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ΕΡΓΑΣΤΗΡΙΟ ΑΝΑΝΕΩΣΙΜΩΝ ΚΑΙ
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ΔΙΠΛΩΜΑΤΙΚΗ ΕΡΓΑΣΙΑ

ΤΟΥ ΒΑΣΙΛΕΙΟΥ ΜΑΡΗ

ΧΑΝΙΑ, 2019

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Περίληψη

Η Κρήτη είναι το μεγαλύτερο απομονωμένο ηλεκτρικό σύστημα στην Ελλάδα. Το νησί τροφοδοτείται με ατμομονάδες, μονάδες diesel, αεριοστρόβιλους και ένα συνδυασμένο κύκλο, τα οποία καίνε ορυκτά καύσιμα συμβάλλοντας σε κοστοβόρα παραγωγή ενέργειας. Ταυτόχρονα, το αιολικό και το ηλιακό δυναμικό της Κρήτης είναι από τα μεγαλύτερα στην Ευρώπη. Στοχεύοντας σε παραγωγή ενέργειας χαμηλού κόστους και στην προστασία του περιβάλλοντος, η ενσωμάτωση ανανεώσιμων πηγών ενέργειας αποτελεί μία σημαντική κίνηση προς αυτή την κατεύθυνση. Απαιτεί ευελιξία, την οποία μπορεί παρέχει η αποθήκευση ενέργειας με μεγάλο βαθμό ενεργειακής αυτάρκειας, βελτιώνοντας παράλληλα την εθνική διασφάλιση προμήθειας ενέργειας.

Αντικείμενο αυτής της εργασίας είναι η εύρεση της καταλληλότερης τεχνολογίας αποθήκευσης ενέργειας για την Κρήτη, έως το 2032, η οποία θα ικανοποιεί τις ανάγκες του συστήματος με την καλύτερη αποπληρωμή. Γι’ αυτό το λόγο χρησιμοποιούμε 2 μοντέλα, τα Energy Storage Computational tool και ES Select. Ειδικότερα, αξιολογούνται διαφορετικές τεχνολογίες αποθήκευσης και βαθμολογούνται με βάση την απόδοσή τους σε διαφορετικές τοποθεσίες του δικτύου ηλεκτρικής ενέργειας. (κατανάλωση, μετάδοση, διανομή, παραγωγή).

Το ESCT αναγνωρίζει 18 εφαρμογές και τα οφέλη τους,κατηγοριοποιημένες ως οικονομικές, αξιοπιστίας και περιβαλλοντικές. Το εργαλείο αυτό βοηθάει το χρήστη να αναλύσει κόστη και οφέλη ενός συστήματος αποθήκευσης σε διάφορα σενάρια ώστε να καθορίσει το ποσό αποπληρωμής. Η οικονομική αξία που αποδίδεται από το μοντέλο μπορεί να αποδίδεται σε υπηρεσίες κοινής ωφέλειας (δημόσιο), ιδιώτες και τελικούς χρήστες, ή σε συνδυασμό αυτών των ομάδων ανάλογα με τη φύση της εγκατάστασης και τις εφαρμογές.

Αναφορικά με το ES Select, η αξιολόγηση των τεχνολογιών βασίζεται σε 2 κριτήρια: τη συνολική βαθμολογία εφαρμοσιμότητας και την πιθανότητα αποπληρωμής. Η βαθμολογία εφαρμοσιμότητας προκύπτει από επιμέρους βαθμολογίες βάσει 4 υπο-κριτηρίων, όπως η ανάπτυξη ή ετοιμότητα για εμπορική εφαρμογή, η καταλληλότητα για την επιλεγμένη τοποθεσία, η ικανοποίηση των αναγκών με βάση τις εφαρμογές και το κόστος εγκατάστασης. Η πιθανότητα αποπληρωμής και η συνολική βαθμολογία εφαρμοσιμότητας υπολογίζονται βάσει μέσω προσομοίωσης Monte Carlo, που είναι υπολογιστικός αλγόριθμος ενσωματωμένος στο ES Select για τη διαχείρηση αβεβαιοτήτων στις παραμέτρους εισαγωγής, περιλαμβάνοντας λειτουργικά χαρακτηριστικά όπως ενέργεια διανομής, ενεργειακή απόδοση, διάρκεια αποφόρτισης και κύκλο ζωής, κόστη, πιθανές εφαρμογές αποθήκευσης και οικονομικά οφέλη. Τιμές για τα οφέλη και τις προοπτικές αγοράς προσδιορίζονται σύμφωνα με προτάσεις από τα Sandia National Laboratories στις ΗΠΑ.

Αρχικά, δεδομένου ότι το ESCT συνδυάζει έως 3 εφαρμογές, αξιολογούνται 2 διαφορετικά σετ των 3 εφαρμογών και από τα 2 μοντέλα καταλήγοντας στο συμπέρασμα ότι δεν υπάρχει ωφέλιμη τεχνολογία αποθήκευσης για το νησί της Κρήτης. Στη συνέχεια, αξιολογούνται περιπτώσεις με σετ των 6 εφαρμογών σε 4 διαφορετικές τοποθεσίες μέσω του ES Select, συμπεραίνοντας ότι η καταλληλότερη τεχνολογία είναι μπαταρίες τύπου NaNiCl για επιλογές αποθήκευσης πάνω από 1 MW και μπαταρίες NaS για επιλογές αποθήκευσης έως 1 MW.

Abstract

Crete is the largest isolated electrical system in Greece. The island is powered by steam units, diesel units, gas turbines and one combined Cycle, which burn fuel oil and diesel oil, contributing to high-cost energy production. At the same time, the wind and solar potential in Crete are among the largest in Europe. With a view to low cost energy production and environmental protection, integrating variable renewable energy in the energy system could help to this direction. The integration of variable energy requires flexibility, which energy storage can provide with a high-degree of energy self-sufficiency, while enhancing the national security of energy supply.

The objective of this thesis is to identify the best-fit energy storage technologies in Crete, until 2032, in terms of their ability to satisfy the energy system needs at the best financial return. Therefore, 2 decision-support models, Energy Storage Computational tool (ESCT) and ES Select tool, support the assessment of appropriate for Crete storage options. More specifically, many different storage technologies serving different sets of storage applications are evaluated and ranked at different grid locations (residential, commercial, transmission, distribution and generation).

