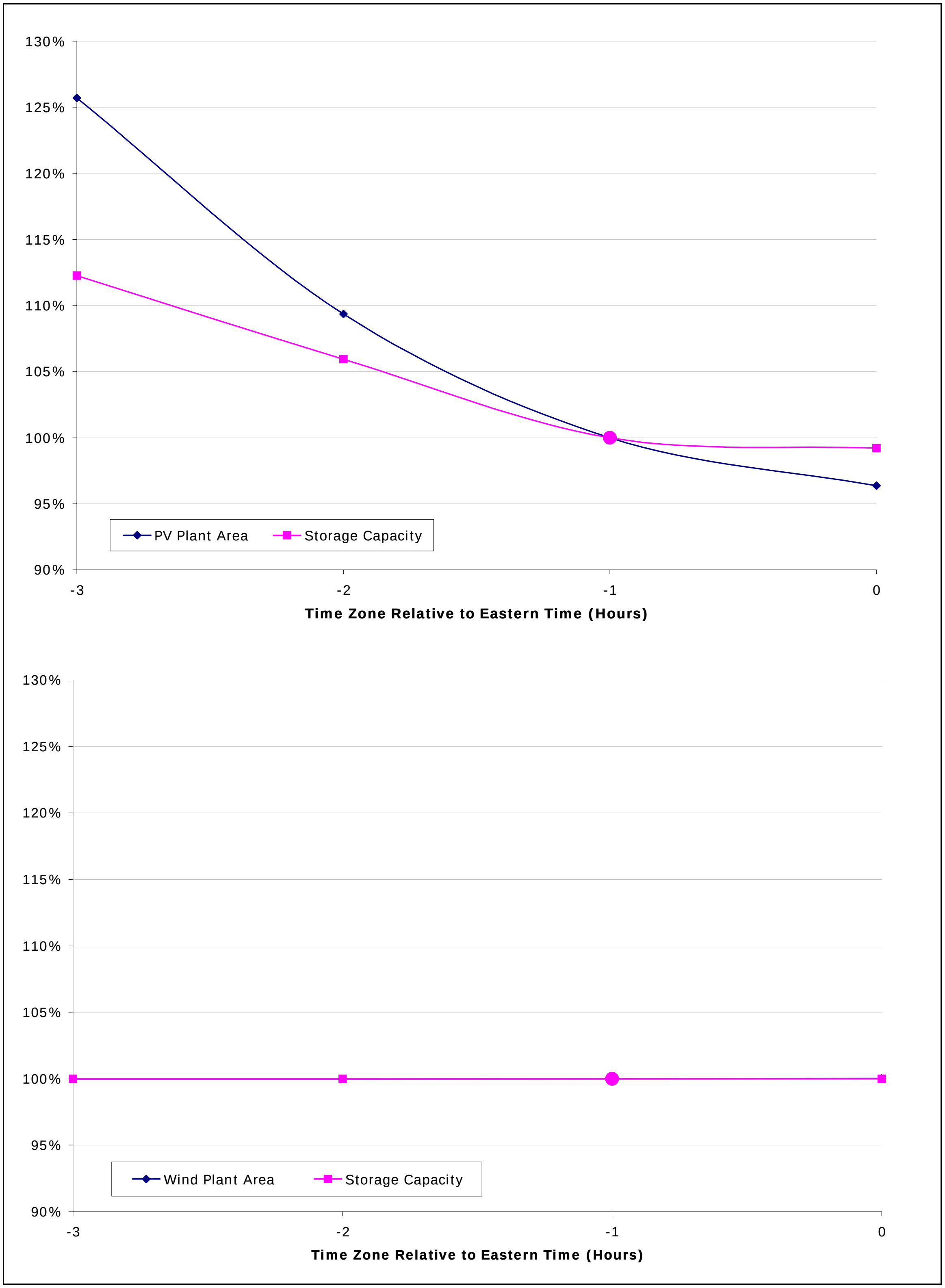

Figure 39: Sensitivity to time zone for PV systems (above) and wind systems (below)

- PV plant area requirements do change significantly with time zone, as expected. If Midland was located in the Pacific time zone (-3 hours), for instance, its PV plant area (at 51,949 km^2) would be in line with those required for Tonopah and Winnemucca (50,063 km^2 and 52,438 km^2 respectively). Similarly, if Midland was uprooted and moved to the Eastern time zone (0 hours), it would require only 39,820 km^2 of plant area, 96% of its actual area.

- The storage capacity of PV plants also changes with time zone, but not to the same degree as plant area requirements. Even in the Pacific time zone, Midland would only need 85 days of storage to satisfy US demand, compared with 197 days for Tonopah and 200 days for Winnemucca. This disparity can perhaps be explained by the very different topography of the Midland region compared to the Nevada locations. The Nevada locations are mountainous, while Midland-Odessa sits on the Great Plains. Mountainous regions will experience less direct sunlight than flat regions, all other things being equal; early and late in the day, the mountains will block the sun, increasing the load on the storage system.

