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Analysis Tools for Sizing and Placement of Energy Storage in Grid Applications

A Literature Review

MG Hoffman
MC Kintner-Meyer
A Sadovsky
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September 2010

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Richland, Washington 99352

Executive Summary

The purpose of this report was to review pertinent literature and studies to identify the current state-of-the-art models and analytical tools that optimize the siting, sizing and economic value of energy storage in a smart grid infrastructure.

Over the last decades, significant research and development has been conducted to improve cost and reliability of energy storage systems. Relatively little work has focused on engineering tools for integrating energy storage into existing or future electric grids. This literature review revealed that only a few software tools partially address the needs for placement, sizing, and overall control strategies of stationary energy storage within a smart grid infrastructure. None of the tools captures the benefits of energy storage comprehensively, which would reveal all of the potential values. None of the tools or models reviewed provides optimization features that seek optimal placement and sizing options within a transmission or distribution system context. Given the findings of this literature review, this report highlights the need for tool development to fill the gap in the grid analytics. It provides some recommendations of guiding principles for advancing the analytical capabilities needed for the engineering and grid planning communities.

In the future smart grid environment, energy storage can potentially deliver multiple benefits that will enhance grid performance, operability and security together with reducing energy production and delivery costs. The many functions of energy storage include its ability to:

- offset additional need for peak generating capacity
- enhance optimal operation of existing generation facilities
- integrate intermittent renewable energy technologies
- provide ancillary services such as load following, area regulation and spinning reserve
- reduce transmission congestion
- defer transmission and distribution upgrades and provide an alternative to inflexible lumpy transmission and distribution capacity additions
- support and enhance demand response resources.

Energy storage can be implemented as modularized and potentially transportable storage systems. The latter could be used from months to years at a particular site and then easily moved to other sites and matched to system growth in an economic and flexible fashion.

Energy storage mitigates some of the current and future challenges that grid operators face to improve the overall economics of the infrastructure while reducing the overall carbon footprint and providing reliable services. Specifically, the challenges include managing peak demand, resolving transmission line congestion, and integrating renewable energy technology in a climate of financial risk adversity that will limit new transmission construction. Another challenge or barrier for the market acceptance of energy storage is the fact that most stakeholders have limited knowledge about the value of energy storage technology, compounded by the fact that grid operators are unclear of how to control it to maximize the entire value of this new technology.

As the U.S. grid transitions toward a smart grid, it will require new technologies and market designs that will utilize existing resources more efficiently and incorporate new entrants and players to providing grid services. Energy storage is likely to play a significant role in providing a spectrum of grid services. Demand side resources are also expected to compete with generation and energy storage resources for similar grid services. To design an optimal or cost-effective portfolio of new and existing components to meet the grid needs requires sophisticated tools that reveal all possible values that each technology could deliver. Because energy storage can provide a broad spectrum of grid services, it becomes increasingly important to model and quantify the sum of all individual values in a consistent manner.

There are numerous energy storage demonstration and research projects going on around the world. In Europe KEMA's GROWDERS project is demonstrating transportable energy storage systems in France, Spain, the Netherlands and Germany to develop an assessment tool for optimal distribution network management and provide conceptual directions for a European Union regulatory framework concerning energy storage. In the United States, the Electric Power Research Institute (EPRI) has an ongoing distributed generation and energy storage program, which includes a smart grid "integrated distribution energy resources management" project on the FirstEnergy system in New Jersey.

The Department of Energy's American Recovery and Reinvestment Act (ARRA) stimulus funding has 37 projects with a combined value of $637 million, which combine smart grid and energy storage functionality. Additionally Recovery Act funding of $2.4 billion is directed towards aiding vehicle battery and component manufacturers. American Electric Power (AEP), the largest United States electric utility, sees vehicle battery manufacturing capability as critical to providing battery technology for their vision of community energy storage (CES). These projects will raise the profile of energy storage significantly with the public and energy regulators. Questions from regulators are almost certain to follow regarding best use of technologies and locational benefits.

The challenges facing energy storage to provide the above services are numerous. The ability to specify storage related applications and to quantify their benefits, including value propositions and placement options would be critical to the adoption of energy storage technology. The lack of regulatory rules to give utilities permission to implement distributed storage, along with limited risk/reward sharing mechanisms between utilities and customers, greatly impact the ability to permit siting energy storage projects. Coordination among stakeholders will be required to optimally connect storage to the grid and aggregate benefits in a manner that will benefit all stakeholders.

For energy storage to be successful in the utility marketplace, it will require that multiple value streams be optimized across ancillary services and energy markets, as well as a grid infrastructure investment. Monetization of energy storage applications requires market structures and rules that allow for this new technology to participate. It requires grid performance targets and goals that are less constrained by the limitations of today's generator performance characteristics and more based on desirable characteristics of the overall system behavior. For non-marketable services, energy storage must compete against best-practice alternative grid asset options. For market adoption, all benefits must be aggregated to yield an acceptable or even better return on investment than competing alternatives. This will require aggregation of multiple benefits for an energy storage system rather than focusing on a single purpose use, such as peak shaving or system reliability improvements. Currently utilities have limited knowledge and familiarity with energy storage technologies from the perspectives of planning, siting, sizing, control strategies, operational considerations, and maintenance, and general engineering practices of energy storage. Eyer and Corey describe the need to be able to analyze and prioritize on a monetary basis various energy storage applications for maximizing the value creation (Eyer and Corey 2010).

Studies, models, and planning tools included for this literature review focused on storage systems and technologies that would be appropriate for transmission and distribution use, which would provide services such as peaking, ancillary services, infrastructure deferral, renewable energy technology integration, and congestion relief. The models included in the review are classified as commercial and non-commercial models (free of charge). The table below shows a condensed list of important characteristics that would be required for optimally locating and minimizing cost of energy storage. As can be seen, none of models has all of the important characteristics all in one software package that would allow assessment of energy storage in the smart grid frame of reference. Additionally, none of these models is specifically focused on optimizing storage. Instead, they are used for calculating system capacity, transmission modeling and/or generation source placement.