ESCT identifies 18 applications and their benefits, categorized as Economic, Reliability, or Environmental. The ESCT helps the user analyse the costs and benefits to determine the storage system's overall value (payback). The user can use the ESCT to analyse costs and benefits of storage deployments under different scenarios and assumptions. The monetary value of the benefits calculated by the ESCT could be attributed to ratepayers/utilities, non-utility merchants, end-users, society, or a combination of these parties, depending on the nature of the deployment and the applications pursued.

Regarding ES Select, the assessment which ranks the technologies is derived on 2 criteria: a total feasibility score and probability of having a payback. The total feasibility score is calculated by aggregating relative feasibility scores of 4 sub-criteria, as maturity or readiness for commercial deployment, appropriateness for the selected grid location, meeting application requirements, and installed cost on the specific grid location. The probability of having a payback and the total feasibility score are estimated through Monte Carlo Simulation, which is a computational algorithm integrated in the ES-Select™ model handling uncertainties of input parameters, including operational characteristics as deliverable power, energy efficiency, discharge duration and lifecycle, and business factors as costs, possible storage applications and financial benefits . Values for application-specific benefits and market potentials are estimated based on recommendations developed by Sandia National Laboratories in the US.

Initially, given the fact that ESCT combines up to 3 applications, 2 different sets of 3 applications are evaluated from both tools concluding that there is no beneficial energy storage technology for the island of Crete. Afterward, cases with sets of 6 applications are ranked at 4 different grid locations using the ES Select tool resulting that the best-fit technologies are NaNiCl for technology options over 1 MW and NaS for technology options up to 1 MW.

Foreword

The study constitutes my Master Thesis in the postgraduate program "Environmental management, sustainable energy and climate change" at the Technical University of Crete. I would like to thank my supervisor, Professor Theocharis Tsoutsos, whose help and support throughout the thesis writing process I greatly appreciate. Furthermore, my gratitude goes to Ms Antiopi Gigantidou, Head of Crete Dispatching Center/Islands Network Operation Department, for her assistance in acquiring energy data and wind data used for estimating the energy curtailment from the wind farms installed in Crete.

Vasileios Maris

Table of contents

List of Tables

Table A.3: Cost and Performance of Advanced Lead-acid Batteries in Utility T&D [Sandia National Laboratories, 2015]

Table A.4: Cost and performance characteristics of new central station electricity generating technologies [U.S. Energy Information Administration, 2018]

List of Diagrams

List of Figures

List of Abbreviations

A-VRFB	Advanced Vanadium Redox Flow Battery
CAES-c	Compressed-Air ES, cavern
CAES-s	Compressed-Air ES, small
DL-CAP	Double Layer Capacitors
EC	Energy Carrier
ES	Energy Storage
ESCT	Energy Storage Computational Tool
LA-adv	Advanced Lead Acid
LIB-e	Lithium Ion - High Energy
MC	Monte Carlo method
Ni-batt	Ni battery
P-Hydro	Pumped Hydro
VRFB	Vanadium Redox Battery
VRLA	Valve Regulated Lead Acid
ZnAir	Zinc-Air Battery

1. Introduction

1.1. Introduction in the energy storage in off-grid systems

Energy in whatever form is an essential commodity globally. It is the most common consumer good and has continued to be a key element to worldwide development. Energy comes in various forms although it can be broadly classified into 2 forms of energy, primary and secondary. Primary forms of energy are the energy sources only involving extraction or capture, with or without separation from contiguous material, cleaning or grading, before the energy contained in it can be converted into thermal or mechanical work. They are usually found in nature and include all energy forms which have not been subjected to any conversion or transformation process. Typical examples are crude oil, coal, biomass, wind, solar, tidal, natural uranium, geothermal, falling and flowing water, natural gas, etc. On the other hand, secondary forms of energy include all energy forms which occur as a result of the transformation of primary energy using energy conversion processes. Figure 1.1 shows the relationship between the primary and secondary energy forms.

Secondary energy forms are more convenient forms of energy as they can directly be used by humankind. They are also known as Energy Carriers (EC). Examples of secondary energy forms are electricity, gasoline, diesel, ethanol, butanol, hydrogen, heat.

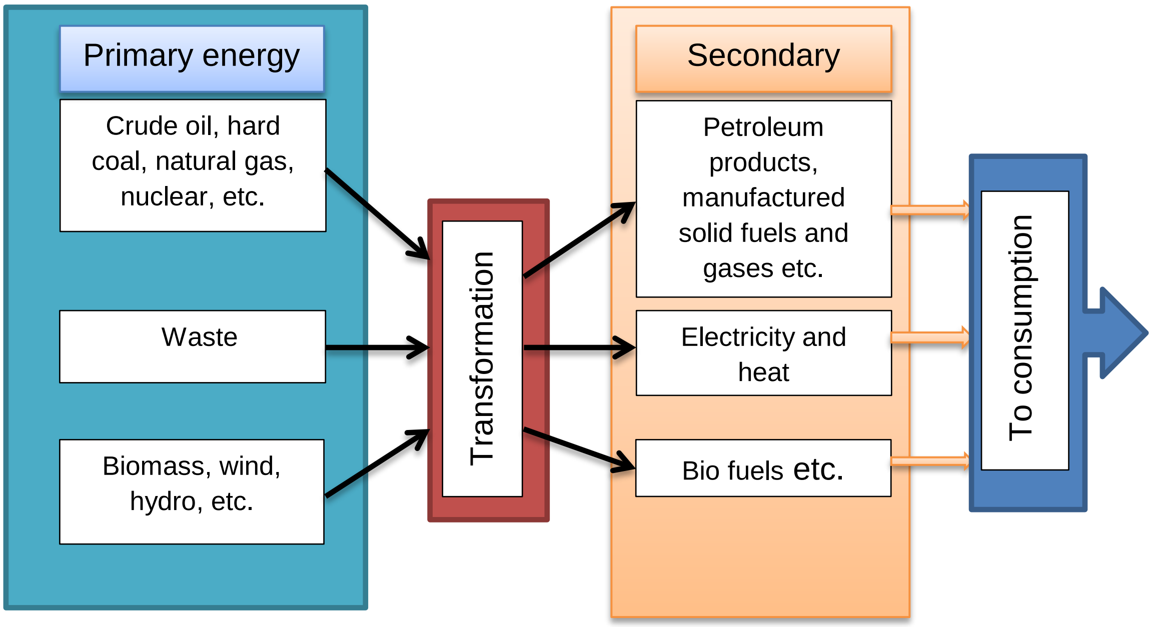


Figure 1.1: Primary and secondary energy [Aneke, 2016]

Cumulatively, energy consumption has been growing significantly over the years. Although there is an increasing trend in the global energy supply, the percentage share of fossil fuel has been decreasing gradually due to the penetration of renewable energy systems. However, this reduction in fossil fuels share in the primary energy supply does not portray in actual terms a reduction in CO_2 emission.

