Pacific Northwest
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PNNL- 29080

Pumped Storage Hydro Model Evaluation Report

Task 1: Tool Assessment

April 2019

Kendall Mongird
Vanshika Fotedar
Patrick Balducci

U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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Executive Summary

Pumped storage hydro (PSH) projects support various aspects of power system operations. However, determining the value of PSH projects and the many services and contributions to the system they provide can be a challenge. The PSH techno-economic studies being carried out by a 5-lab consortium are defining extensive modeling approaches for evaluating the economic benefits of PSH projects. To enhance the impact of the valuation approach and follow-on techno-economic studies, Pacific Northwest National Laboratory (PNNL) will be developing a set of online tools that industry could adopt and use to advance PSH projects in the US. The problem is that the research team is not entirely clear on the features of the tools that would offer the most significant impact to industry. Thus, year one of this effort is designed to first define the needs of industry before developing the PSH valuation tool.

The first step in defining industry needs is to evaluate existing tool packages, including those created by DOE and those by industry groups, to both measure usage levels and define tool attributes that maximize industry impact. The second step in this process will be to hold a workshop designed to elicit direct industry input.

Given the breadth and nature of the task, which is to define ideal model attributes, the research team did not constrain the assessment to storage valuation tools. Several tools were assessed, and their characteristics compared against a list of "ideal" attributes that included ease of use, generalizability of results, and analytical flexibility. Information regarding usage and impact were then compared to specific model attributes to define which attributes appear to drive success.

The following key lessons and implications can be drawn from the analysis:

- Models with high ease of use were often the most adopted by industry, though they did not necessarily have high publication reference records, meaning a published article made direct reference to the tool. For example, REScheck™ and COMcheck™, two tools which share a site, have seen a high amount of web traffic and usage. Similarly, Storage Value Estimate Tool (StorageVET®), an energy storage valuation model, has a large number of organizations using it despite a low publication reference record. A common feature between these models is that they are web-hosted, theoretically making them more easily accessible with graphic user interfaces (GUIs) that are more navigable.

- Models with higher usage statistics were typically free and/or open source. While it may be unsurprising that this attribute could be considered a draw for users, there is the potential for overestimating the tool's value based on popularity due to the fact that some users may have used the model simply because it was free and not because it is the best model.

- Models that offer more in-depth analysis and a wide coverage of applications (e.g. VOLTTRON ™, GridLAB-D™, and Integrated Valuation of Ecosystem Services and Tradeoffs (InVest)) have shown a high number of publication references (Figure E.1) as well as showing a high number of downloads in the case of GridLAB-D™. It should be noted that the figure below does not include the model with the highest number of publication references (EnergyPlus™) as it has been removed to show clearer distinction between the remaining tools.

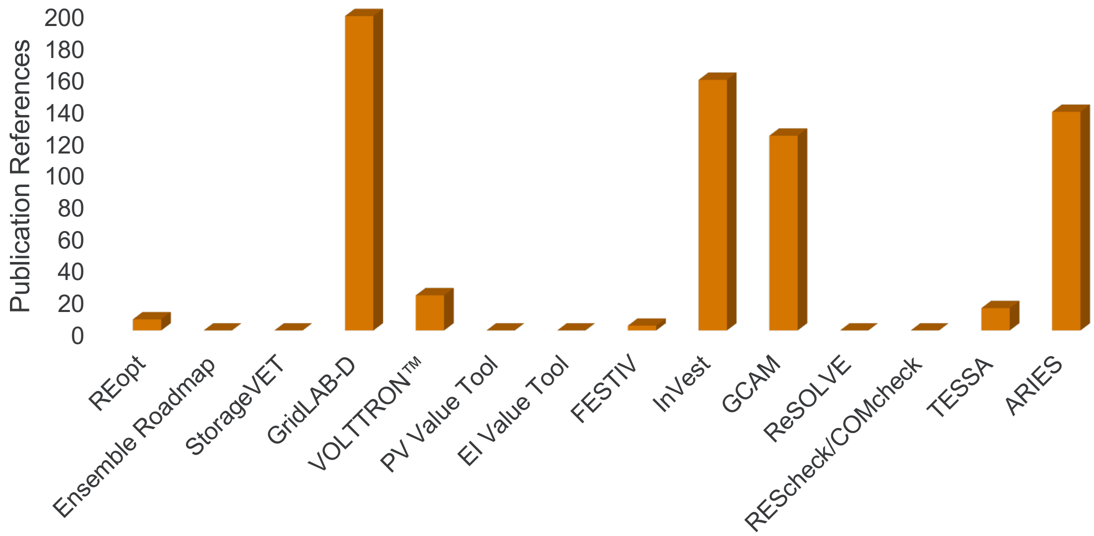

Figure E1. Unique Publication References to Model Names – EnergyPlus™ Excluded

- The most popular model within the evaluation list was EnergyPlus™. This tool has the highest number of publication references (2,034) of all models considered and contains both a high ease of use level as well as broad application flexibility. Its high usage may be correlated, however, with the presumed wider audience conducting energy consumption modeling compared to the audiences for some of the other tools in this list.

- Models that were low in both general usage and publication reference generally did not exhibit characteristics considered ideal by the research team. Some of these models offered a narrower range of analytical applications or lower generalizability of results. This would automatically restrict the pool of potential users to those who fall within a narrow range of specific technologies or applications.

This report also explores two model structures for the PSH tool: decision tree-based, which would guide the user through the valuation methods defined in the PSH techno-economic studies currently being carried out by DOE, and an all-inclusive comprehensive model. The strengths of each were explored and a hybrid approach was defined that would embed a price-taker model into the decision tree approach. Such an approach would provide a comprehensive approach for modeling small-scale PSH while recognizing the challenges associated with implementing a price-maker approach in an all-inclusive model.

Insight gained in this analysis of other models can aid in narrowing down the list of effective and sought-after attributes, and in defining model structure. Next steps toward developing a model for storage valuation will be to gain direct industry input through workshops.

Acknowledgments

We are grateful to Sam Bockenhauer and Marisol Bonnet of the Water Power Technologies Office (WPTO) at the U.S. Department of Energy. Without their guidance and WPTO's financial support, this project would not be possible.