- The wind system undergoes no changes whatsoever as it is moved across time zones. For the PV plant, an hour's change in time zone changes the plant requirements by a substantial amount because the periods of high solar flux are closely correlated to periods of peak demand. Wind fluxes do not have the strong diurnal patterns of solar fluxes, though there is usually an increase in wind speeds during daytime hours, as the sun heats the air (this can be seen in Figure 28). However, this increase is too inconsistent and diffuse to lead to a strong correlation of wind output with electricity demand.

11.4 Sensitivity of Turbine Distribution for Combined Locations

For simplicity, all combined locations are modelled with equal contributions from each location; for example, the combination of all eleven wind locations allocated an equal number of turbines to each location, regardless of its individual performance. There is no reason to assume that this is an optimal distribution of the wind plant; it is quite likely that a different mix could result in a higher performance for the combined plant. This analysis investigates the effects of varying the turbine distribution for the Amarillo/Dodge combined wind location, from its default 50/50 allocation.

Figure 40 displays the results of this analysis, both in absolute (top) and relative (bottom) terms. The default 50/50 distribution is indicated by the large circular data points and is used as the 100% baseline in the lower figure. The horizontal axis moves from left to right in the direction of an increasing contribution from the Dodge City location. As the top chart shows, the plant area appears to follow a near-parabolic curve as the Dodge City capacity fraction increases, with a minimum near (60%, 196,312 km^2), a reduction in plant area of 1,178 km^2, or 0.04% smaller than the 50/50 default distribution. The required storage capacity, on the other hand, appears to follow three distinct near-linear relationships as Dodge City's capacity fraction increases. The minimum storage capacity of 102 days at a 42% Dodge City capacity fraction is 6.7% lower than the 109 days used for the default combination.