CO_2 emissions from fossil fuels have been identified as a major global environmental threat due to its contribution to global warming. For the past years, many efforts have been made to reduce CO_2 emission in order to mitigate the associated environmental impact. These range from creating new and innovative energy conversion technologies to improving the efficiency of existing energy conversion technologies. Furthermore, reducing energy wastage from a variety of industries whether domestic or commercial by storing them for future use has a very significant impact in reducing CO_2 emission. The need to balance the mismatch between energy supplied to the grid and the energy actually used from the grid by storing the excess energy is equally important to achieving a low carbon economy. It is against this backdrop that energy storage is believed to be essential in the modern energy supply chain as it will help to plug the leakages and improve efficiency. As a result of this, energy storage has recently attracted the attention of governments, stakeholders, researchers and investors as it may be an essential link in the energy supply chain.

For example, it is a fact that there is no system that is 100% thermodynamically efficient. The energy losses in most systems occur in the form of heat which is usually lost to the environment. These waste heats are essential resources that if captured and stored, can serve as a useful energy resources for other processes. Apart from the waste heat, energy storage will also play a significant role as the world moves to a low carbon economy where more energy is envisaged to be extracted from renewable resources. One major challenge facing most renewable energy resources, especially solar and wind, is that they occur intermittently which makes them unreliable for steady energy supply. Through the energy storage concept, these renewable resources can be made to be reliable and steady energy sources. This can be achieved by storing the excess energy generated when renewable resources are available and re-use the stored energy when renewable resources are not available.

In the engineering term, energy storage is focused on the concept of storing energy in the form in which it will be reused to generate energy whenever needed. It is required for a wide range of different time and size scale as shown in figure 1.2. As indicated in the figure, the range of storage can be from capacitors which stores as little of 1Wh of energy for few seconds to chemical compounds which can be used for grid scale storage of several TWh of energy for years.

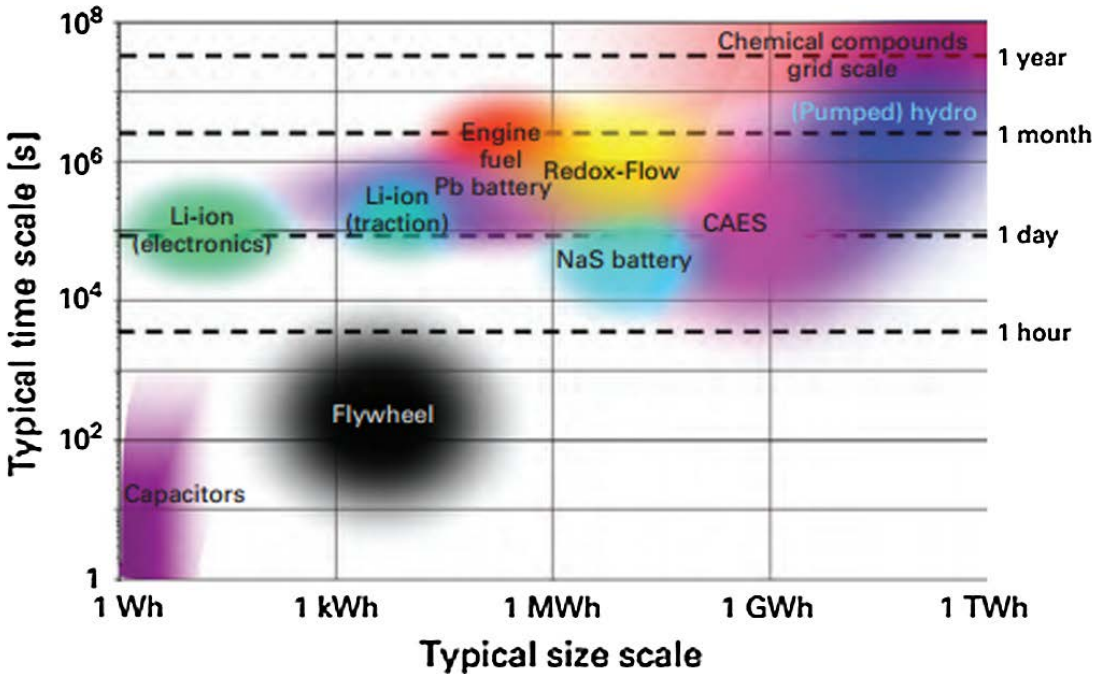


Figure 1.2: Typical time and size scales associated with sufficient storage technologies [Aneke, 2016]

The general concept behind secondary energy storage is to capture energy produced at one time for use at a later time. The process of capturing the energy is generally regarded as the charging while the process of releasing the energy to be used is regarded as the discharging. The energy is stored using different kinds of materials which are commonly referred to as the energy carriers. Figure 1.3. shows the diagrammatical representation of the energy storage concept.

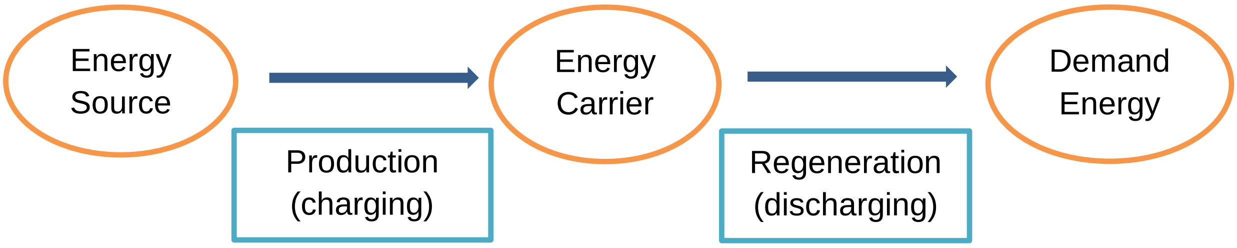


Figure 1.3: Energy storage concept

1.2 The electrical system of Crete

Crete is the largest isolated electrical system in Greece. During August of 2017 peak load was 636 MW and annual energy demand was 3.019.581 MWh or 3.019 GWh. The island is powered by: Steam units, Diesel units, Gas turbines and one Combined Cycle in Chania which burn fuel oil and diesel oil. Thermal units burn expensive fuel contributing to high-cost energy production.