Table ES- 1. Summary Characteristics of Reviewed Energy Storage Models

Non-commercial Model	Homer	ReEDS	NEMS	RETScreen	Energy Plus	Kermit	GridLabD
Characteristic/Component (below)							
Locational marginal pricing (LMP)		X	X	X			
Energy storage	X	X	X	X	X (a new module has been developed)	X	X
Arbitrage	X	X				X	
Energy storage by node	X			X	X		X
Round trip efficiency	X	X	X	X		X	X
Minimizes system investment	X	X	X				
Show single or multiple ancillary service value streams	Yes	No	No	Yes	No	Yes	No
Aggregation of multiple ancillary services value streams?	No	No	No	No	No	No	No

Commercial Model	GE MAPS	Ventyx System Optimizer/ ProMod	Power World	Energy 2020	Integrated planning model (IPM)	Dynast ore	SynerG EE
Characteristic/ Component							
Locational marginal pricing	Yes	Yes - ProMod	Yes	Yes	Zonal basis (cut plane)	No	No
Energy storage	Yes - basic option is pumped Hydro	Yes - ProMod	Possible	Yes - including efficiency	Pumped hydro only	Yes	No
Arbitrage	Yes	Yes - ProMod including efficiency	Hard but possible	Yes	No	--	No
Energy Storage by node	Yes	Yes - ProMod	No	Yes	No	Yes	No
Round trip efficiency	Yes	Yes - ProMod	No	Yes	No	No	No
Minimizes system investment	No	Yes – only Optimizer	No	No	Yes	No	No
Show single or multiple ancillary service value streams	Yes	Yes	Yes	Yes	No	Yes	No
Aggregation of multiple ancillary services value streams?	No	No	No	No	No	No	No

The tables above show that there are non-commercial and commercial models that reveal ancillary services values. Unfortunately no model reviewed in this study aggregates multiple ancillary services values from energy storage systems, much less does so for multiple technologies.

To optimize the value of energy storage in distribution or transmission systems, the full range of ancillary services, including regulations services, load following and automatic generation control, need to be modeled on a time scale from seconds or minutes over a period of a year, by a comprehensive energy storage model. A new modeling tool with these capabilities could change how the grid is used and radically reduce the costs for ancillary services.

Energy storage is likely to become integral to the grid, just like electric motors have become ubiquitous in everyday life over the last century. Achieving this will require development of modeling tools that utilities can use to compare competing technologies and application benefits. This will allow the utility to optimize siting and minimize long-term cost of the energy storage system components they will need to deploy to enable benefits that the future smart grid is expected to offer. Future implementation of smart grid infrastructure may, in part, depend on the availability of such tools. Making one or more successful models available to utilities could significantly change the pace at which the US grid transitions to a modern infrastructure that will meet national energy security and climate goals.

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Acronyms and Abbreviations

AEP	American Electric Power
ASME	American Society of Mechanical Engineers
ARRA	American Recovery and Reinvestment Act
BESS	battery energy storage system
CAES	compressed air energy storage
CEC	California Energy Commission
CES	community energy storage
CSP	concentrating solar plant
DC	direct current
DESS	distributed energy resource(s)
DOE	U.S. Department of Energy
ECP	electricity capacity planning
ELD	electricity load and demand
EMM	electricity market module
EPRI	Electric Power Research Institute
ERCOT	Electric Reliability Council of Texas
GIS	geographical information system
GVEA	Golden Valley Electric Authority
HVAC	heating ventilating and cooling
IEEE	Institute of Electronics and Electrical Engineers
IPM	Integrated planning model
LESR	limited energy storage resources
LMP	locational marginal pricing
MW	megawatt
MWh	megawatt-hour
NASA	National Aeronautics and Space Administration
NEMS	National Energy Modeling System
NYISO	New York Independent System Operator
ORNL	Oak Ridge National Laboratory
PNNL	Pacific Northwest National Laboratory
ReEDS	Regional Energy Deployment System
RETs	renewable energy technologies
SMES	superconducting magnetic energy storage
WECC	Western Electricity Coordinating Council

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Introduction

This literature review was undertaken in response to an increasing number of questions raised by the electric infrastructure planning community concerning planning tools that would address the unique characteristics of energy storage in a future smart grid environment. There have been many studies done on energy storage over the last several decades. The scope of this review was limited, in general, to studies done in the year 2000 or later. These studies cover a wide range of technologies, see Appendix A. Options range from various short timeframe devices, such as superconducting magnetic energy storage (SMES), used for reliability purposes through battery systems that can be modularized to allow quick delivery and ease of installation for any ancillary service use or distribution system purpose, to large-scale classic pumped hydropower systems, which can back up the largest single generation unit, single contingency outages for major utilities.

In a smart grid environment, the question of optimal storage technology type, sizing and placement that maximize the value of the investment has not been addressed in a systematic way. Previously, the options for locating pumped hydropower systems have been limited to just a few locations, and thus have predetermined siting issues. In the United States, 99% of energy storage currently in use is in the form of pumped hydropower[1]. ProMod software is used widely in the Western Electricity Coordinating Council (WECC) region to assess selected capacity additions involving pumped hydropower. With the advent of smaller and modular storage systems (batteries, for example) that could be placed virtually anywhere in the bulk power system, the need for new modeling tools that assess storage placement and sizing arises.

Study Objectives and Approach

This report addresses the following questions:

- What literature, studies or reports exist that include references to analytic tools for energy storage sizing, location, and optimization in the smart grid environment?
- What capabilities do transmission or capacity modeling tools have for energy storage sizing, location and optimization in the smart grid?
- Do the reviewed transmission capacity models meet the need to optimize energy storage sizing, location and optimization for grid implementation?
- Are there further actions that need to be taken to model electric utility use of energy storage and if so, what steps could be taken?

[1] Electric Power Research Institute (EPRI), slide 3, Energy Storage Systems for the Electric Enterprise: Markets, Value and Costs Analysis, 2d Energy Storage Summit, 25 May 2010, San Diego CA

This review explored the capabilities of tools and study methods used currently by transmission planners to place and size energy storage systems as part of the infrastructure capacity planning process. A search was conducted for analytical tools used in the electric power infrastructure planning communities, including energy storage sizing and transmission and distribution planning tools. The search included other non-electric energy applications, such as thermal energy storage for cooling commercial buildings, with the goal of gleaning insights into sizing and controls methodology that may be applicable for electric power applications.