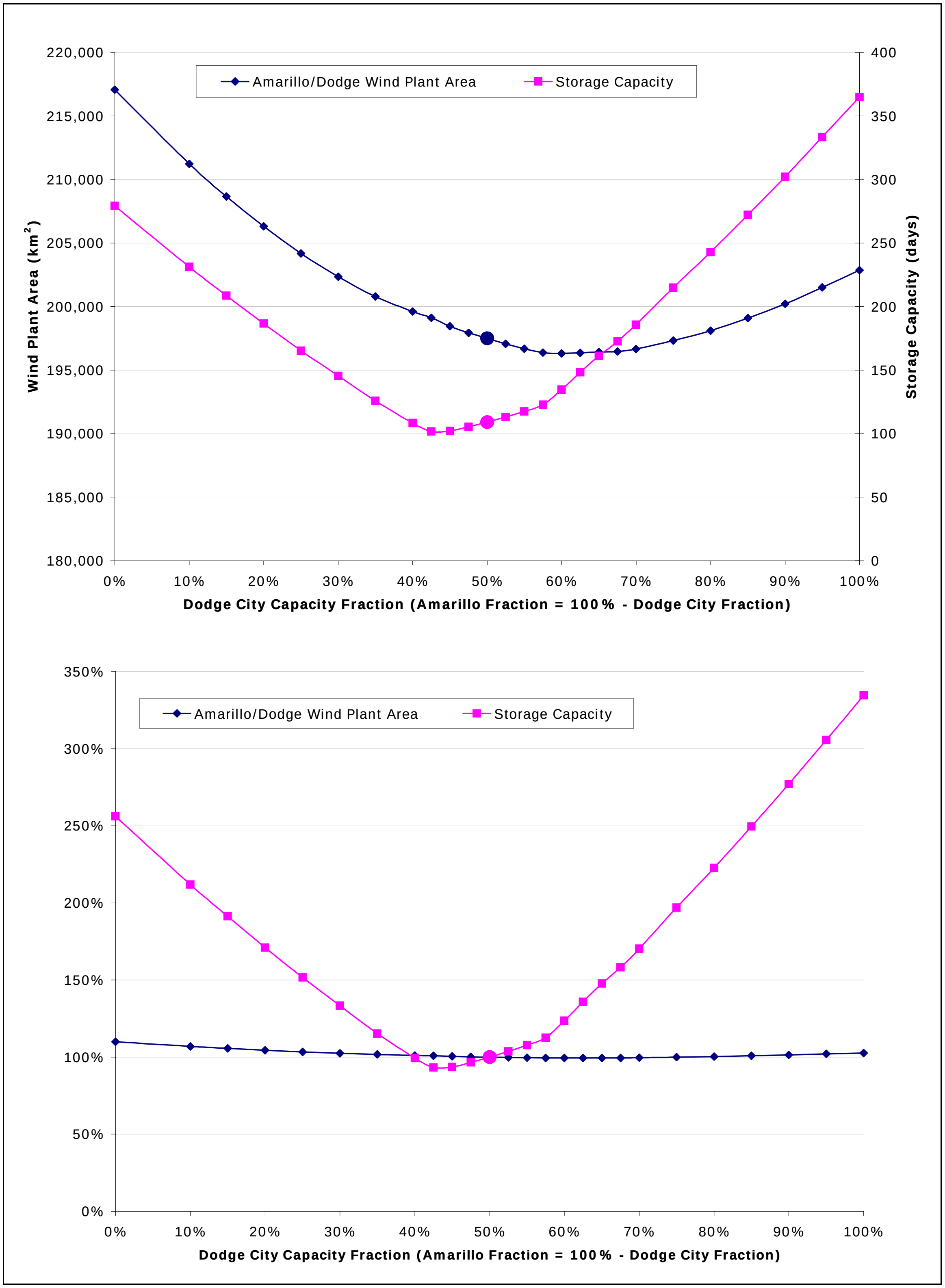

Figure 40: Effects of varying Amarillo/Dodge turbine distribution, in absolute numbers (above) and normalized to the results for a 50/50 distribution (below).

As the lower chart demonstrates, storage capacity is far more sensitive than plant area to changes in the turbine distribution, varying from 93-234% of the default distribution. The wind plant area only varies between 99-110% compared to the default (although this represents a change in area of over 20,000 km^2, so the change is hardly negligible). Both charts confirm the acceptability of using a 50/50 distribution as the default for modelling; it is sufficiently close to both minima to represent an adequate compromise between the two quantities, in the absence of more detailed information about the viability of either location for the large-scale production of wind-generated electricity.

11.5 Sensitivity to Unserved Load

The constraint used in the primary optimization for this work was to limit the number of unserved hours to no more than four per year, on average. Unserved hours are those in which the storage drops below the minimum acceptable level (25%, in this work), with the result that the generating plant and storage system are together unable to meet the total demand. This constraint places bounds on the storage capacity for any given plant size: too few unserved hours and the storage capacity is deemed to be oversized; too many and the storage capacity is insufficient to meet demand. For any plant size, there is a range of storage capacities that will meet a given constraint on unserved hours, and the model iterates until it finds a storage capacity that lies within this range.

The rather low four-hour-per-year maximum—equivalent to 0.041% and 0.046% of the total time modelled for PV and wind systems respectively—is designed to ensure that the renewable system (along with storage) is capable of meeting demand over the period modelled. It implicitly assumes that the system will be able to accept storage levels that drop below the minimum level on rare occasions. The practical effect of relaxing the unserved hours constraint would most likely be that supplemental conventional generators would be required to stand by when storage levels drop close to the minimum, ready to meet electrical demand. The analysis presented here investigates the effects of allowing the total number of unserved hours to vary between 0.01% and 25% of the total hours modelled.

The results of the analysis for both PV and wind systems are shown in Figure 41. As the maximum number of unserved hours increases, the plant areas for both PV and wind systems undergo relatively modest declines, while the storage capacities decline far more sharply. When the allowable unserved hours reach 5% of the total time modelled, the PV plant area has dropped by 5%, while storage capacity is down 58% from its default situation. In fact, it is possible to come close to eliminating the need for storage for PV systems by allowing up to 23% unserved hours. At this point, the required storage capacity is only 3.1 days, a 96% decrease from the 76 day default (PV plant area, meanwhile, has declined by only 22%). This means that substantial amounts of conventional generation would be required in addition to the renewable plant, averaging 72 GW. Interestingly, the large drop in required storage capacity does not appreciably change the output characteristics of the storage system, which still must be able to generate up to 600 GW. Since the energy conversion component of storage plants will make up a substantial fraction of its cost, it is questionable whether such a large reduction in storage capacity would yield commensurate savings.