At the same time, the wind and solar potential in Crete are among the largest in Europe. After the liberalization of the RES electricity market and the subsidy from the EU and National Funds, many companies installed Wind Farms. Since 1993 when the first Wind Farm (WF) was installed in Sitia, 202 MW of WFs are installed in Crete which is the 20% of the installed power capacity. Remote monitoring systems have helped the rise of the Wind Power penetration and the secure operation of the System. Continuous monitoring, protection and operational improvements contributed to greater utilization of the wind potential and more economic operation. The annual capacity factor of the Wind Farms reaches 30% while some WFs in good positions can reach 40%.

In addition, 96 MW of photovoltaic are installed in the fields and on the roofs in Crete Island and the annual capacity factor of the PV Parks can reach 20%. The energy of all those PV parks covers much of the morning peak every day, throughout the year and has stabilized the voltage in the villages in the countryside. PV production covers 13% of the daylight consumption of the island and 6,5 % of the annual consumption. Table 1.1 shows energy production units, quantities of energy produced and fuel burnt and costs for the island of Crete during 2017.

Table 1.1: Energy production costs for the island of Crete during 2017 [HEDNO, 2018]

unit	MWh	fuel	quantity (tn)	quantity (kL)	cost (euro/tn)	cost (euro/kL)	cost (euro/MWh)
steam units	1.030.588	heavy oil 3.500	454.229	-	352	-	96
internal combustion engine units	718.710	heavy oil 3.500	191.420	-	352	-	67
internal combustion engine units	892	diesel oil	-	11	-	815	190
gas turbines	616.231	diesel oil	-	21.483		815	239
wind farms	512.832	-	-	-	-	-	99
photovoltaic	140.033	-	-	-	-	-	100
TOTAL	3.019.286						

From the beginning of the installation of the WFs, a tailor-made digital communication protocol was developed in order to receive real-time data 'live' data in the Dispatching Center SCADA system and send upper limit set-points to the WFs. In the Dispatching center of Crete, a SCADA and LFC (Load Frequency Control) system operates since 1992. The WF management system was embodied in the existing SCADA system.

Management programs for the WF have been developed which send set-points every 2 minutes and determine the maximum output of WFs. They take into consideration the Technical Minimum of the units in operation, and the maximum allowed penetration of the WFs which is ranged around 30-40% depending on the weather conditions or other distractions of the grid. The algorithm is: Any time the actual set-point to the WFs is the minimum of:

- Load-Technical Minimum
- Load* C% (allowed penetration)=Load* 30-40%
- Installed WF capacity

Depending on the technology, the output power of the WF is restricted in various ways:

- By stopping some Wind Turbines,
- Adjusting the pitch control Wind Turbines
- By means of power electronics

The following table shows the wind farms installed on the island of Crete.

Table 1.2: Operating wind farms on the island of Crete and their capacity. [HEDNO, 2017]

wind farm	capacity (MW)
ROKAS	12,90
AIOLOS	10,00
AHLADIA	10,00
KRYA	10,00
ANEMOESA	5,00
PLASTIKA	11,90
PLATYBOLA	3,00
ENERCON	2,50
YDROAIOLIKI (ΑΙΟΛΙΚΗ ΠΕΛ)	9,35
XONOS-IWECO	4,50
XIROLIMNI-DEI	3,00
ENVITEC-BATALI	5,40
ROKAS-MODI 2	4,80
DIETHNIS AIOLIKI	7,20
AHLADIA EPEKTASI	1,20
KRYA EPEKTASI	1,20
AKOUMIA	7,20
ROKAS-KALOGEROS LI	3,60
ΟΑΣ ΣΗΤΕΙΑΣ SIF	1,20
ANEMOS-ALKIONIS KA	6,30
ΜΟΥΣΟΥΡΩΝ ΚΑ	2,55
ΚΟΥΛΟΥΚΟΝΑΣ RE	4,80
ΑΝΕΜ/ΕΣΣΑ ΕΠΕΚΤ ΜΑ	1,20
ENVITEC ΒΑΡΔΙΑ AG	5,40
KOPRINO SP	7,20
OAS 500 kW SIF	0,50
ΜΟΙΡΩΝ Α/Π ΜΟ	5,25
ΑΣΙΔΕΡΩΤΑΣ SP	2,40
ΤΕΡΝΑ ΑΓ.ΒΑΡΒΑΡΑ ΒΑ	14,45
EPANOSIFI PR	5,95
IWECO ΜΕΓ. ΒΡΥΣΗ ΜΟ	4,95
ΞΗΡΟΛ 1&2 SI3	10,20
ΒΟΣΚΕΡΟ ENEL H3	5,95
ENTEKA SI3	2,70
TOTAL	**193,75**

1.3. Scope

This thesis looks at the exploitation of the large wind potential of Crete by installing energy storage technologies which store wind energy replacing energy produced by fossil fuels. This results in cost-effective energy production and reduced emissions to the environment. The study is composed of 2 parts, the possible additional energy production and the selection of appropriate energy storage technology to store this energy.

Therefore, we calculate energy production in case all set-points equal 1 which means the maximum possible output for the wind farms. Then we find the difference between the maximum possible energy and the real produced energy during 2017, which is the energy to be stored. After that, we need to find if there is an energy storage technology that can store this amount of energy and at the same time be beneficial.

2. Experience in energy storage

Electricity storage is not a new idea. In the 1780s, Galvani introduced "animal electricity" and later, in 1799, Volta invented the modern battery. In 1836, batteries were adopted in telegraph networks while in the 1880s, lead-acid batteries were the original solution for night-time load in the private New York City area direct current (dc) systems. The batteries were used to supply electricity to the load throughout high demand periods and to soak up excess electricity from generators throughout low demand periods for sale later. The first U.S. large-scale electricity storage system was 31 MW of pumped hydro storage in 1929 at the Connecticut Light & Power Rocky River Plant. As of 2011, 2.2% of electricity was stored worldwide, mostly in pumped storage. In addition, there are many projects and studies referring to energy storage applications with a view to cost-effective and more environmentally friendly energy production. Some of these projects are cited below.