Because this review was limited to energy storage technologies that are supportive of the smart grid concept, which requires modularity or ease of installation, studies of management systems to optimize the use of pumped hydropower facilities that have siting limitations were not included. Large compressed air energy storage (CAES) systems are also limited in their siting flexibility and consequently, studies for management of these systems were not reviewed.

The intent of this report is to shed light on the capabilities of current energy storage modeling tools and thereby, provide both policymakers and software developers a better understanding of what needs to be accomplished in the future.

Background

Energy storage is neither a source of generation nor a consumer of electric energy (other than losses internal to the particular system, which is measured as round trip efficiency), but it can be both at certain times. It can function as a generator with limited energy (during the discharging mode) and as a load during the charging mode. The fact that energy storage has a limited energy content creates a significant challenge to the planning process. Similar to a generator, energy storage injects electric power into the transmission or distribution system as needed for reliability or peaking purposes.

The history of implemented energy storage projects began with pumped hydropower over 100 years ago. Large pumped storage systems have been used to deal with peak demand or reliability issues, as well as single plant outage contingencies. To date, pumped hydropower systems were commonly used for bulk energy storage. These systems have large reservoirs, which allowed the transmission planning community to treat it as a generation asset dispatched during daytime (peak) periods, to meet peak loads and using off peak power to refill the reservoirs. With the emergence of small scale energy storage technologies such as chemical (batteries) and mechanical energy (flywheels), the need for balanced charging and recharging becomes imperative for the optimal utilization of storage devices.

In the last 20 years, there have been several non-hydropower energy storage projects of note. Puerto Rico Electric Power Authority completed start-up testing and began commercial operation of a 20-MW/14-MWh battery energy storage system (BESS) facility in April 1995 (Farber de Anda and Fall 2005). The battery system was installed to provide rapid spinning reserve and frequency control for the utility's island electrical system. Golden Valley Electric Authority (GVEA) in Alaska, in December 2003, installed a BESS to improve the reliability of service. In the event of a generation or transmission related outage, it can provide 27 MW of power for 15 minutes (http://www.gvea.com/about/bess/). There is also the 5-MW peak, 2.5-MWh BESS that is now in commercial operation at the Exide Battery Recycling Facility in Vernon, California (http://www.sandia.gov/ess/Publications/Conferences/2002/HUNT%20-%20VRLATestDataALandCA.pdf). As these few examples indicate, the application of the storage varies over a wide range. Very little information is found in the literature discussing how each energy storage project was designed so that it would maximize its value to the overall system.

As utilities have dealt with issues of renewable energy technology integration and system reliability and demand response, they have initiated several energy storage technology proof-of-concept projects. For a wide-scale deployment or even for a deployment beyond the pilot state, the need for analytical tools that assess the optimal placement and control of energy storage becomes more and more apparent.

Discussion of the Value of Energy Storage

Energy storage can be instrumental to integrate renewable energy technologies on the rapidly evolving smart grid. Energy storage could be applied to time shift renewable energy from off-peak generation to on-peak times. Time shifting of renewable energy can also reduce transmission bottleneck potential by storing the energy close to the end user or by using underutilized transmission paths at night. The latter raises the overall capacity factor on the lines involved. This also has the potential to increase overall revenues for transmission providers who might not be able to carry the same renewable energy at peak load hours, causing the energy to be dumped or sold at lower value market.

There are detailed assessments and forecasts for energy storage technology and the benefits that certain end users will gain by adopting it. Table 1 provides a sample list of end users and benefits.

Table 1: Energy Storage Benefits by User (Eckroad 2002)

User	Benefit
Electric utilities	•Responsive supply system •Replace inefficient peaking power plants •Improve transmission and distribution equipment
Individual users (businesses/neighborhoods)	•Managing electricity costs •Reduce financial losses caused by outages
Independent system operators	•Balance regional loads •Stabilize transmission systems

EPRI provides estimates of the monetary savings that can be achieved through some of these benefits (Eckroad 2002). For example, the California Energy Commission (CEC) and the U.S. Department of Energy (DOE) estimate that over 10 years, time-of-use energy cost management is estimated to provide up to $4,021 million in benefits (Eckroad 2002). End-user financial losses can be reduced by up to $1,430 million, and up to $230 million can be saved in avoided transmission access charges (Eyer and Corey 2010).

Energy Storage in Particular Markets

The following provides an overview of some benefits that energy storage technology can provide to end users including a more detailed discussion of inefficiencies in certain market sectors and the role that energy storage technology can play in mitigating those inefficiencies. The goal is to document ways in which energy storage has been deployed or can be deployed by various market participants or for particular functions.

Ancillary Services

Ancillary service prices are often more volatile than energy prices (Hirst and Kirby 1997). EPRI also notes (Interconnected Operations Services Working Group 1997) that prices for contingency reserves vary hourly and exhibit the same kinds of fluctuations exhibited by energy prices. One particular use of energy storage in this area is to provide faster response services. According to EPRI, the capabilities of many energy storage systems are particularly well suited to providing shorter deployment durations.

As an example of an energy storage technology within this market niche, we can consider the ancillary service of regulation. Regulation is the most expensive ancillary service, and energy storage already plays a role in optimizing performance in this regard. The New York Independent System Operator (NYISO), for example, states that regulation is accomplished by committing limited energy storage resources (LESRs) and some demand side resources whose output or demand is raised or lowered to follow moment-by-moment changes in the load (NYISO Ancillary Services Manual 2009).

More broadly, KEMA Consulting notes that the increasing use of variable renewable generation resources can render grid operations more volatile (KEMA Consulting 2010). Ancillary services will need to play a larger role in reducing this volatility, and energy storage technologies can perform this role.

Electricity Supply

Ali Nourai of American Electric Power (AEP) has referred to energy storage as a "game-changer" for the utilities industry in "Utility AEP Plans Backyard Energy Storage" (LaMonica 2009b). The particular implementation of storage that Nourai refers to involves providing relatively small storage units to groups of houses within neighborhoods. This would be significant because of its security implications; collections of small storage devices are not as susceptible to attack as a single large device or power plant.