Acronyms and Abbreviations

ARIES	Artificial Intelligence for Ecosystem Services
CPUC	California Public Utility Commission
DOE	Department of Energy
EPRI	Electric Power Research Institute
ESP	Ensemble Streamflow Prediction
FESTIV	Flexible Energy Scheduling Tool for Integrating Variable Generation
GUI	graphical user interface
IEEE	Institute of Electrical and Electronics Engineers
InVEST	Integrated Valuation of Ecosystem Services and Tradeoffs
NREL	National Renewable Energy Laboratory
PNNL	Pacific Northwest National Laboratory
PSH	Pumped Storage Hydro
PV	photovoltaic
SNL	Sandia National Laboratories
StorageVET®	Storage Value Estimation Tool
TESSA	Toolkit for Ecosystem Service Site-based Assessment

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1.0 Introduction

Pumped storage hydro (PSH) projects support various aspects of power system operations. However, determining the value of PSH projects and the many services and contributions to the system they provide can be a challenge. The PSH techno-economic studies being carried out by a 5-lab consortium are defining extensive modeling approaches to evaluating the economic benefits of PSH projects. To enhance the impact of the valuation approach and follow-on techno-economic studies, Pacific Northwest National Laboratory (PNNL) will be developing a set of online tools that industry could adopt and use to advance PSH projects in the US. The problem is that the research team is not entirely clear on the features of the tools that would offer the most significant impact to industry. Thus, year one of this effort is designed to first define the needs of industry before developing the PSH valuation tool.

Obtaining value from PSH operation requires a broad and comprehensive tool capable of conducting evaluation under a variety of circumstances and parameters. Currently, there are an assortment of models available; however, the industry lacks a single cohesive tool that is capable of piecing together all available capabilities, locations, technologies, and other factors necessary for thorough analysis. The complexity of correctly valuing energy storage operation, including PSH, is derived not only from the assets themselves but also in the competition of applications at a given time. More to that effect, the limitations of the asset on a physical level need to be accounted for to allow or disallow specific operations. It is also important to note that small- and large-scale PSH require different model types. Small-scale PSH (i.e., under 10 MW) can be addressed using a price-taker model. Price-taker models assume that the presence of the asset in the region's grid would not shift market prices. Large-scale PSH must use a price-maker model because the enormity of the resource would disrupt grid operations and shift market prices. Such models evaluate grid operations to determine how costs change as the composition of grid assets is altered or are operated differently. Due to the challenge of building price-maker models, this modeling effort must consider whether it is feasible to build a comprehensive model or whether a decision-based modeling approach with perhaps an embedded price-taker model is more appropriate. These complexities beg the question of what an ideal tool would look like to properly model them and what structure it would take.

PNNL has been tasked by the U.S. Department of Energy (DOE) with identifying existing tool packages (both those created by DOE and those created by industry groups) to both evaluate their impact and define which components have been proven successfully as useful to industry. The purpose of this assessment is to collect information regarding what makes a tool useful to industry and successful based on usage and impact. Given the broad task, tools were included in the evaluation that branch into other areas of assessment such as building energy efficiency and environmental services. The sections that follow includes a list of attributes considered by the researchers to be those of an ideal model (Section 2), Sections 3 offers a comparison between two model structures – decision tree and comprehensive. Section 4 provides an overview of the models selected for evaluation and the attributes they possess. Lastly, we evaluate the correlation between model attributes and usage and impact (Section 5).

2.0 Ideal Model Attributes

Storage can encompass a broad range of technologies, capabilities, and scales that can be difficult to model and value. Furthermore, the markets and environments available for deploying these systems also vary widely and have differentiating structures and values. Being able to accurately capture the operational value of a system/technology and offering that capability in an accessible and easy-to-use manner is paramount to a good tool. Accurate valuation, however, is not the only capability that an ideal model will contain. Other aspects branch into several other categories from the interface of the program to how accessible it is to users.

Based on our review of existing models, the list that follows describes what is believed by the researchers to be some of the most desirable traits a model can have. While some of these characteristics are more realistically obtainable than others, especially in combination with one another, they are all important to consider.

- **Publicly available and open source –** An ideal model will not only be comprehensive and accurate, but free to use by the public and accessible in a way that extensive training is not required by the user to implement it. Furthermore, a good model will allow for the public to adapt it to their needs through open source methods.
- **Modeling flexibility** – Models oftentimes only incorporate a handful of applications or use cases under a rigid set of guidelines. Ideally, a model will offer a wide range of uses and modeling techniques that the user has the ability to select between, subject to their needs. Currently, many models only include the ability to examine a small set of applications, or even a single primary application to evaluate under a specific scenario. Expanding out from this to allow for a versatile tool - in technology type, size, or a multitude of other factors, to examine the available applications and their benefits would offer high value. Additionally, allowing the flexibility to change the timescale of the operations modelling would be highly valuable.
- **Thorough representation of the internal state of the technology –** The potential applications and benefits of an energy storage system – whether electrochemical, mechanical, or otherwise, is highly dependent on the internal state of the technology. This could include factors such as thermal state, state of charge, deterioration of capacity, losses due to evaporation (in the case of pumped storage hydro), or other parameters. A tool that is meant to provide operational value of any technology should be able to accurately characterize it. The ideal model will not only incorporate these factors into its structure, but could also proactively estimate components.
- **Broad geographic applicability –** Many valuation tools only allow the user to examine applications and uses within specific regions. An ideal tool would be flexible enough to examine the available operations and applications across a broad span of locations so that the user may compare different scenarios.
- **Acknowledgement of system size impacts –** When evaluating a specific asset and its operational effects, it is common for a model to ignore effects it may have on the environment it will exist within. For example, a common assumption with energy storage assets is that the effects on the electrical system are easily managed or absorbed into the grid and the asset is simply a price-taker. However, storage assets of larger scale – typically found in pumped storage which can reach into the multiple gigawatts of capacity, will most definitely cause shifts in grid operations and, therefore, market prices. Price-maker models,

therefore, are the solution for these assets. In a more general sense, an ideal model overall would offer the ability to distinguish between assets and their scales to accurately represent any impacts.