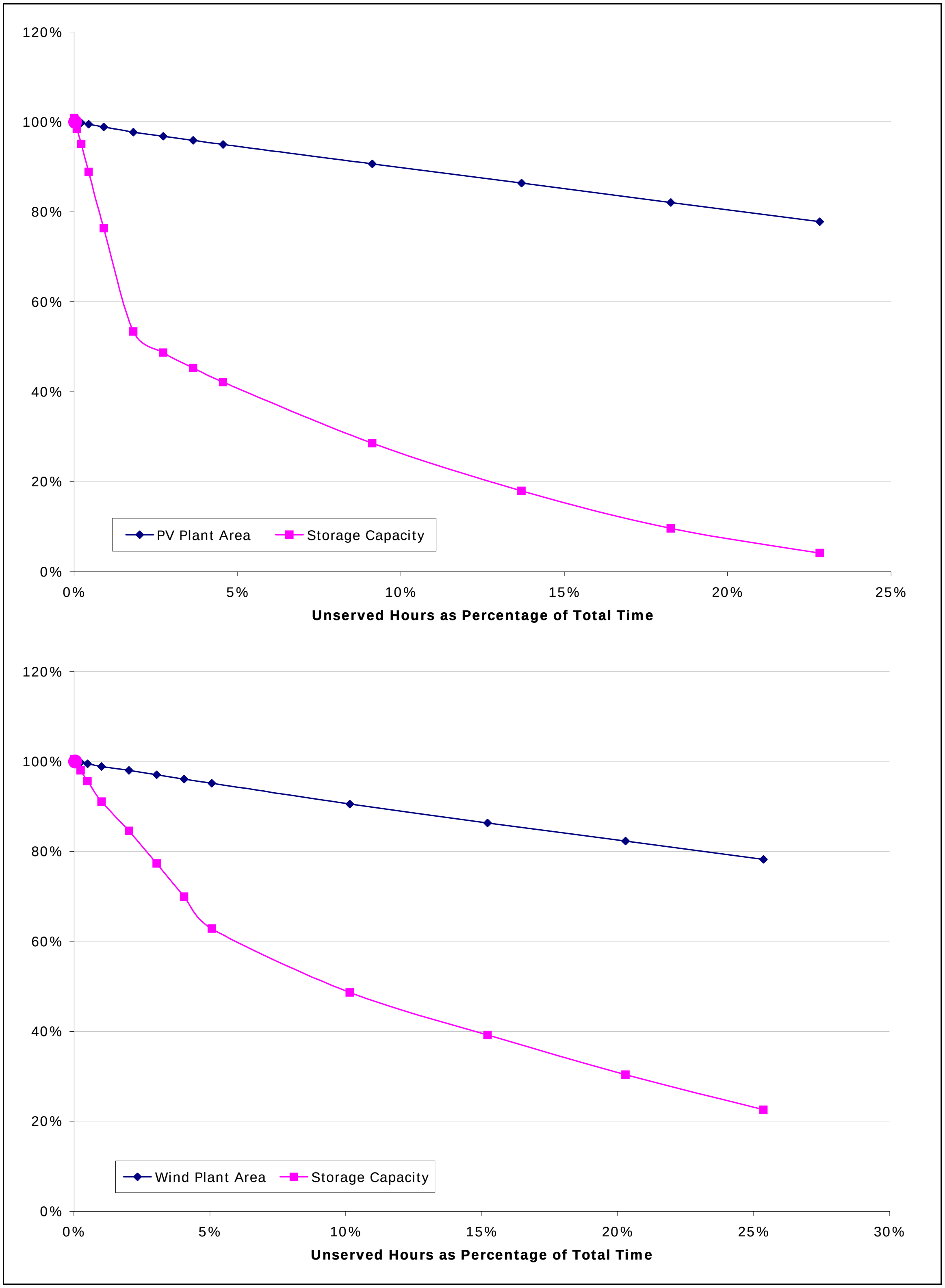

Figure 41: Sensitivity to unserved hours for PV plants (above) and wind plants (below)

The storage capacity reductions for wind are more modest but still substantial: at 5% unserved hours, plant area and storage capacity have declined by 5% and 37% respectively. At 25% unserved hours, plant area and storage capacity have declined by 22% and 67% respectively. Conventional backup averaging 66 GW would be required to ensure this system met demand. As with the PV system, the smaller plant size and storage capacity does not reduce the output characteristics of the storage system, which must still provide up to 620 GW on demand.

11.6 Sensitivity to Excess Energy Generation

All the modelling in this work uses the constraint that excess energy (that is, energy in excess of storage capacity that cannot be used to satisfy current demand) shall be no more than 1% of total demand. Once the overall energy balance has been satisfied (Equation 10), the excess energy production grows rapidly as a linear function of plant size. The excess energy constraint serves to fix an upper bound on plant area and a lower bound on storage capacity, while the constraint on unserved hours fixes the converse. However, the 1% maximum is entirely arbitrary; it allows an "apples to apples" comparison of renewable plants using a variety of input parameters, but any chosen excess energy figure, applied consistently, would do the same.

The use of such a low figure for the excess energy constraint may imply that excess energy is undesirable, but it is not clear that this would always be the case. A utility may choose to build a plant that produces a greater quantity of excess energy for export markets, to produce an ancillary commodity such as hydrogen for transportation markets, or to provide a buffer in the case of extreme weather events. In any case, the utility is not required to accept excess energy production; it could simply elect to shut down renewable generation until storage was once more able to accept energy. This analysis investigates the consequences to plant area and storage capacity of accepting quantities of excess energy up to 100% of the total demand.

When the excess energy constraint is relaxed, both PV and wind systems experience a large decline in storage capacity for only a small increase in plant area, according to Figure 42. For PV systems, a 19% drop in storage capacity—from 77 days to 63 days—is attainable by allowing the excess energy production to increase from 1% to 5% of total demand. This remarkable improvement comes with only a 3% increase in PV plant area (1,092km^2). Wind systems experience a smaller but still significant 11% drop in storage capacity, from 108 days to 96 days, for the same increase in excess energy production, and a 781 km^2 increase in plant area. If the system is allowed to produce excess energy equivalent to total demand (100% excess), the PV storage capacity requirements drop by 48% to 40 days, while PV plant area increases by only 8% in total. For wind, the storage capacity drops by 36% to 70 days, for an 8% increase in plant area.