Another application of energy storage for utilities is grid stabilization. In contrast to AEP's "backyard storage approach", grid stabilization involves warehouse-sized installations of storage devices (for example, lead-acid batteries) that pump large amounts of electricity onto the grid for short amounts of time (LaMonica 2008a). This can equalize electricity supply and demand, and has the benefit of making generators run more efficiently and of ensuring steadier frequency.

Scope of Literature Review

A targeted literature search was performed with the assistance of the Pacific Northwest National Laboratory (PNNL) Reference Library staff. Their approach was to use key words related to energy storage analysis and designed to query a comprehensive literature database, including the following sources:

- Journal of Solar Energy Engineering -transactions of the American Society of Mechanical Engineers (ASME)
- Computers & Chemical Engineering
- European Power Electronics Journal
- Solar Energy
- Institution of Engineering and Technology Renewable Power Generation
- Applied Thermal Engineering
- Renewable and Sustainable Energy Reviews
- Energy
- 5th International Conference on the European Electricity Market
- Renewable Energy
- Energy and Buildings
- Power Engineering 2007: International Conference on Power Engineering - Energy and Electrical Drives Proceedings
- Applied Energy
- Electrical Engineering in Japan
- EPRI Technical Reports and Publications.

In addition to the above, the Lexis-Nexis tool was used to search the following sources:

Major Newspapers	MAJPAP
Magazine Stories, Combined	MAGS
Current Abstracts	CURABS
Journal of Physics Research	JLPHYR
Journal of Research of the National Institute of Standards and Technology	JRNIST
Journal of Technology	JNLTEC
Journal of Technology & Science	JNLTSC
Nanotechnology Business Journal	NANOBJ
Technology Business Journal	TECHBJ
Modern Power Systems	MOPOMG
The Electricity Daily	ELCDLY
The Electricity Journal	ELCJNL
Energy and Utility News Stories	ALLNWS
Energy and Utility Stories	ENENWS
Power Economics	POWRMG
Energy Optimization News	ENCON
Power Engineer	PWRENG
Power, Finance and Risk	POFIRI
PR Newswire - Energy Stories	PRNEWS
Public Utility News Stories	UTIL
Public Utilities Fortnightly	PUF
Financial Times Energy Newsletters	FTENRG
Generation Week	PGTMKT
Platts Energy Business & Technology	GEB
Global Power Report	GPR

We primarily focused on key words that were descriptors for planning tools, analytical tools, planning models, energy storage technologies, asset placement and sizing of storage, and optimization tools. The outcome of the first search was then reviewed for relevance and applicability. A total of 1,125 abstracts were reviewed and of these, 31 references were deemed sufficiently relevant to be submitted to a detailed review. This final cut set of reference material is categorized as shown in Table 2.

Table 2: Categories of Reference

Category	Percent of total
Technology related papers: categories storage by technology or subsystem	45%
Energy storage sector use: utility, industrial, commercial, residential	20%
Renewables related energy storage application	15%
Mechanical, thermal, miscellaneous	15%
Economic assessment of storage and policy	4%
Tools that analyze storage	<1%

Summary Review of Models with Energy Storage Modeling Capabilities

Both non-commercial and commercial software were reviewed in this study. Non-commercial models have been developed for academic and regulatory use, were typically developed by government agencies and are available at no cost. These models are sophisticated and the real cost to using them is the learning curve for both the software and utility concepts involved. These models include: HOMER; ReEDS; NEMS; RETScreen, and EnergyPlus. They are often used by electric utilities and regulators outside of the United States because of their low cost.

Commercial models, typically costing thousands of dollars, are offered for sale by private entities. These models are generally very sophisticated, require the input of large quantities of detailed data, and are used in capacity and operational planning, transmission network upgrade analysis and the preparation of long-term planning cases for submission to utility regulators. Commercial models include: GE MAPS; the Ventyx -- ProMod and System Optimizer; Power World; Energy2020; IPM, and Dynastore (the EPRI energy storage tool).

Most of these models will perform time slicing and optimization trade-offs between generation and transmission, provide the locational value of various resources, quantify the air quality impacts of generation and minimization of system investments, and have some ancillary service dispatch capability. A summary description of these models is presented below based primarily on information gathered by reviewing handbooks and published information on each software package and also by talking with vendor representatives.

Readers should note that the reviewed models frequently undergo revisions. Therefore, capabilities discussed below will likely change in the future.

Non-Commercial Models

Non-commercial models are described below.

National Energy Modeling System (NEMS)[2]
The problem of optimally determining power system characteristics, including the characteristics of various storage technologies to be used, occurs within the EMM (Electricity Market Module) of NEMS. Within this module, the optimization procedure is performed by the ECP (Electricity Capacity Planning) sub-module, which receives input from several sources, including the ELD (Electricity Load and Demand) sub-module (which, in turn, provides the ELD with approximate load curves).

The purpose of the optimization engine in the ECP is to project how the electric power industry will alter its future generating capability in response to changes in costs, technologies, demand, and other parameters. The ECP allows planners to consider the trade-off between investment and operations with a dispatching component.

[2] National Energy Modeling System. http://www.eia.doe.gov/oiaf/aeo/overview/

To quote the NEMS EMM Handbook, “The objective function of the planning component is to minimize the total, discounted present value of the costs of meeting demand and complying with environmental regulations of the entire planning horizon.”

The ECP allows planners to account for the following:

- New capacity additions
- Construction costs
- Computation of avoided costs
- Emissions banking
- Pollution control retrofits
- Capacity requirements.

The model uses a linear programming formulation and solves for multiple years simultaneously. Some of the constraints involved are as follows:

- Demand for electricity is met
- Minimum reliability requirements are met
- Emissions limits are not exceeded.