- **Optimization of services** – An ideal valuation model in the case of energy storage is not only capable of offering a selection of services but is also capable of correctly valuing them. For a given dispatch time horizon, the model should be capable of choosing the optimal schedule of actions that will derive the most value. With energy storage, for example, energy within the asset is competed for both on a time and per-application basis; the ideal model will be able to mathematically determine how to best use the energy available without double counting benefits.
- **Ease of use and system compatibility –** Not only should a tool be extensive in its analytical capabilities, it should also be accessible to the person who uses it. Models that are difficult to understand, require extensive training to use, have consistently faulty features, or are incompatible with a variety of operating systems are undesirable and users will be forced to overcome hurdles that will be burdensome no matter how sophisticated and valuable the model may be. Having a graphical user interface (GUI) that is not only compatible with most hardware (whether by being web-based or through other methods) but also easy and painless to navigate allows for a tool that will be more widely accepted and utilized. Adding on to this, the model should also generate output that is easy to understand by the operator and delivered in a format that is compatible with most systems.
- **Internal data retrieval capability –** Those looking to use a model to conduct an analysis may have limited experience or capability to obtain the data and information they require to evaluate it. A model that is capable of automatically retrieving data from the necessary sources that is up-to-date and accurately applied removes a barrier of usage from the tool. An example of this would be if an energy storage system were performing arbitrage within a market territory, the model would be capable of retrieving historical and/or forecast energy prices from the market for them and applying appropriately.
- **Accounting for forecast uncertainties** – Perfect forecast of an asset's operation, the system it exists within, and the environment encompassing it is unachievable and an ideal model will take this into account. This can be included by having the modeled operation of the asset factor in uncertainty when mathematically optimizing or providing valuation for a time horizon. Value must be measured not as the absolute maximum achievable value, but as the risk-adjusted maximum value, as applicable.
- **Support availability and timely updates –** An ideal model will offer a means of communication that is frequently monitored for users to reach out to when issues arise. Ideally this will be someone familiar enough with the tool to solve the issues and respond in a timely manner. Furthermore, the model should not be created and then left unattended to the point it becomes obsolete as technologies and environments evolve beyond it. A perfect model will be monitored and adjusted to both correct issues quickly and also to make changes so as to best reflect the real world to the highest degree possible.

3.0 Decision Tree Models vs. Comprehensive Models

When building a tool, the structure of its capabilities is an important consideration when thinking through how it is going to be utilized and what the users will achieve through it. For this report, there are two model structures being considered: decision trees and all-inclusive comprehensive models. This section will compare and highlight the benefits and downsides of both.

Decision trees are tools that lead the user step-by-step by beginning with a question and following down a path based on the response. Each path branches until another decision node is reached where the user is asked subsequent questions to eventually lead them towards a conclusion. The point of such a tool is not necessarily to evaluate data explicitly within it, but rather to guide the user through the steps they should take to meet their needs, even pointing them toward specific models. The user would walk along paths that are situationally defined and arrive at a destination that fits their specific needs.

An example of a decision tree tool is the roadmap developed by CEATI International regarding Ensemble Streamflow Prediction (ESP) models for those looking to gain information regarding river flow and volume forecasts. The tool integrates an interactive framework that is hierarchical in its approach to assist the user in making long-term hydrologic forecasts based on the availability of streamflow prediction methods they can choose from. The roadmap approach integrates embedded notes and links to assist the user in making a decision of how to go about their forecast (Quebbeman 2018).

Figure 3.1below demonstrates the tree users are walked through. The different nodes represent ideas or solutions that the map suggests based on answers to the previous questions. For example, if the user states that they (1) could benefit from ensemble methods, (2) they have streamflow forecast ensembles developed, and (3) they do not want to use meteorological data, then the model would send them to the Statistical Techniques node in the upper right-hand corner (Quebbeman 2018). If a roadmap model has the analytical tools built in intrinsically, it would then perform the statistical techniques. If not, then it may suggest products that can complete the necessary calculations as this one does.

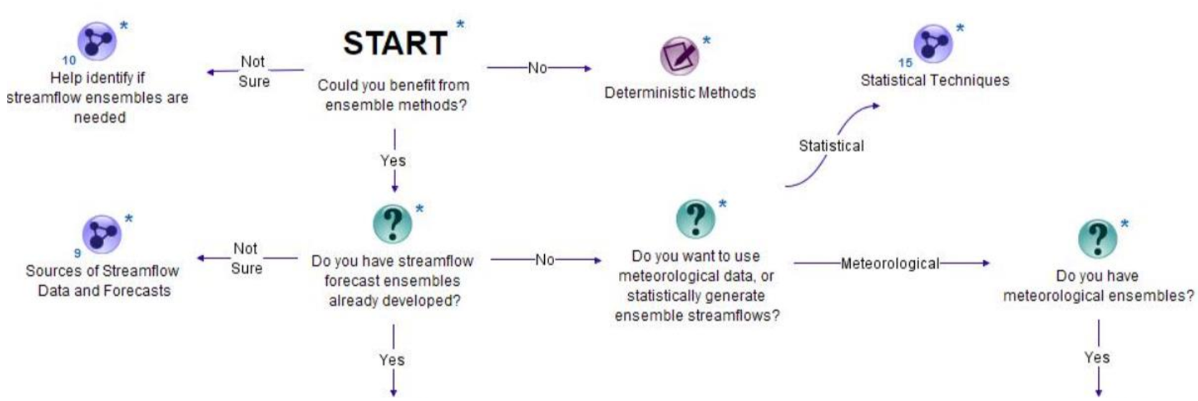

Figure 3.1 Demonstrative Roadmap Flow from Ensemble Streamflow Prediction Model

Positive aspects of the roadmap model is the flexibility for the user to get to the end result that is highly specific to their situation due to the self-selecting nature of the tool. Its structure also allows the developers to update subcomponents of the model as new capabilities or methodologies are developed over time. Similarly, new paths can be added as solutions develop that weren't previously possible. Negatives of decision tree models could include a lack of built-in analytical capabilities, as they serve as more of an information provider than an analysis provider.