City of Anaheim, public utilities department, 2014, White Paper Analysis of the Operational and Technological Options for Energy Storage Systems, Energy Storage System Plan

The development of the Energy Storage System Plan (ES Plan) and the approved work effort was a response to mandates established by Assembly Bill 2514 (AB 2514), which was signed into law on September 29, 2010. ES technologies store energy from thermal, chemical or mechanical sources for use at a later time. Energy storage systems (ES systems) are identified by the bill as a component of the future electric grid that includes the continued integration of more intermittent renewables and more local generation. AB 2514 requires that all utilities state-wide, which serve more than 60.000 customers, analyse and adopt policies for the procurement of ES systems. Specifically, this bill directed the California Public Utilities Commission (CPUC) to hold proceedings for all investor-owned utilities (IOU) and required the governing boards of all POUs to conduct an assessment to determine appropriate targets, if any, for each utility to procure viable and cost-effective ES systems.

The City of Anaheim, Public Utilities Department is required to comply with the bill as it is a publicly owned utility (POU) with 115.000 electric customers. Regarding the Department, the bill requires that on or before October 1, 2014, the City Council shall determine the need for energy storage system procurement targets to be achieved by December 31, 2016. On April 17, 2012 the City Council manipulated the Department to develop an ES Plan that would identify the technical feasibility of ES systems, potential benefits to the Department and based on cost/benefit analysis, recommended targets of procurement. The ES Plan defines ES systems, how they are used on the grid, the current technologies available and the currently defined uses for the technology. The viability of ES systems and their cost-effectiveness were both evaluated. The Department reviewed its existing and near future needs and developed a case study to evaluate the use of an ES system within the distribution grid. Software created for the Department of Energy (DOE) by Navigant Consulting (*ES Computational Tool (ESCT) Version 1.2*) was used to evaluate the cost-effectiveness of an ES system in the case study.

Georgiev, 2015, Techno-Economic Energy Storage Assessment in Denmark 2030, A case of selecting best-fit storage technologies with ES-Select decision-support tool

The Danish energy policy sets ambitious green transition targets, which are aiming to transform Denmark to a fossil fuel-free country by 2050. Reaching these targets involves integrating large quantities of variable renewable energy in the energy system. The integration of variable energy requires flexibility, which energy storage can provide a high degree of energy self-sufficiency, while enhancing the national security of energy supply. The objective of this thesis is to identify the best-fit energy storage technologies in Denmark, until 2030, in terms of their ability to satisfy the energy system needs at the best financial return. A highly interactive decision-support model ES-Select™ supports the assessment of appropriate for Denmark storage options as Batteries, Compressed-Air and Thermal Storage.

Sreekanth et al, Energy and Building Research Center, 2016, Potential of Energy Storage Technologies for Electrical Power System in Kuwait

This research paper aims to emphasize the advantages of energy storage technologies (ESTs) as an approach to effectively dealing with future energy demand, particularly for the State of Kuwait. This paper studies the economic evaluation and analysis of 4 important forms of ESTs and their integration into the power generation stations of electrical power system in Kuwait, in particular, those with high potential for resolving issues related to the optimization of the power supply and high demands at peak loads. ES-Select tool is utilized for the feasibility study. This allowed the evaluation of various ESTs in terms of their applications, characteristics, costs, and benefits. The collected data were analysed to verify the suitability of different ESTs based on their financial feasibility for installation in the selected location and their use in the present electrical power system. The optimal use of these ESTs within the power system is considered, as well as their technical feasibilities. The study demonstrates that in the electricity sector of the State of Kuwait, compressed air storage and pumped hydro are the most probable options for ESTs, followed by NaS, based on its economical assessment corresponding to the selected location.

Sreekanth et al, Energy and Building Research Center, 2018, Feasibility Analysis of Energy Storage Technologies in Power Systems for Arid Region

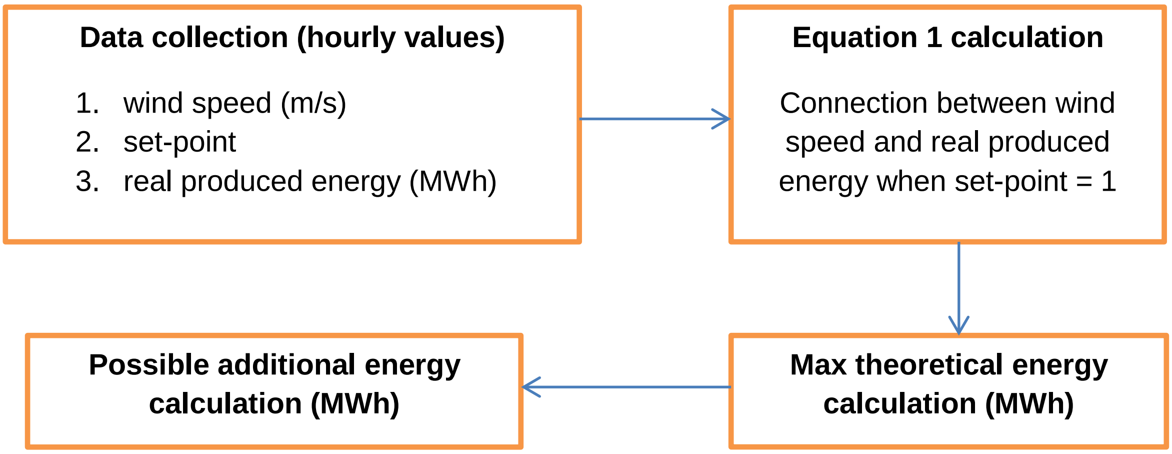
The focus of this study was the benefits of energy storage technologies (ESTs) as a step of managing the future energy demand, by considering the case of electric power systems (EPS) in arid regions. The evaluation of different forms of ESTs' integration into the existing EPS, especially those with higher potential for solving issues related to the optimization of the power supply and high demands at peak loads, was carried out. 2 interactive programs, ESCT and ES-Select, were utilized in the feasibility study that allowed evaluating various ESTs with regard to their characteristics, costs, benefits, which was carried out for the first time in this region. The study investigated a variety of power ranges within the power system components including bulk generation, transmission, distribution, commercial and industrial and residential users. These tools were used to address the price and cost components assuming a normal distribution, as well as the cycle life, size, efficiency, cash flow, payback, benefits range, and market potential of 19 important ESTs about the arid region. The obtained data were all combined to verify the appropriateness of these ESTs, which has been followed by determining the optimal use and best probable physical placement of these ESTs into the EPS, by allowing for the economic, environmental, and technical feasibility. The study concluded that the compressed air energy storage (CAES) is the most promising option followed by pumped hydro storage (PHS) and sodium-sulfur battery (NaS), based on the technical and economic evaluations of the different ESTs in arid regions.