What is happening is that storage is allowed to remain at full capacity for a greater proportion of the time modelled. However, a pure technical analysis such as this one does not assist in determining the "best" level of excess energy generation. The optimal excess energy generation would likely be determined by using (among other things) an economic analysis to find the point where the marginal cost of installing more PV panels would equal the marginal savings in reducing storage capacity, but that kind of computation is beyond the scope of this work. What is clear is that the storage capacity is very sensitive to allowable excess energy generation, and that the manipulation of this constraint may allow a much smaller storage capacity to be used for only a small penalty in plant area.

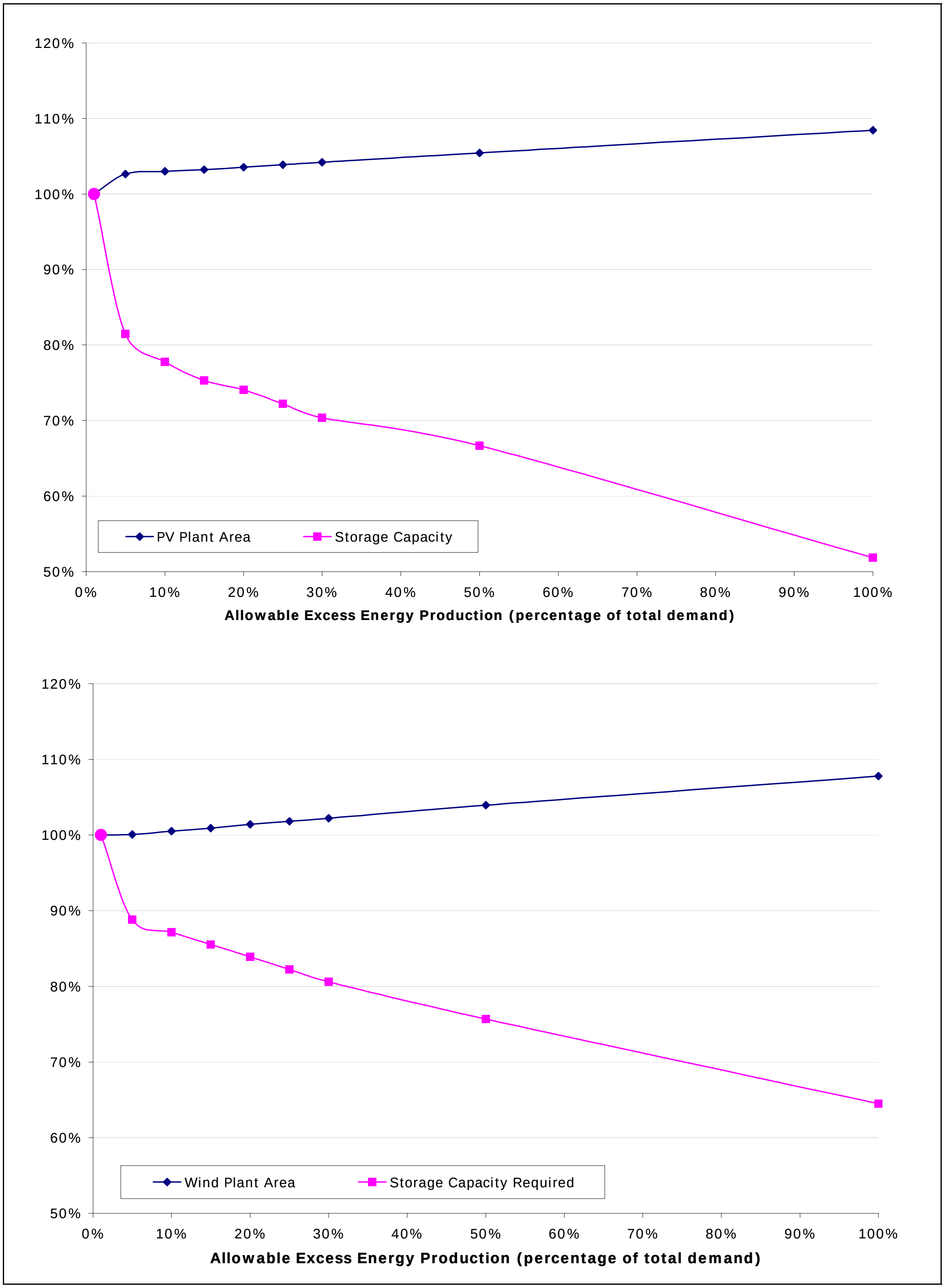

Figure 42: Sensitivity to excess energy production for PV plants (above) and wind plants (below), normalized to results for 1.0% maximum excess energy.

12. Conclusions

The main findings of this work are as follows:

- **Historical "backcasting" is a powerful tool for evaluating renewable energy systems.** The use of historical data dispels the doubts often attached to stochastically generated data, by allowing the modelling of several dispersed renewable plants under actual climate conditions. Similarly, the use of several consecutive years of climate data (nine or ten years in this work) ensures that the modelled climatic fluxes are representative of actual weather conditions. The 2000 hourly electrical demand used in this work may contain small errors due to the plethora of data sources used, but there is little doubt that it portrays an electrical demand pattern very close to the actual one for that year.