All-inclusive models, as their name suggests, include a single interface that includes the analytical capabilities inherently. These tools can be powerful and thorough in providing analysis, however, where they fall short oftentimes is in flexibility to provide the user with information and additional resources should the analysis be outside the scope of the tool's capabilities. Also, it would be exceptionally difficult to embed a price-maker model in a comprehensive model.

An example of an all-inclusive model is Storage Value Estimation Tool (StorageVET®) - an energy storage valuation model developed by the Electric Power Research Institute (EPRI). The tool is publicly available, open source, and also web-hosted by EPRI. The tool optimizes the simulation of energy storage devices subject to the specifications that the user inputs across a variety of parameters and constraints. Users provide inputs and data and the model co-optimizes operation of the energy storage device across a specified time horizon. An image of the interface of StorageVET® is shown in Figure 3.2 (Damato 2017). This is an example of a price-taker model.

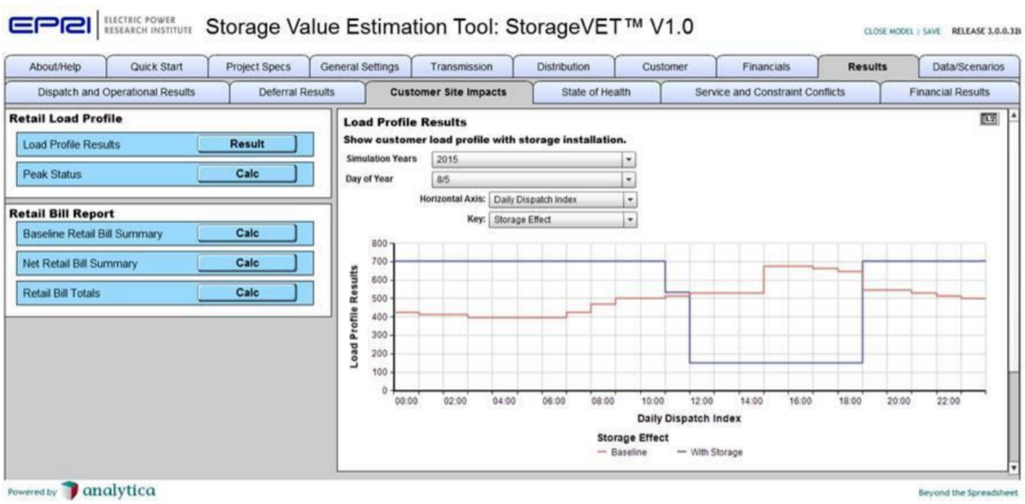

Figure 3.2. StorageVET® Interface

Models that take a similar form to StorageVet® act as a single interface through which to define value. Where they succeed in comparison to the decision tree type models is in their analytical depth and computational capabilities. Oftentimes, however, they are more difficult to use and require a higher level of knowledge to operate compared to decision tree models which can acts as a barrier to users.

A hybrid approach could be defined that embeds a price-taker model into the decision tree approach. Such an approach would provide a comprehensive approach for modeling small-scale PSH while recognizing the challenges associated with implementing a price-maker approach in an all-inclusive model.

4.0 Model Review

PNNL collected models for review based on suggestions, investigation, and known models from previous research. All models included except for the ensemble streamflow forecast roadmap are publicly available. The list of models reviewed is shown below in Table 4.1 along with information about their developers, their description, the accessibility level, and where they can be found. This is not intended to be a complete list, but enough to glean insight into tool attributes that are effective and appealing to an audience.

Table 4.1. Review of Existing Publicly Available Models

	Developer	Description	Accessibility	Website
REopt	National Renewable Energy Laboratory (NREL)	This techo-economic model optimizes energy systems for buildings, campuses, communities, and microgrids. It can include generation, energy storage, and renewable resources to recommend the optimal mix of assets to meet specific savings or performance targets. It is typically used to optimize systems over an entire year but can conduct analysis at smaller time granularity. The tool has been under development since 2007 and was initially created to find renewable energy projects that were cost-effective (NREL 2019a).	Lite Web Tool offers a limited selection of full tool's capability free of cost for external use.	https://reopt.nrel.gov/
Ensemble Streamflow Forecast Roadmap	CEATI International	This tool is a roadmap of ensemble models that are used to produce a long-term hydraulic forecast based on historical data on precipitation and river conditions. The output consists of predictions regarding river flow and volume in the future. This decision tree model goes through a variety of stages from (1) determination of objectives and need, (2) data availability, (3) verification, and finally to (4) post-processing. It works off an interactive interface that leads the user towards the correct solution for their investigation (Quebbeman 2018.)	Not Public, only available to Hydropower Operations and Planning Interest Group within CEATI International	https://www.ceati.com/projects/publications/publication-details/?pid=0429

	Developer	Description	Accessibility	Website
StorageVET®	EPRI	StorageVET works to optimize energy storage operation at the transmission, distribution, and customer level. The tool was initially built to evaluate within the California markets exclusively, using specific datasets and market services. The tool co-optimizes across a wide range of energy storage technologies across multiple time granularities using a Gurobi optimization engine. It also includes a web-based interfaced and is free to the public (EPRI 2019).	Publicly available, open-source	http://www.storagevet.com
GridLAB-D™	PNNL	Power distribution system simulation and analysis tool for the design and operation of distribution systems. It provides a flexible interface that integrates a variety of analysis tools including distribution automation models and software integration tools. It simultaneously coordinates individual devices using differential equations across their individual timescales. The tool is typically used by utility engineers and regulators who need to simulate a power system and its assets (US DOE 2018a).	Open source, accessible from GitHub	https://www.gridlabd.org/
VOLTTRON™	PNNL	A scalable, open-source distributed control and sensing software platform that supports a wide range of applications, such as managing end-use loads, increasing building efficiency, integration of distributed variable renewable energy, accessing storage, or improving electric vehicle charging. It is intended to analyze data streams within	Open Source, accessible from GitHub	https://volttron.org/