All the above projects refer to energy storage technologies assessment and 2 interactive programs, ESCT and ES-Select, are utilized for this reason. The same happens with our study so we cite those projects for comparison reasons as can be seen in chapter 5.2.

3. Methodology

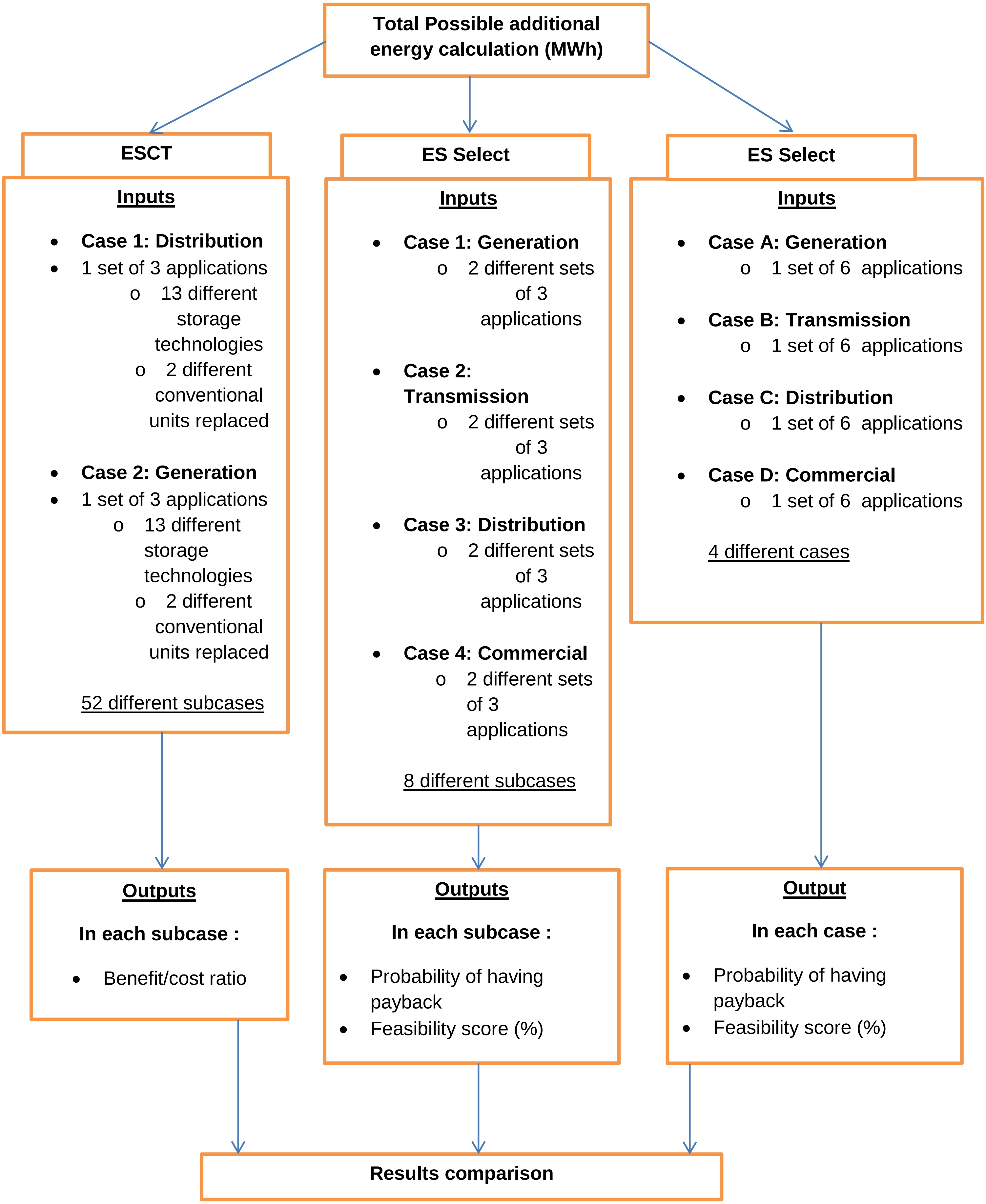
The first part is the calculation of possible additional energy. For each one of the 34 wind farms operating on Crete during 2017, we follow the steps shown in diagram 3.1.

Diagram 3.1. Possible additional energy calculation



We calculate the total possible additional energy that comes from all the wind farms operating on Crete and then we use ESCT and ES Select to find a technology that can store this energy. So, for the second part, we follow the steps shown in diagram 3.2.

Diagram 3.2. Energy storage technologies assessment



3.1. Possible additional energy calculation

In order to calculate the possible additional energy that could be produced and be stored, we collected wind and energy data for 34 wind farms (table 1.2) operating on the island of Crete from the Crete Dispatching Center/Islands Network Operation Department. For each type of data, we have mean hourly values for each day during the whole year (8760 values).

a) Real produced energy (MWh)

b) Wind speed (m/s)