- **Solar photovoltaic systems require the lowest land areas and storage capacities of the modelled technologies but the highest nominal generation capacity and average storage output power.** PV plant area requirements ranged from 41,328 km^2 for Midland-Odessa, Texas to 71,938 km^2 for Seattle, Washington. These areas are 59% and 177% larger than the 25,921 km^2 that Turner—using aggregated annual data—estimated would be required to meet US electrical demand [11]. The benefits of the hourly approach taken here were further illustrated by the IESVic ESM's ability to model the energy storage systems necessary to allow the renewable plant to meet demand when climate fluxes are absent—systems that Turner acknowledged were necessary, but was unable to treat quantitatively. The required storage capacities for photovoltaic systems ranged from Midland's 76 days of average demand to 266 days for Seattle. These huge storage capacities are partially the result of the modelling constraints chosen, but are indicative of the scale of the undertaking required.

Although the PV systems perform relatively well in land area and storage capacity requirements, they require very high power output capacities. The modelled PV systems have installed capacities ranging from 2.9 – 5.1 TW, 3.6 – 6.3 times as large as the 811 GW installed capacity of the US electrical system in 2000. In addition to this, the storage system requires a peak output capacity of 617 GWh/h, itself comparable in size to the current US generating system. The average storage output for the modelled PV systems is between 370 – 380 GWh/h, equivalent to over 300 large conventional power plants.

- **The performances of solar technologies are strongly dependent on the plants' locations relative to electricity demand.** The bulk of the 2000 US electrical demand is located in the Eastern time zone, reflecting that region's high industrial, commercial, and population density. Most of the modelled solar plants, by contrast, are located in the Central and Pacific time zones, where solar insolation tends to be higher. Although the location of the solar plant was expected to play some role in evaluating its suitability, it was surprising to see just how influential a factor it was. The Nevada plants were expected to be among the better-performing locations, due to the high insolation in that region, but were instead among the worst. Eastern locations such as Philadelphia, on the other hand, were among the best performers, despite having mediocre insolation. In fact, there were generally greater performance differences between time zones than within them: all the Pacific locations required larger land areas and storage capacities than all the Central locations, most of which themselves required larger storage capacities than the Eastern locations. The best explanation for these variations in performance seems to be that the Eastern and Central plants' outputs are more closely matched to demand, reducing the requirement for storage. An alternative explanation may be that the Pacific locations were all near mountain ranges, which obscure the sun for a number of hours each day, especially during winter.

- **Decentralizing solar production does not improve plant area or storage requirements by appreciable amounts.** In addition to the single PV locations described above, a number of combined PV locations were modelled. In these situations, the plant area was divided evenly among two or more locations, each using its own insolation characteristics to generate electricity. Although the decentralization of generation capacity may be desirable for a number of reasons, there are few performance improvements over single locations. The plant areas, storage capacities, and peak storage outputs all fall within the range bounded by the single locations; only the average storage output shows a small improvement for some combined locations, dropping 10 GWh/h to 360 GWh/h.

- **Wind systems require large amounts of land and have high storage capacity requirements, but have lower nominal output capacities and storage power generation requirements.** The best-performing single wind location, Dodge City, Kansas required almost 203,000 km^2 of plant area, rivalling in size the entire urbanized area of the United States in 2000. At the other end of the scale, North Bend, Oregon required a wind plant area of over 446,000 km^2. The storage capacities required were also much higher than for PV systems, ranging from 257 days of average demand for Pierre, South Dakota to 506 days for Goodland, Kansas. These larger capacities reflect the much longer outages characteristic to wind systems; while it is virtually assured that there will be some solar radiation every day, most locations can experience several consecutive days with little to no wind. During these periods, the storage system will be responsible for meeting demand. However, in comparison to the very large generating plant capacities for PV systems, wind plant capacities ranged from 1.3 – 2.7 TW; still much larger than the current conventional generating system, but lower than the 2.9 – 5.1 TW required by PV systems.

Although the wind systems require higher storage capacities than PV systems, they do so at a lower level of storage generation output. Unlike solar radiation, which is present only during daytime hours, wind is present most of the time, albeit often at low levels. This means that the storage system will most often supplement wind generation rather than standing in for it entirely, as in the PV systems. The result is that the average storage output for the single locations ranges between 265 – 324 GWh/h. In further contrast to the PV storage systems, which rarely generate less than 275 GWh/h (see Figure 24), wind systems are required to generate at low levels quite frequently (Figure 31). The storage output distribution for wind systems is also more spread out than for PV systems. This may be a mixed blessing: on one hand, the lower average output levels of the wind storage systems place a smaller burden on the generating equipment; on the other, the output levels of the wind storage systems fluctuate over a much wider range according to wind levels, making the storage output more difficult to predict.