	Developer	Description	Accessibility	Website
		buildings to provide usable information regarding its operation and energy consumption. Currently it is used across small, commercial, municipal, and connected buildings (PNNL 2017).		
PV/EI Value	Developed by Sandia National Laboratories (SNL), transferred to Energy Sense Finance	PV Value is a consumer-based photovoltaic (PV) valuation platform built to develop the market for solar. EI Value is a more comprehensive tool by the same developer that integrates PV Value into its structure in valuing overall energy efficiency of a building. Both models are used to assign value to residential and commercial PV systems across the U.S. They are web-based applications that use selectable inputs to conduct both income and cost approaches to value solar and energy efficiency. SNL developed the spreadsheet version that served as a precursor to the web PV Value tool (Energy Sense Finance 2019).	Easy access, free registration	https://www.pvvalue.com
FESTIV – Flexible Energy Scheduling tool for Integrating Variable Generation	National Renewable Energy Laboratory (NREL)	A power systems operation tool that simulates the behavior of the electric power system subject to variability of operations. The tool works to allows researchers to explore different strategies for operating reserves. It covers multiple timescales and uses sub-models for automatic generation control that are interconnected. The output includes both economic and reliability metrics (NREL 2019b).	Internal Use by NREL, can be used by external users after contact	https://www.nrel.gov/grid/festiv-model.html

	Developer	Description	Accessibility	Website
InVEST – Integrated Valuation of Ecosystem Services and Tradeoffs	Stanford University	This tool includes a collection of open-source models that can be used to map goods and services from nature including food, water purification, and others. The model is spatially-explicit and takes maps as input data. It can return metrics regarding economics of biophysics at a local, regional, or global scale. The models are based on production functions that evaluates how functional changes impact system output. Users can select which services are relevant to them (Stanford University 2019).	Free, open source	https://naturalcapitalproject.stanford.edu/invest/
GCAM - Global Change Assessment Model	PNNL	GCAM is an integrated assessment tool that tracks scenarios of how the U.S. electric power grid may be impacted by climate change. It is a dynamic-recursive model that can be used to evaluate the impact of policies such as carbon taxes, regulations, or deployments of energy technology. The model can be used to simulate scenarios from a variety of sources. Its output includes a forecast of energy supply and demand, emissions, climate effects of numerous greenhouse gases, and others (PNNL 2019).	Open source, accessible from GitHub	http://www.globalchange.umd.edu/gcam/
ReSOLVE	Created by E3 for California Public Utility Commission (CPUC)	Optimal investment and operational expansion model for integrated resource planning. The tool selects a combination of assets (solar, hydro, wind, etc.) to optimize across subject to constraints. Resources are added to meet renewable portfolio standards across 10-20 years.	Open source	http://cpuc.ca.gov/General.aspx?id=6442457210

	Developer	Description	Accessibility	Website
		Includes fixed costs of new resources, transmission, and the operating costs of the assets. Overall allows to for scenario analysis subject to adjustable assumptions regarding costs of energy and other limitations (E3 2017)		
REScheck	Energy Codes, U.S. Department of Energy	Residential compliance check model for builders, designers, and contractors. It allows the user to quickly determine if a low-rise residents meets code and simplifies the process for building officials, inspectors, and planners. The tool can be used for tradeoff calculations for buildings under three-stories. It works by performing a U-factor x Area calculation for heat loss which is then compared to the UA calculation for a building that meets code (U.S. DOE 2018b).	Free, publicly available	https://www.energycodes.gov/rescheck
COMcheck	Energy Codes, U.S. Department of Energy	Commercial compliance check model for builders, designers, and contractors. Allows the user to determine if a high-rise residential, or commercial building meets code. (U.S. DOE 2019a)	Free, publicly available	https://www.energycodes.gov/comcheck
EnergyPlus™	U.S. Department of Energy	Energy consumption model for whole buildings. Used by engineers, architects, and researchers to model consumption (heating, cooling, ventilation, lighting, etc) along with water usage. Includes sub-hourly timesteps that can be defined by the user. The output includes a detailed summary report with selectable time resolution (U.S. DOE 2019b).	Free, open-source, and cross-platform	https://energyplus.net/

	Developer	Description	Accessibility	Website
TESSA – Toolkit for Ecosystem Service Site-Based Assessment	BirdLife International	A non-specialist toolkit for evaluating ecosystem services and defining which services are of value at a specific site as well as identifying obtainable benefits compared to alternative land uses. The tool is used to understand the impacts of changes at a specific location to better planning decisions that can improve biodiversity conservation and ecosystem service supply. This tool provides information on potentially significant services as well as the data needed to evaluate them and the methodology for data collection (BirdLife International 2019).	Free, publicly available	http://tessa.tools/
ARIES - ARtificial Intelligence for Ecosystem Services	Azati Corporation	A networked software tool that assesses ecosystem service valuation using artificial intelligence and spatial data. The model integrates data and models that can simulate environmental systems as well as socioeconomic ones. The underlying software is k.LAB which finds the economic benefit link to ecosystem services. It can conduct spatial assessments, optimization of payments for services from ecosystems, and spatial policy planning (Azati 2019a).	Free, open access	http://aries.integratedmodelling.org/

From the list in Table 4.1, the researchers evaluated each tool based on its characteristics and matched them against the list of ideal attributes of a model mentioned previously in Section 2. Figure 4.1 below shows the results of this evaluation for each of the models. Darker colors indicate that an attribute is represented strongly in the tool and lighter colors are areas where the model is missing or is not as strong in that feature. For example, StorageVET®, which offers a web-based tool with an easily navigable GUI, scored high on ease of use.

Rating was at the discretion of the researchers as they accumulated information about each model and evaluated its interface as capable. Cells that have a diagonal slash through them indicates that the characteristic is not applicable (or not applicable as so far observed by the researchers).