Other requirements include constraints on the storage technology. Energy storage can be used as a means of general load shifting or peak shaving. To maintain conservation of energy, there is a constraint imposed that requires that the dispatched energy be replaced in the storage unit at a later time plus the energy losses. However, the chronological order of charging or and discharging is lost in NEMS’s representation of the load in a load duration format. Using NEMS 9 timeslices to represent the entire load duration curve, load will be shifted by means of storage from the peak to the off-peak time periods within a season. Because of the loss of chronology in the time domain, this may mean that storage can only shift blocks of energy of the granularity of the timeslice definition, which is by season. This means that the storage strategy represents diverse storage strategies ranging from daily cycling (charge-discharge) to seasonal.

The amount of storage to use is a decision variable that is a component of the objective function. The model optimally selects the placement of storage in any of the 13 predetermined geographical EMM regions.

Regional Energy Deployment System (ReEDS)[3]
Like NEMS, ReEDS uses a linear programming approach to solve for certain decision variables pertaining to electricity generation. The objective function is a sum of costs that are to be minimized. The components of the objective function are as follows:

- Capital and operating costs of new wind plants
- Cost of new transmission for wind
- Capital and operating costs of new concentrating solar power (CSP) plants
- Cost of new transmission for CSP
- Capital cost of conventional generators
- Fuel and operation costs of conventional generation
- Capital cost of new transmission lines
- Capital cost of new storage capacity
- Fuel and operating costs of storage
- Cost of a carbon dioxide tax.

ReEDS considers four storage technologies: pumped hydropower, compressed air, batteries, and thermal storage. The model explicitly takes into account projected capital costs for installation, projections for fixed operations and maintenance, and projections for round trip efficiency of the storage technologies. Projections can be made through the year 2050.

Both the capacity of storage units and the dispatch of energy from those units are treated as decision variables. As with NEMS, energy dispatched from the storage units must be replaced. This replacement generation is also treated as a decision variable. The only difference to NEMS is that ReEDS represents the load duration curve with 12 timeslices as opposed to 9 in NEMS.

The storage variables also appear in other constraints. For example, ReEDS includes a reserve margin requirement constraint to assure that the total amount of energy (generated and dispatched from storage) will be sufficient to meet the demand in various peak periods. Similarly, there is a normal operating reserve constraint. Account is also taken of the round trip efficiency of the storage technology. The amount of energy needed to replace energy dispatched from the storage unit will be a function of the round trip efficiency of that unit.

[3] Regional Energy Deployment System (ReEDS) (formerly known as the Wind Deployment System or WinDS) http:www.nrel.gov/analysis/reeds/

HOMER[4]

HOMER helps users optimally determine the characteristics of micro power (kilowatt to 10s of kilowatt) generation units. In contrast to some of the other models considered, HOMER does not model the entire electricity grid, so the location of storage units and other components within the system modeled are not explicitly considered. Its principal value is that it helps users optimally configure localized electricity projects. The developers of HOMER are working on another model called ViPOR, which will model the entire grid.

HOMER provides the user with considerable flexibility. It can specify buying and selling constraints, and allow for the electricity generated to supply a user-specified range of the expected load. Like NEMS and ReEDS, HOMER models transmission line capacity. Additionally, the storage unit can be used to model arbitrage. HOMER also has the advantage of highly refined time slices – it has the capability of modeling by minutes within a given year.

EnergyPlus[5]

EnergyPlus is a building simulation model. It allows the user to enter various input parameters such as building size, desired method of heating, etc. To quote the EnergyPlus manual, "EnergyPlus is an energy analysis and thermal load simulation program. Based on a user's description of a building from the perspective of the building's physical make-up, associated mechanical systems, etc., EnergyPlus will calculate the heating and cooling loads necessary to maintain thermal control set points, conditions throughout a secondary heating ventilating and air conditioning (HVAC) system and coil loads, and the energy consumption of primary plant equipment as well as other simulation details that are necessary to verify that the simulation is performing as the actual building would." [p.1]

EnergyPlus does not perform the entire life-cycle cost analysis for the model it considers. The goal of the simulation is to extract data that can later be fed into software that does perform this kind of analysis. The output of EnergyPlus is therefore the input for other programs that perform analysis similar to what was described for NEMS/ReEDS/HOMER.

Newer versions of EnergyPlus incorporate storage capability. For example, Version 3.0 models storage technology by reconfiguring the photovoltaic model to separately account for inverters and storage systems. Additionally, a new thermal storage module has been developed wherein users are given the option of specifying the size of the storage unit.

RETScreen[6]

Clean energy project analysis software is a unique decision support tool developed with the contribution of numerous experts from government, industry, and academia. The software, provided free-of-charge, can be used worldwide to evaluate the energy production and savings, costs, emission reductions, financial viability and risk for various types of renewable-energy and energy-efficient technologies (RETs). RETScreen allows the user to assess a variety of different, clean energy technologies. These include wind energy, small hydropower, photovoltaic (on-grid and off-grid), biomass, and others. RETScreen compares these clean energy technologies to a

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[4] https://analysis.nrel.gov/homer/

[5] EnergyPlus software. http://apps1.eere.energy.gov/buildings/energyplus/ep_inut_creaton.cfm

[6] http://www.retscreen.net/ang/home.php

conventional “base case” specified by the user, to determine the financial viability of the proposed technology and to determine how cost effective the clean technology is relative to conventional technologies.

While RETScreen allows the user to model a variety of different technologies, the software follows the same general approach in each case. This approach involves the following five steps:

- First step: the user enters energy model parameters. These include, but are not limited to, the following: the location of the energy project, the type of system used in the base case, and the clean technology in the proposed case. Loads are also entered, where applicable. In this step, RETScreen calculates the annual energy production or energy savings.

- Second step: cost analysis. This step involves inputting various financial parameters such as initial, annual, and periodic costs for the proposed clean technology. The user can also enter benefits attained in the proposed case that result from avoiding certain base case costs.

- Third step: the user has the option of determining the annual reduction in greenhouse gas emissions. As with the financial data, the comparison is made between the proposed clean technology system and the user defined base case.

- Fourth step: the user enters additional financial parameters. These include avoided cost of energy, production credits, greenhouse gas emission reduction credits, inflation, discount rate, and others. RETScreen then calculates several financial indicators, such as the net present value of the project. A cumulative cash flow graph is also provided.