- **Wind systems are not sensitive to location relative to demand.** In comparison to PV systems, which experienced large variations in land area and storage requirements depending on the plant's location relative to demand, wind systems' performance does not seem to change at all. Performance was much more dependent on average wind speeds, regardless of the location. Once more, this is due to the much more random behaviour of wind compared to solar output; solar plant output corresponds roughly with each day's demand curve (see Figure 23), while the correlation for wind is very weak (see Figure 28 and Figure 29).

- **Decentralized wind systems outperform single locations in both plant area and storage requirements.** Each combination of wind locations modelled required either a lower plant area or storage capacity than the individual plants alone, and some outperformed the constituent locations in both. For example, Amarillo/Dodge City's plant area of 197,516 km^2 is lower than the >200,000 km^2 area required for each individual location, and its 108 day storage capacity is markedly lower than Amarillo's 276 days or Dodge City's 366 days. Indeed, it is in storage requirements that the performance improvements of combined wind locations are most apparent. The storage capacities for the combined wind locations range from 108 – 294 days, in most cases far below the requirements for individual locations. In fact, the 294-day requirement for the Dodge City/Casper combined location appears to be something of an outlier; the second-highest storage capacity is for Amarillo/Pierre at 208 days, far below the required storage capacity for even the lowest individual location. Combined locations also tend to shift the storage output distribution further to the low end of the range (Figure 31), further increasing the advantage wind systems have over PV systems in this area.

- **Hybrid wind/PV systems show some promise for mitigating the disadvantages of each technology.** The best performing of the wind and PV systems (Midland-Odessa and Amarillo/Dodge, respectively) were used to evaluate the performance of combined wind/PV systems. A large number of hybrid systems were modelled by varying the relative contributions of each generating technology. The most interesting result was this: up to a 35% wind penetration, the system storage capacity does not increase over that of a pure photovoltaic system (77 days). Since PV systems have, in general, much lower storage capacity requirements than wind systems but much higher nominal power output capacity requirements, this result points to a possible means by which the total system output capacity could be reduced without giving up low storage sizes. Furthermore, the storage output distribution for hybrid systems changes very quickly as the wind proportion increases, bringing it close in shape to the distribution for wind systems alone (Figure 35). This means that the storage will need to function near its peak output power capacity less frequently. Hybrid wind/PV systems, in short, can minimize storage capacity, lower the required installed capacity relative to PV systems alone, lower the required plant area relative to wind systems alone, and cause the storage system to operate at an average level of power output close to that of wind systems.

- **For both wind and PV systems, plant areas and storage capacities are sensitive to storage input and output efficiencies.** Storage is the great unknown in this work. Since there are no examples of energy storage facilities anywhere near as large as those modelled in this work (and no prospect of any being built soon) it was necessary to use a more or less arbitrary estimate of the storage input and output efficiencies. The 80% input/60% output efficiencies used may correspond to an electrolyzer/ fuel cell combination like those envisioned in many hydrogen-economy scenarios, but it should be emphasized that it is at this point no more than an educated guess. Because of this uncertainty, the sensitivity of the wind and PV systems to storage efficiencies was evaluated. It was found that, as expected, the renewable plant area increased as the roundtrip storage efficiency decreased, due to the increased energy losses in the storage throughput. The plant area was unaffected by the specific mix of input and output efficiencies used to arrive at a given roundtrip efficiency. Storage capacity, on the other hand, was very sensitive to the output efficiency, and less so to the input efficiency. The required storage capacity rises significantly as output efficiency decreases, but *decreases* slightly as input efficiency becomes lower (Figure 38). What was surprising was that storage capacity was sensitive to input efficiency at all; the output efficiency has a substantial effect on storage capacity since the storage will need to hold enough energy to overcome losses in the output process, but the storage system is blind to losses incurred at its input. The most likely explanation is that a higher input efficiency results in earlier storage saturation and excess energy generation, forcing the binary search algorithm to increase the storage size to meet the modelling constraints.

- **Storage capacities are very sensitive to optimization constraints.** As described in Chapter 7, the optimizations in this work were performed using two binary searches: the first to define the relationship between plant size and storage capacity, and the second to discard unworkable systems to arrive at a specific combination of the two. The first operated by constraining the allowable number of unserved hours to no more than four per year, on average. The second constrained the amount of excess energy the plant produced to no more than 1% in excess of demand. It was found that relaxing either of these constraints had significant effects on the results. If the allowable number of unserved hours was increased, both the plant area and storage capacity requirements dropped significantly (Figure 41), although supplemental generation would be required to meet demand during these times.

More interesting were the effects of increasing the amount of allowable excess energy the plants could generate: for both wind and PV systems, the required storage capacity dropped sharply for a relatively small increase in plant size. For instance, if the Midland-Odessa plant was allowed to produce 25% energy in excess of demand, its plant area would increase by only 4%, but the storage capacity would decrease by 28%, from 77 to 56 days. Since renewable generation plants could simply shut down during periods of excess generation, these results point to a potentially interesting method of reducing storage capacity from the very high levels recorded in the main results of this work.