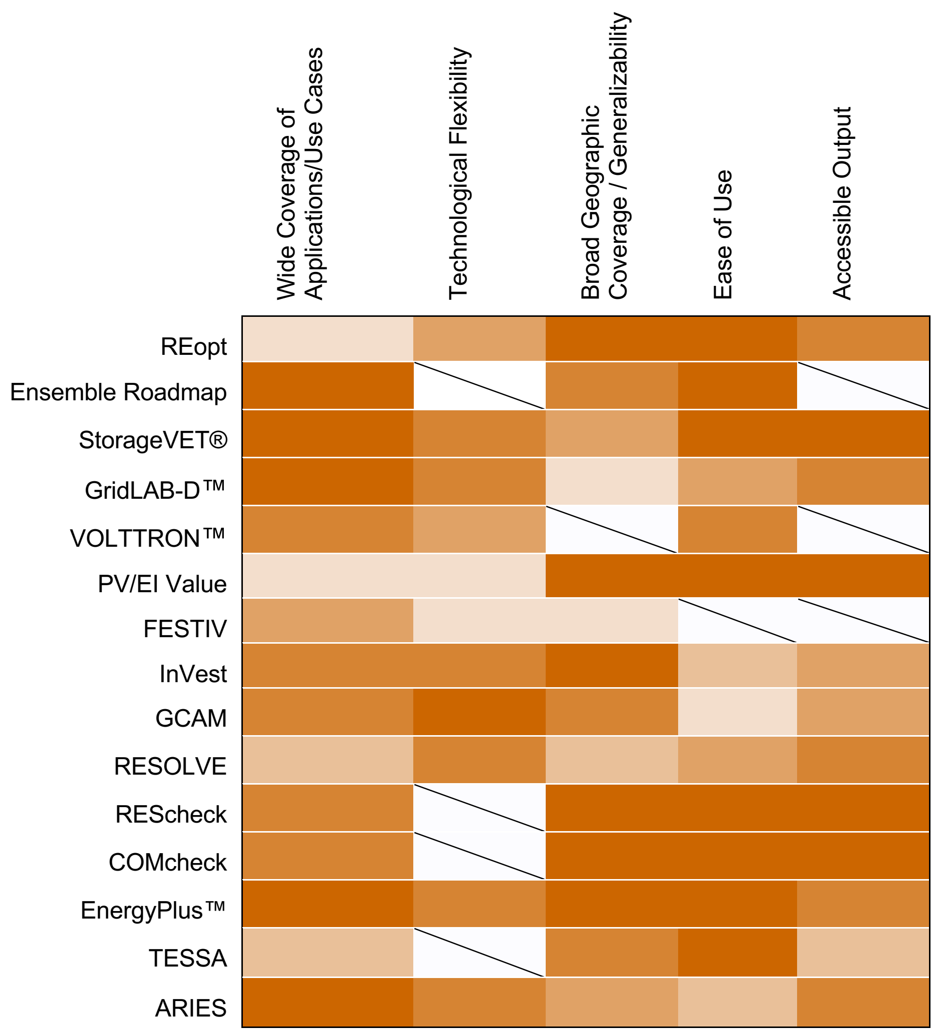

Figure 4.1. Capabilities Diagram of Models Included in Review

By displaying the models in this way it is easier to show which ones are succeeding in each category. For example, very few of the models evaluated here have high technological flexibility but nearly half are considered to have higher ease-of-use.

5.0 Relationship between Usage and Attributes

As part of the investigation into the models discussed in the previous section, PNNL collected information regarding usage statistics of each of the models as available or shared by the developers. The information gathered can aid in discovering which attributes seem to drive higher usage of a model/tool. Many of the operators of the listed models did not respond to data requests regarding their usage statistics or stated they were unable to share them. Usage statistics for these tools was generated from information found elsewhere (publications, tool descriptions, etc.).

Table 5.1 below presents several usage and impact metrics. The column regarding unique publication references was generated by searching for times when the name (acronym) of the model appears in unique publications in both Scopus and Institute of Electrical and Electronics Engineers (IEEE) Xplore publication searches, the latter catching those that fall under the category of engineering specifically. For models that have a more common name (e.g., PV Value), the word "tool" was added to the end of the search in an attempt to generate more applicable results or the full acronym of the model name was spelled out. The results of each search were sorted through to eliminate references to tools that are not the tool in question.

Table 5.1. Usage Statistics for Models Included

	General Usage Statistics	Source	Unique Publication References
REopt	• >10,000 partner and client sites • 5,326 users • 17,831 webpage hits	Blakley (2019)	7
Ensemble Roadmap			0
StorageVET®	• 1,240 active user accounts • >500 organizations represented • 21 active projects	Helmen et al. (2018)	0
GridLAB-D™	• Approximately 85,000 downloads across numerous download sites	Fuller (2019)	197
VOLTTRON™	• 200 mailing list subscribers • 1200+ views on GitHub with 109 clones (38 unique cloners) and 6,262 commits • More than 30 public and private sector users	Haack (2019)	22
PV Value Tool	• 2,000 user manual downloads per year on average • 12,092 historical downloads (as of 2015)	Sandia (2015)	0
EI Value Tool	• 13,000 stand-alone users at the time when this report was created • 118,000 solar PV scenarios valued	Energy Sense Finance (2019)	0
FESTIV	• 5 developer publications	NREL (2019b)	3

	General Usage Statistics	Source	Unique Publication References
InVest			157
GCAM	7,755 commits on GitHub	GitHub (2019)	122
ReSOLVE	Used by multiple studies	E3 (2019)	0
REScheck/COMcheck	>3 million website hits	Cole (2019)	0
EnergyPlus™	• 45,000 – 52,000 downloads • Average of 43,000 downloads per update	U.S. DOE (2019c); Roth (2019)	2,034
TESSA	9 peer-reviewed publications and numerous case studies developed	Birdlife International (2019b)	14
ARIES	14 publications and 17 case studies	Azati Corporation (2019b)	137

The frequency of each tool's appearance in publications, a metric that comparable across each model, is shown in Figure 5.1. EnergyPlus™ is a clear outlier (highlighted grey) within the group as it is highly mentioned within publications. To get a better look at the remaining tools, Figure 5.2 shows the same plot with EnergyPlus™ excluded. The models that stand out as those with high publication reference are EnergyPlus™, GridLAB-D™, InVest, GCAM, and ARIES.