- Fifth step: the user has the option of determining how uncertainty in the financial parameters specified in step 4 affects the financial viability of the project.

The key outputs of this software are as follows:

- Development of a suite of new models to evaluate energy efficiency measures for residential, commercial and institutional buildings; communities; and industrial facilities and processes.

- Expansion of the RETScreen Climate Database to 4,700 ground-station locations around the globe and incorporation of the improved National Aeronautics and Space Administration (NASA) Surface Meteorology and Solar Energy Dataset for populated areas, directly into the RETScreen software.

RETScreen allows the user to model energy storage, in the form of a battery, for off-grid applications such as photovoltaic projects. In Version 4 of RETScreen, the same model is used for off-grid wind and other technologies. RETScreen suggests values of battery size to the user. This suggestion is made based on a formula involving the desired number of days of autonomy. The formula calculates the appropriate battery size by month, and the suggested battery size is the maximum of these monthly values over the year.

GridLab D[7]

This is open source software developed by PNNL and available at sourceforge.net. The software is designed to do detailed time series simulations, track consumer reaction, track costs and benefits in scenarios, extract impacts at higher levels and is focused on residential end use devices. Modules model a range of the electrical system including: generators, markets, transmission and distribution power flow and appliances. Customization of modules is possible and requires a degree of sophistication. The user interface is currently optimized for research efficiency and not graphically rich or easy-to-use. The model does not include energy storage capabilities.

Kermit

This is a software product used by KEMA to analyze the bulk power system for integrating renewable energy sources. This is not a commercial software product but an analysis tool for high-level study where automatic generation control must be modeled; control area interconnections simulated and generator inertia can be modeled by balancing authority, not nodes. The time span for modeling is generally 1 second to 1 hour, so a 24-hour model simulation can be done in a balancing area for wind, congestion and regulation services in 15 to 30 minutes. Energy storage efficiency and response rates are included in the model. The model is not optimized for transmission and distribution use and does not deal with transient response or load flow analysis. The model considers the location of renewable resources but not energy storage. KEMA is currently working on converting a German distribution planning tool, Elektra, for use in the United States for analysis of distribution feeders with high penetration of distributed generation and will include energy storage eventually.

Commercial Models

The commercial models reviewed in this study are discussed below.

GE MAPS

This package provides a full range of time slicing as well as transmission line capacity and generation costing. It can be used to consider locational marginal pricing of demand response and distributed generation and energy storage. It will also estimate energy storage arbitrage and deal with the round trip efficiency of storage. GE MAPS does not treat the minimization of system investment but can import information in zonal or nodal formats from other GE software products, and can be run in a parallel environment for faster simulation. Ancillary services dispatch is done with co-optimization of reserves. This model is widely used, and General Electric supports the model with data for all three major interconnections (Western Electricity Coordinating Council – WECC, Eastern Interconnection, and Electric Reliability Council of Texas, ERCOT) within the United States. Energy storage can be accounted for chronologically and by location.

Ventyx System Optimizer/ProMod

[7] http://sourceforge.net/projects/gridlab-d/

System Optimizer is a screening tool used with load curves to do system capacity analysis, and ProMod is a detailed production costing system that uses detailed direct current (DC) power flow for analysis. Normally System Optimizer can be used to screen possible futures and ProMod would be used to create detailed plans. Its time slicing limitation is for hourly load duration curves and is limited to only 1 week per month of analysis over a maximum 30-year period. Locational marginal pricing of demand response, distributed generation and energy storage are done with the ProMod module, and this module also has the capability of estimating arbitrage, including storage efficiency. Energy storage can be accounted for by location.

Power World

This model solves for instantaneous solutions to load balance, allowing it to display highly graphic depictions of system status. Time slicing is done with simultaneous auto stepping. This model presents depictions of the specified network topography based on loads, generation and line configurations in use at a particular point in time. It does not optimize generation and transmission scenarios or perform production costing. Locational marginal pricing of demand response, distributed generation and energy storage are done with "injection groups", which requires a detailed knowledge of how to use the product. The model will not consider energy storage arbitrage. Air quality impacts of generation must be assessed in post processing. Optimal costing relies on exogenous data. In addition, energy storage cannot be accounted for by location.

Energy 2020

This model uses load curves to balance generation in a manner similar to using debits and credits in standard accounting. Weather, fuel prices, regulation policies and energy contracts are all part of the model, which makes it useful for agent-based analysis to aid policy decisions by regulators. Optimization trade-offs can be performed and locational marginal pricing is supported for energy efficiency, demand response, distributed generation and energy storage. Energy storage can also be accounted for by location. The model can address air quality impacts of generation as well as the integration of renewables with energy storage. It does not minimize system investment costs or currently handle ancillary services dispatch, but data files can be transferred to Power World for this functionality. Energy 2020 can be used to predict outage costs.

Integrated Planning Model

Time slicing is done with segments and percentages of segments based on high load, low load, and shoulder load hours. The model is not chronological. Optimization trade-offs can be based on cut plan segmentation. Locational marginal pricing is performed on a solid basis, energy efficiency and demand response can be entered as S curves, and distributed generation can be modeled. However, energy storage in the form of pumped hydropower is all that can be modeled. Energy storage is accounted for chronologically and not by location. Ancillary services load following and spinning reserve can also be modeled. This model will determine air quality impacts of generation and can estimate minimum system investment.

Dynastore

This energy storage only software can model 12 weeks per year for up to 30 years. Hourly modeling can be done within a particular week. The model does not deal with capacity expansion of transmission versus generation. Originally this model was used to minimize operating costs of a range of thermal plants from various utilities that were part of the original study. There are no provisions for locational marginal pricing or energy storage locations on a power grid. The model does not estimate arbitrage or round trip efficiency. Fuel types can be specified, but there are no air quality impacts. The model can deal with ancillary services dispatch of energy storage for spinning reserve, load following, and frequency regulation.

SynerGEE[8]

Previously name Stoner Software, this is software for modeling electrical distribution systems. Oracle or SQL server based software that will link with geographical information systems (GIS) and GE Energy software. Software distribution analysis and optimization for radial or network feeders including load flow and fault analysis. This software supports reliability calculations, protection and coordination, switching and contingency planning, multiyear analysis and load forecasting, operations and real-time support as well as economic evaluation of options. SynerGEE does not currently consider energy storage or distributed generation. All of this software is driven by customer requests for new features. There is currently customer interest in adding support for high penetration rate distributed generation analysis.