12.1 Discussion

All of the renewable systems described in this work would require the industrialization of large expanses of land—much of it with great scenic value—comparable in magnitude to the entire urbanized area of the United States. In terms of installed generating capacity and land area required, it would be several times larger than the current electricity infrastructure. The environmental effects of this level of infrastructure development—from resource extraction to manufacture to generation to storage to transmission—are unknown, but will doubtless be substantial. If transportation (roughly two-thirds of the current overall energy demand) were brought under the aegis of electricity—as in many hydrogen-economy scenarios—the land area and storage requirements would be multiplied accordingly.

The power densities of the renewable technologies in this work range from 10 – 16 $W \cdot m^{-2}$ for PV systems, and 1.0 – 2.8 $W \cdot m^{-2}$ for their wind counterparts. These power densities are for the generating plants alone; they do not include the areas required for extraction and refinement of the raw materials for the plant, nor do they account for storage facilities, transmission and related infrastructure. Renewable power densities—already an order of magnitude below those of conventional generating plants—would certainly drop even lower if these factors were taken into account.

This work does not deal with the economic aspects of large-scale renewable installations, preferring to leave such issues to those more qualified to deal with them. However, many technical papers on renewable energy include the claim that renewable technologies are dropping in price, soon to reach the point where they will be cost-competitive with conventional forms of generation such as natural gas, coal, or nuclear fission. This claim ignores the enormous storage and/or backup systems required to enable renewable technologies to meet society's demand for energy services. Without storage or backup, renewables *may* become cost-competitive with conventionals, but they will *not* be competitive in performance, as Figure 1 indicates. Storage and backup technologies may allow renewables to perform as well as conventional technologies in meeting society's demand for energy services, but integrated renewables/storage systems will likely be more costly than conventional technologies for some time to come. The results in this work indicate that such a system would require storage technologies with capacities ("tank sizes") large enough to satisfy weeks of average demand, capable of sinking several terawatts of electricity, and with generation capabilities equivalent to hundreds of large conventional power plants, in addition to the renewable generating capacity required.

Of course, none of the above factors precludes a move to renewables. People may consider the trade-offs and decide that such a transformation is worthwhile nonetheless. However, for all the public awareness of the problems and unpleasant compromises inherent in our current electricity generation technologies, little attention is devoted to those of the major renewable alternatives. The analysis presented in this work is intended to spark some discussion of the issues of the scale requirements and overall technical feasibility of renewables. Of course, it does not exhaust the range of possible considerations; for example, the very important questions of the economic, social and political feasibility of such a wholesale transformation of the electricity system.

12.2 Future Research

As mentioned above, the renewable plant areas in this work are, on balance, likely to err on the side of optimism. For a variety of reasons listed in Chapter 1, the actual plant areas will probably be much larger. Just one refinement—accounting for changes in air density at higher elevations—could increase wind plant areas by over 10%. Similarly, it is likely that a more sophisticated photovoltaic model—one that took into account the reduced efficiency of PV panels in low light conditions, for instance—would also result in larger area requirements for these systems. Future versions of the IESVic ESM ought to include these factors, among others.

Other results in this work indicate some promising avenues of research. One of the more interesting is the question of how renewables will interact with conventional technologies at lower levels of penetration. For example, how much renewable capacity would be required to satisfy 30% of electrical demand? How much conventional capacity is displaced by a given level of renewable capacity in the system? How do renewables differ in their interaction with peaking technologies such as natural gas generation compared to baseload generators such as nuclear fission?

The high correlation of PV performance with the plants' locations relative to demand also raises some questions. Recall that the Nevada PV plants performed very poorly relative to expectations based on the high levels of insolation in those locations. Would their performance improve if they were exclusively dedicated to satisfying local demand, such as California's?

There is a set of complex optimization problems to be solved in order to find the best-performing combinations of wind plants, or of wind/PV hybrid systems. In this work, combined locations were selected on a more or less arbitrary basis, and the analysis of wind/PV hybrid systems merely used the best-performing locations for each technology. There is no reason to suppose that the locations chosen resulted in the best-performing combinations, though they are undoubtedly broadly representative of the results that can be expected.

This work made a number of simplifying assumptions, one of the largest being the decision to aggregate the entire US hourly electrical consumption into a single hourly demand vector. While this is a great improvement over methods that rely on annual aggregate consumption figures, it tends to subsume important information into one figure. Although the results presented here are minimum figures, it may be possible to mitigate renewables' land area and storage requirements to some degree by disaggregating electric demand and building a more realistic networked model of a renewables-powered North American electricity system. In such a system, decentralized plants producing electricity in excess of local demand would first attempt to export it to other regions based on their requirements, resorting to storage only if there were no export markets available. In order to achieve this in a realistic manner, the model will need to include a module to calculate energy losses in power conditioning and transmission.

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