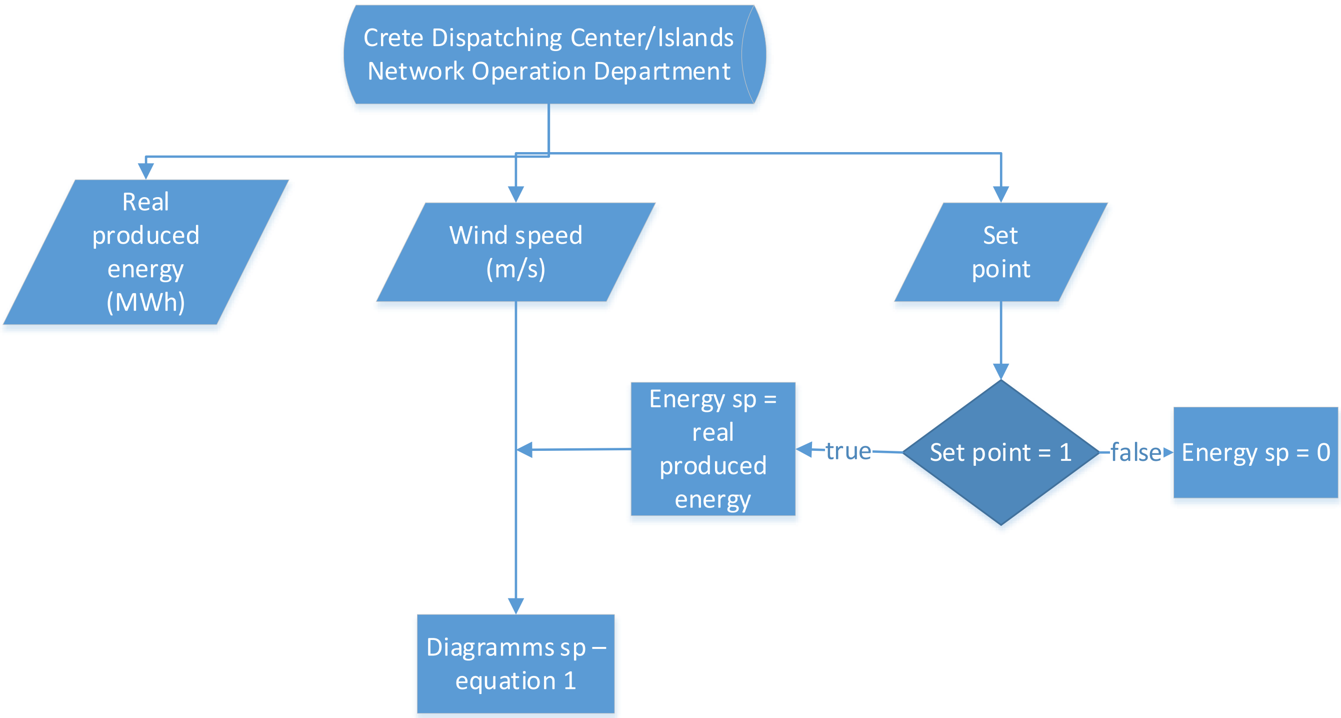
c) Set-points: These vectors show the energy exploitation of the wind farm (for example set-point = 0,8 means that the Wind Farm should not exceed 80% of the installed power (it there in so wind it will produce 0).

For each wind farm:

1) Using only real produced energy values with set-point = 1 and the corresponding wind speed values, we find the equation (equation 1) that gives the relation between energy production and wind speed (energy sp).To do this we use Microsoft Excel, selecting these data and then: chart tools - > layout -> trend line -> polynomial.

Equation 1 = polynomial (order 3)

Diagram 3.3. Equation 1 calculation

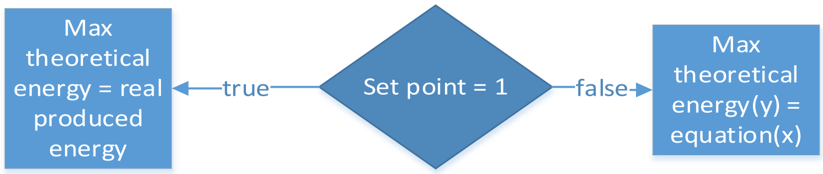


It should be noted that in case that set-point is < 1 then we do not take into account these values for the calculation of equation 1.

2) According to this equation, we calculate the max theoretical energy (energy if all set points equal to 1). More specifically:

If set point = 1 then max theoretical energy = real produced energy

If set point < 1 then max theoretical energy (y) = equation (x), where x = wind speed



3) We calculate the possible additional energy (energy curtailment) as:

Max theoretical energy - real produced energy

4) We calculate the curtailment ratio:

Possible additional energy / real produced energy

3.2. Simulation tools options

Table A.2 in Annex F shows the main categories of energy storage simulation tools. Energy storage tools often have overlaps in applications and therefore main applications of tools are represented with a black dot and secondary applications are represented with an open dot. According to Table A.2, ES select tool and Energy storage computational tool are appropriate for electricity storage technology screening and electricity storage cost effectiveness, so these tools seem to be ideal for our case. In addition, many previous energy storage projects use these tools as mentioned in chapter 2.

3.3. Energy storage computational tool methodology

The DOE (Department of Energy) Office of Electricity Delivery and Energy Reliability (OE) and the National Energy Technology Laboratory (NETL) tasked Navigant Consulting, Inc. to develop the Energy Storage Computational Tool (ESCT) to identify and quantify the benefits accrued through services provided by storage projects.

The ESCT identifies 18 applications and their benefits, categorized as Economic, Reliability, or Environmental. The ESCT helps the user analyse the costs and benefits to determine the storage system's overall value. With this tool, the user can determine project costs and benefits to gain a clearer understanding of the financial benefits of storage deployment. The user can also use the ESCT to analyse costs and benefits of storage deployments under different scenarios and assumptions. The monetary value of the benefits calculated by the ESCT could be attributed to ratepayers/utilities, non-utility merchants, end-users, society, or a combination of these parties, depending on the nature of the deployment and the applications pursued. The primary and secondary benefits that the ESCT calculates are assumed to accrue to the owner unless otherwise specified in the name of the benefit.

However, in determining the total value of storage, the ESCT aggregates all benefits regardless of who the likely benefactor is. Therefore, if the user wishes to carry out a more detailed cost-benefit analysis that is more specific to user benefits, the user can designate which of the various benefits accrue to the user specifically and complete this analysis separately. The tool was not designed to yield results to be used in regulatory hearings or other similar proceedings. Ultimately, the results of the tool are intended for educational/screening purposes only and are meant to provide insight that can be used in conjunction with other analyses to understand more clearly the impact and benefits of storage to the grid.

Figure 3.1 depicts the overall methodology that the tool employs to determine the monetary value of an energy storage deployment. In summary, the ESCT:

1. Characterizes energy storage projects in terms of technologies employed, location on the grid, regulatory structure, owner, and applications.