Tables 3 and 4 summarize the capabilities reviewed above for non-commercial and commercial software, respectively, that provide energy storage modeling and analysis functions.

Table 3: Summary of Non-commercial Software Characteristics with Energy Storage Modeling Capabilities

Non-commercial Model	Homer	ReEDS	NEMS	RETScreen	Energy Plus	Kermit	GridLabD
Characteristic/Component (below)							
Locational marginal pricing (LMP)		X	X	X			
Energy storage	X	X	X	X	X (a new module has been developed)	X	X
Arbitrage	X	X				X	
Energy storage by node	X			X	X		X
Round trip efficiency	X	X	X	X		X	X
Minimizes system investment	X	X	X				
Show single or multiple ancillary service value streams	Yes	No	No	Yes	No	Yes	No
Aggregation of multiple ancillary services value streams?	No	No	No	No	No	No	No

[8] http://www.gl-group.com/en/8672.php

Table 4: Summary of Commercial Software Characteristics with Energy Storage Modeling Capabilities

Commercial Model	GE MAPS	Ventyx System Optimizer/ ProMod	Power World	Energy 2020	Integrated planning model (IPM)	Dynastore	SynerGEE
Characteristic/Component							
Locational marginal pricing	Yes	Yes - ProMod	Yes	Yes	Zonal basis (cut plane)	No	No
Energy storage	Yes - basic option is pumped Hydro	Yes - ProMod	Possible	Yes - including efficiency	Pumped hydro only	Yes	No
Arbitrage	Yes	Yes - ProMod including efficiency	Hard but possible	Yes	No	--	No
ES by node	Yes	Yes - ProMod	No	Yes	No	Yes	No
Round trip efficiency	Yes	Yes - ProMod	No	Yes	No	No	No
Minimizes system investment	No	Yes – only Optimizer	No	No	Yes	No	No
Show single or multiple ancillary service value streams	Yes	Yes	Yes	Yes	No	Yes	No
Aggregation of multiple ancillary services value streams?	No	No	No	No	No	No	No

Reviewed Studies

Studies of energy storage applications and related literature were reviewed during the course of this work to gain an understanding of the modeling methodology that was employed. Material reviewed in this activity is included in the bibliography.

One study (versus model) came close to including all of the important characteristics for storage model optimization in a smart grid environment (Walawalkar and Apt 2008). This study detailed a methodology for screening the locational value of energy storage resources, but did not include a model that could be run on a network analysis software system.

Finally, a recently developed tool that appears to closely match the desired modeling capability is described in the Institute of Electrical and Electronics Engineers (IEEE) paper entitled "Optimal Integration of Energy Storage in Distribution Networks" (Celli et al. 2009). Its abstract claims that the tool will assist system operators in defining better integration strategies for distributed storage systems in distribution networks and in assessing their potential as an option for a more efficient operation and development of future electricity distribution networks.

Discussion of Results

Numerous and extensive models and reports were discovered that deal with energy storage technologies and their application in particular situations (e.g., renewables integration, transmission, distribution or end use). There are also a large number of well-known consultants who advertise their services for energy storage siting studies and also models for optimizing gas storage and district heating systems. However, the above review leads to the conclusion that currently there is no single software tool that includes energy storage modeling in the smart grid-relevant context of all the following:

- Generation capacity
- Transmission and distribution line configuration options
- Demand response and energy efficiency planning functionality
- Cost minimization over long-term time frames.

Many existing modeling tools consider energy storage in more limited environments.
Despite the range and quality of these resources, no models or tools were found that specifically deal with sizing and locating energy storage under any optimality criterion that would be useful for infrastructure development. This is likely caused by numerous factors:

- Complexity of the problem
- Requirements for multidisciplinary resources
- Lack of familiarity on the part of utility transmission and distribution engineers with energy storage technology
- Utilities engineer's preferences for wires and substations
- Most importantly, the opinion of many engineers involved in energy storage, is that such a model cannot be built.

Needed Model Attributes and Recommended Pathway for Development

The future implementation of a reliable and low-carbon electricity infrastructure may depend, in part, on the availability of infrastructure-specific models. Making models and analytical tools available to the planning communities could significantly enhance the planning process to improve grid future operation to enable higher utilization of the infrastructure with a lower carbon footprint.

Attributes

The following characteristics would be useful attributes of an energy storage optimization model tailored for use in a smart grid environment:

- fast modeling capability, meaning a limited number of nodes for analysis with the ability to aggregate models up from distribution to transmission and include balancing area market factors

- capability to economically optimize (locational value, sizing and technology selection) of energy storage siting against competing technologies (distributed generation, demand response, etc.) by node in transmission or distribution applications against predetermined load profiles to include the aggregation of ancillary services

- options to optimize the storage solution around particular uses such as ancillary services, renewable integration (at generation side or end use), energy or capacity use, stationary or modular siting

- means for inputting updatable equipment costs, maintenance costs and power conversion system options that show ramp rates.

A further desirable attribute would be that the model reflect the market environment for energy storage including an open ancillary service market and the ability to allow the aggregation of multiple value streams including both generation and transmission services characteristics.

Recommended Development

We conclude that effort should begin immediately to develop a software-based capability to assess the technical and economic attributes of energy storage specifically reflecting the operational demands and opportunities presented by the smart grid environment. The following are the recommended steps to achieve such a product:

1. A survey of interested parties, including modeling software developers, utilities, regulatory agencies, energy storage vendors, and customer advocates should determine when this work should be done and what the goals will be.

2. A general outline of what the software module could and should provide would be developed.

3. After assessing interest of stakeholders, a working group should be tentatively established that would include representatives of utilities, transmission and distribution modeling software vendors and regulators.

4. A value proposition for the development of the software should be scoped and costs of the work estimated.

5. All involved parties would need to develop a funding plan for software development.

6. The entity charged with developing the software would proceed with the work employing frequent consultations with a steering committee representing the stakeholders.