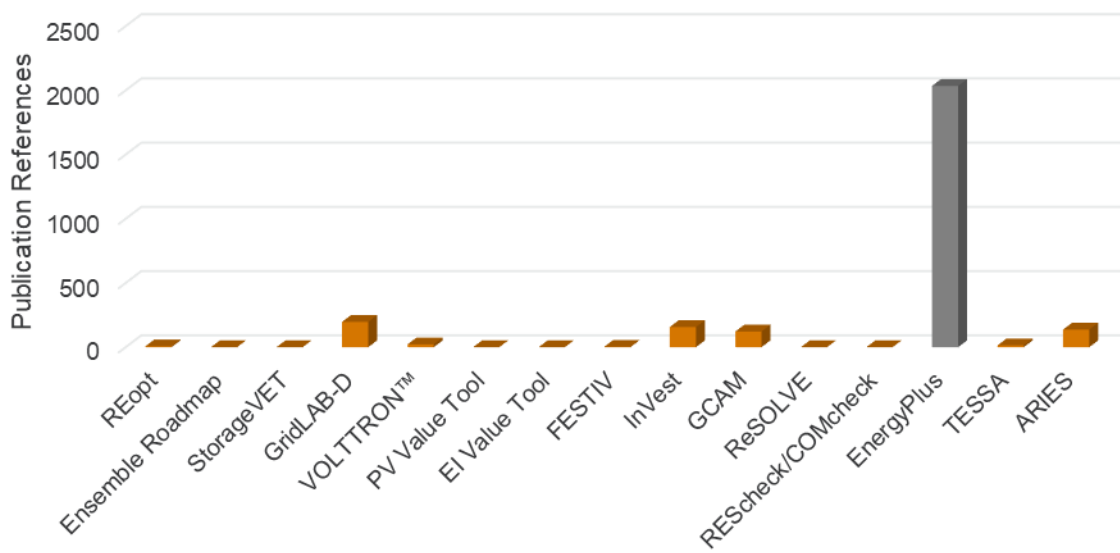

Figure 5.1. Unique Publication References to Model Names with EnergyPlus™

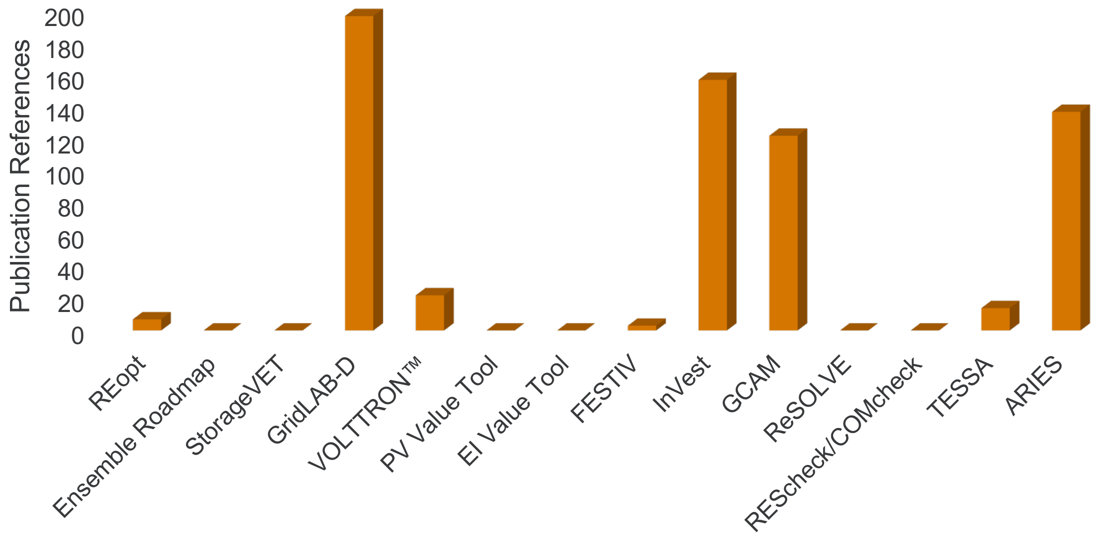

Figure 5.2. Unique Publication References to Model Names – EnergyPlus™ Excluded

Based on the information gathered, we can observe the following:

- Models with high ease of use (REopt, REScheck/COMcheck, StorageVET®) did not necessarily have high publication reference records though they show high usage in other ways. REScheck and COMcheck, which share a site, have seen a high amount of web traffic and StorageVET® similarly has a large number of organizations using it. A common feature between these models is that they are web-hosted, theoretically making them more easily accessible with GUI that are more navigable.

- Models that offer more in-depth analysis and a wide coverage of applications such as VOLTTRON™, GridLAB-D™, and InVest show a high number of references within publications and a high number of downloads in the case of GridLAB-D™. Regarding the latter, the tool is expansive and flexible while also being open source, a combination that could make it the go-to model for utility engineers and others. Looking into the reviews left on the model, a majority gave it high ratings in both features and design, but slightly lower ratings in ease of use and support (SourceForge 2019).

- EnergyPlus™ has the highest number of publication references of all models considered and contains both a high ease of use level as well as a broad application flexibility. Its high usage may be correlated, however, with the presumed wider audience conducting energy consumption modeling compared to the audiences for some of the other tools in this list. Updates for the model are fully documented and reported and released twice per year. The tool has committed support from DOE.

- Models that were low in both general usage and publication reference generally did not show strong characteristics of an ideal model. RESOLVE, for example, was built for the CPUC and therefore restricts its capabilities to the California operating region.

One caveat to consider when looking to compare these statistics is the amount of time each of the models has been available to users. Those with higher usage and publication mentions may have their popularity inflated by the fact that they've been around longer than other, less mentioned, models. With that in mind, there is still useful information in examining what makes each of these models popular to users.

From this analysis we can develop a robust list of attributes that would be key to developing a good model. These attributes and characteristics range widely from ease of use to computational capability. Many of the models that seemed to have high usage were typically easy to use and able to carry out the specified analysis or tasks without high effort on the part of the user. Furthermore, popular models were free to use while also being comprehensive in their analytical capabilities.

Insight gained in this analysis of other models can aid in narrowing down the list of effective and sought-after attributes. Next steps towards developing a model for storage valuation would be to gain input from the industry or others through workshops that present on what was found here.

6.0 Conclusion

This report identified and characterized existing tool packages in order to inform the development of a PSH valuation tool. The research team evaluated a range of tools across multiple industries and collected information regarding their strengths and weaknesses. From there, a correlation was drawn between usage and impact of the models and the characteristics that are common in successful models.