A suggested methodology for energy storage modeling should include the following:

1) set timeframe for study in years

2) screen for location using methodology from NETL Report -2008/1330 and/or Optimal Integration of Energy Storage in Distribution Networks, 2009 IEEE Bucharest Power Tech Conference (Walawalkar and Apt 2008)

3) determine ancillary services requirements based on location

4) compare competing technologies

5) if energy storage is an option at this stage, size power conditioning system based on ancillary services needs

6) size energy storage technology based on worst case needs for ancillary services

7) choose most economic storage technology based on anticipated cycling regimen.

Conclusions

This literature review resulted in finding no models that would be useful for sizing, placement and optimization of energy storage in a smart grid environment. In this environment, no existing models appear capable of selecting the preferred type of storage technology, and its capacity and location for optimal placement and functionality on the electric grid.

Both commercial and non-commercial software models exist with energy storage modeling capabilities appropriate to current needs for planning and operating the present grid infrastructure. Commercial planning models are widely used by the industry. In the area of ancillary services modeling, commercial models typically have a wider range of functionalities than non-commercial models. The non-commercial planning models generally have less functionality related to energy storage issues than the commercial planning models. The non-commercial planning models are not as widely used by members of the utility industry.

To influence the introduction of energy storage into the utility culture effectively, there must be a convenient and easy-to-use model that incorporates energy storage as well as demand response for providing ancillary services. Without such a tool to familiarize electric utility planners with the technology of energy storage and methods for maximizing the value of energy storage, the adoption of this technology by utilities will continue to be very slow, if not glacial. Energy storage has the potential to be a game changer in renewable integration, power quality and system reliability. The key to adopting energy storage as a conventional technology will require a modeling tool that details multiple value streams provided by energy storage and demand response, and the pathways by which they can be realized.

We recommend that effort should begin immediately to develop a software-based capability to assess the technical and economic attributes of energy storage specifically reflecting the operational demands and opportunities presented by the smart grid environment.
Without the ability to analyze network features of transmission and distribution, storage system technologies and their efficiencies, along with their cost benefits for various value streams, there is no ability for the utility to make comparative business decisions that will enable the optimal siting of energy storage. In light of the above considerations, we believe that a software tool that facilitates this kind of decision making is of great importance for the enhancement and expansion of the electric infrastructure and the integration of various renewable energy resources. Because interest in smart grid and renewable energy technologies has increased dramatically in the last few years, we believe that it is imperative to fully understand the challenges and applications for energy storage technology that lie ahead.

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APPENDIX A

Storage Technologies

Appendix A Storage Technologies

Table A- 1. Storage Technologies

Storage Technologies	Main Advantages (relative)	Disadvantages (Relative)	Power Application	Energy Application
Pumped Storage	High Capacity, Low Cost	Special Site Requirement		●
CAES	High Capacity, Low Cost	Special Site Requirement, Need Gas Fuel		●
Flow Batteries: PSB VRB ZnBr	High Capacity, Independent Power and Energy Ratings	Low Energy Density	◑	●
Metal-Air	Very High Energy Density	Electric Charging is Difficult		●
NaS	High Power & Energy Densities, High Efficiency	Production Cost, Safety Concerns (addressed in design)	●	●
Li-ion	High Power & Energy Densities, High Efficiency	High Production Cost, Requires Special Charging Circuit	●	○
Ni-Cd	High Power & Energy Densities, Efficiency		●	◑
Other Advanced Batteries	High Power & Energy Densities, High Efficiency	High Production Cost	●	○
Lead-Acid	Low Capital Cost	Limited Cycle Life when Deeply Discharged	●	○
Flywheels	High Power	Low Energy density	●	○
SMES, DSMES	High Power	Low Energy Density, High Production Cost	●	
E.C. Capacitors	Long Cycle Life, High Efficiency	Low Energy Density	●	◑

● Fully capable and reasonable

◑ Reasonable for this application

○ Feasable but not quite practical or economical

APPENDIX B

Trademark Information

Appendix B Trademark Information

COMMERCIAL MODELS

DYNASTORE
Electric Power Research Institute, Inc. (EPRI)
Palo Alto, CA
http://my.epri.com/portal/server.pt?open=512&objID=210&mode=2&in_hi_userid=2&cached=true

ENERGY 2020
Systematic Solutions, Inc.
Xenia, OH
http://www.energy2020.com/

GE-MAPS™
GE Energy
Devin Van Zandt
Phone:518-385-9066
http://www.ge-energy.com/products_and_services/products/concorda_software_suite/concorda_maps_engine.jsp

The Integrated Planning Model (IPM®)
ICF International
Fairfax, VA
http://www.icfi.com/Markets/Energy/energy-modeling.asp#2

KERMIT
KEMA Services, Inc.
Glendale, CA
http://www.kema.com/services/consulting/utility-future/generation/WindPPA.aspx

PowerWorld®
PowerWorld Corporation
Champaign, IL
http://www.powerworld.com/Default.asp

PROMOD
Ventyx®
Atlanta, GA
http://www.ventyx.com/analytics/promod.asp

SynerGEE Electric
GL Industrial Services
Mechanicsburg, PA
www.gl-group.com/en/8672.php

NON-COMMERCIAL MODELS

EnergyPlus™
Department of Energy
Washington, DC
http://apps1.eere.energy.gov/buildings/energyplus/

GridLab D ™
Pacific Northwest National Laboratory (PNNL)
Richland, WA
http://www.gridlabd.org/

HOMER
National Renewable Energy Laboratory (NREL)
Golden, CO
https://analysis.nrel.gov/homer/

NOTE: NREL has granted HOMER Energy the license for HOMER
Homer Energy
Boulder, CO

National Energy Modeling System (NEMS)
Energy Information Administration (EIA)
Washington, DC
http://www.eia.doe.gov/oiaf/aeo/overview/#nems

Regional Energy Deployment System (ReEDS)
National Renewable Energy Laboratory (NREL)
Golden, CO
http://www.nrel.gov/analysis/reeds/

RETScreen®
Ottawa, Ontario
Canada
http://www.retscreen.net/ang/home.php