The defined attributes and characteristics ranged widely from ease of use to computational capability. Overall, many of the models with high measures of usage and impact appeared to have the following attributes in common:

1. They were typically easy to use and able to carry out the specified analysis or tasks without significant effort on the part of the user;
2. They were free to obtain and, in some cases, open-source;
3. They were comprehensive in their analytical capabilities; and,
4. They offered a broad generalizability of results or offered the ability to model a wide range of locations/technologies.

It should be noted that this list of positive attributes is not exhaustive, nor is the list of models included in the evaluation. This report did not seek to evaluate every model available but rather to glean general insight into which attributes appear to draw users and propel industry forward.

This report also explores two model structures for the PSH tool: decision tree-based, which would guide the user through the valuation methods defined in the PSH techno-economic studies currently being carried out by DOE, and an all-inclusive comprehensive model. The strengths of each were explored and a hybrid approach was defined that would embed a price-taker model into the decision tree approach. Such an approach would provide a comprehensive approach for modeling small-scale PSH while recognizing the challenges associated with implementing a price-maker approach in an all-inclusive model.

This evaluation was conducted as the first part of a multi-part effort towards the development of a comprehensive and effective energy storage valuation tool. Results gained from this investigation of other models can aid in narrowing down the list of effective and sought-after attributes. Next steps toward developing a model for storage valuation will be to gain input through industry workshops. Feedback obtained from stakeholders can further refine our understanding of industry needs.

7.0 References

Azati Corporation. 2019a. “Making science matter in decision making: for policy where nature counts.” Accessed 04/04/19. http://aries.integratedmodelling.org/?page_id=632.

Azati Corporation. 2019a. “ARIES publications.” Resources. Accessed 04/09/19. http://aries.integratedmodelling.org/?page_id=546.

BirdLife International. 2019a. “Assessing ecosystem services – TESSA.” Accessed 04/04/19. https://www.birdlife.org/worldwide/science/assessing-ecosystem-services-tessa

BirdLife International. 2019b. “TESSA Publications.” Accessed 04/09/19. http://www.birdlife.org/worldwide/science/tessa-publications

Blakley, H. Email to Vanshika Fotedar. April 8, 2019.

Cole, P. Email to Vanshika Fotedar. April 4, 2019.

Damato, G. 2017. “StorageVET® in Action: Storage Value Estimation Tool.” CEC EPIC Symposium. Electric Power Research Institute. October 18.

E3. 2017. “RESOLVE Model Documentation: User Manual.” For California Public Utility Commission. September. Accessed 04/04/19. https://volttron.org/sites/default/files/publications/VOLTTRON_Efficient_Grid_2017.pdf

E3. 2019. “RESOLVE: Renewable Energy Solutions Model.” Accessed 04/09/19. https://www.ethree.com/tools/resolve-renewable-energy-solutions-model/

Energy Sense Finance. 2019. “PV Value: Premier Valuation Solution.” Accessed 04/04/19. https://www.energysensefinance.com/products

Electric Power Research Institute (EPRI) . 2019. “Storage Value Estimation Tool (StorageVET®).” Accessed on 04/04/19. https://www.storagevet.com/.

Fuller, J. Email to Vanshika Fotedar. March 26, 2019.

GitHub. 2019. “GCAM – The Global Change Assessment Model.” JGCRI/gcam-core. Accessed 04/07/19. https://github.com/JGCRI/gcam-core.

Haack, J. Email to Vanshika Fotedar. March 26, 2019.

Helmen, U. Damato, G., Evans, M., Ravikumar, R., and Minear, E. 2018. “ESIC Working Group 1: Grid Services and Analysis.” November 28.

PNNL. 2017. “VOLTTRON: A Technology for Efficient Buildings and Integration of Distributed Energy Resources with the Grid.” Accessed 04/04/19. https://volttron.org/sites/default/files/publications/VOLTTRON_Efficient_Grid_2017.pdf

PNNL. 2019. “Joint Global Change Research Institute: Global Change Assessment Model.” Accessed on 04/04/19. http://www.globalchange.umd.edu/gcam/

National Renewable Energy Laboratory (NREL). 2019a. “REopt: Renewable Energy Integration & Optimization.” Accessed on 04/04/19. https://reopt.nrel.gov/

NREL. 2019b. “Flexible Energy Scheduling Tool for Integrating Variable Generation.” Accessed 04/04/19. https://www.nrel.gov/grid/festiv-model.html

Quebbeman, J. 2018. “Benchmarking of Ensemble Streamflow Forecast Usage in Hyropower Planning.” CEATI International. Report #0429. July.

Roth, A. Email to Vanshika Fotedar. March 28, 2019.

SourceForge. 2019. “GridLAB-D.” Accessed on 04/08/2019. https://sourceforge.net/projects/gridlab-d/reviews.

Sandia National Laboratories (SNL). 2015. “PV Value®.” Balance of Systems and Soft Costs. Accessed 04/04/19. https://energy.sandia.gov/energy/renewable-energy/solar-energy/photovoltaics/solar-market-tranformation/pv-value/

Stanford University. 2019. “InVEST: Integrated valuation of ecosystem services and tradeoffs.” Natural Capital Project. Accessed 04/04/19. https://naturalcapitalproject.stanford.edu/invest/.

U.S. Department of Energy (DOE). 2018a. “GridLAB-D: A Unique Tool to Design the Smart Grid.” August. Accessed 04/04/19. https://www.gridlabd.org/.

U.S. DOE. 2018b. “Building Energy Codes Program: REScheck.” November. Accessed 04/04/19. https://www.energycodes.gov/rescheck.

U.S. DOE. 2019a. “Building Energy Codes Program: COMcheck.” January. Accessed 04/04/19. https://www.energycodes.gov/comcheck.

U.S. DOE. 2019b. “EnergyPlus.” Accessed 04/04/19. https://energyplus.net/.

U.S. DOE. 2019c. “EnergyPlus.” Buildings. Accessed 04/09/19. https://www.energy.gov/eere/buildings/downloads/energyplus-0.

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Pacific Northwest National Laboratory

902 Battelle Boulevard
P.O. Box 999
Richland, WA 99354
1-888-375-PNNL (7665)

www.pnnl.gov