2. Identifies the economic, reliability, and environmental benefits the storage project could yield.

3. Guides the user through the process of entering data required for calculating the monetary value of benefits and associated capital and O&M costs.

4. Estimates the NPV of the energy storage system over its lifetime, displayed as graphs and tables.

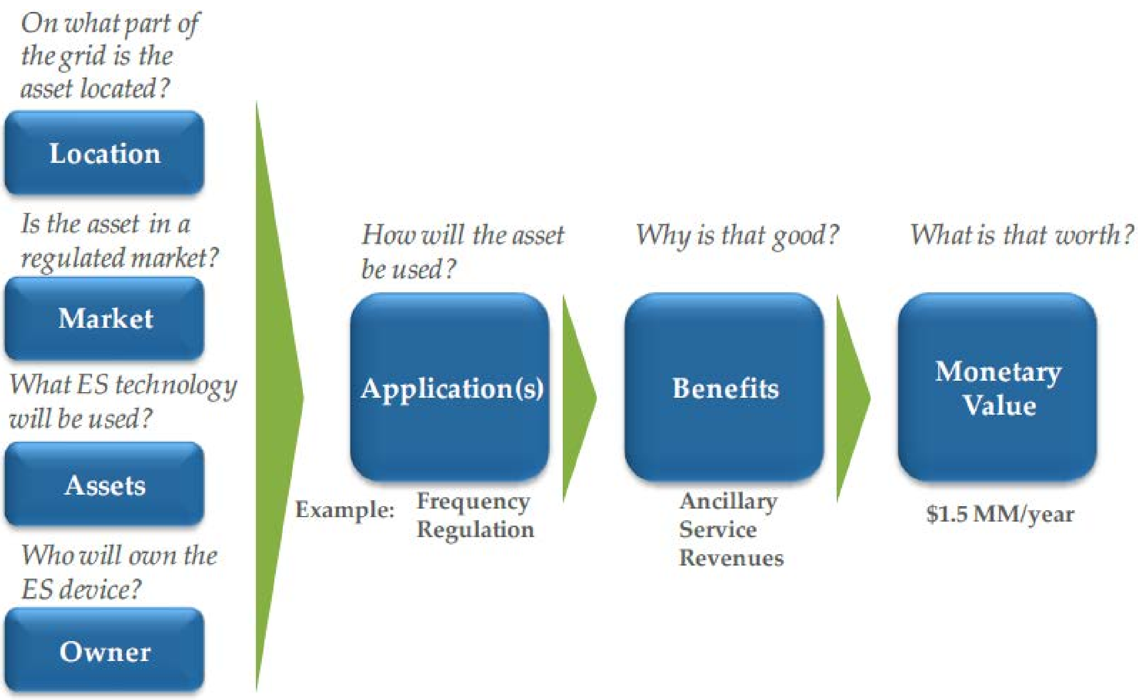


Figure 3.1: Methodology for Determining the Monetary Value of an Energy Storage Deployment [U.S. Department of Energy, 2012]

Figure 3.2 illustrates the overall architecture of the ESCT. Although the tool is contained in a single Excel™ file, it has 3 distinct modules. The design of the tool is based on a modular structure that ensures ease of use and allows the tool to be more easily updated. Module I is the Asset Characterization Module (ACM), Module II is the Data Input Module (DIM), and Module III is the Computational Module (CM).

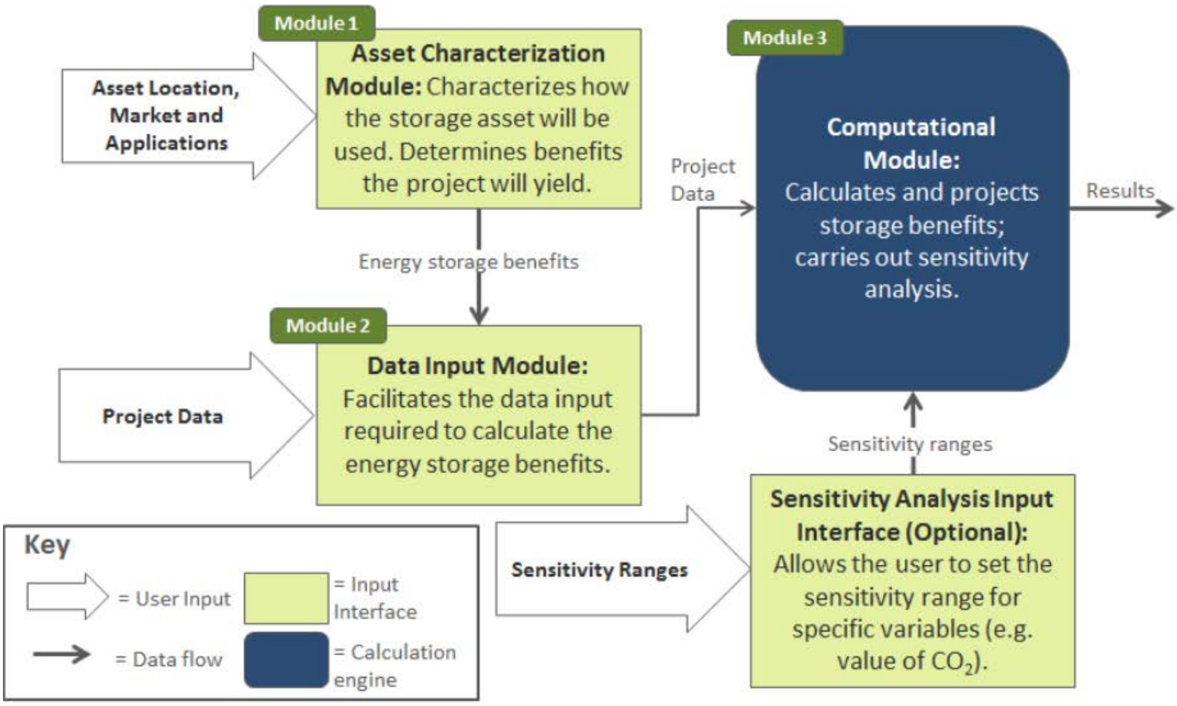


Figure 3.2: ESCT Architecture [U.S. Department of Energy, 2012]

Figure 3.3 illustrates how the user experiences the tool. It is principally designed to help the user navigate the complex tool in a way that is transparent, easy to follow, and in a way that will reduce errors and make it easy to track down errors if they are made.

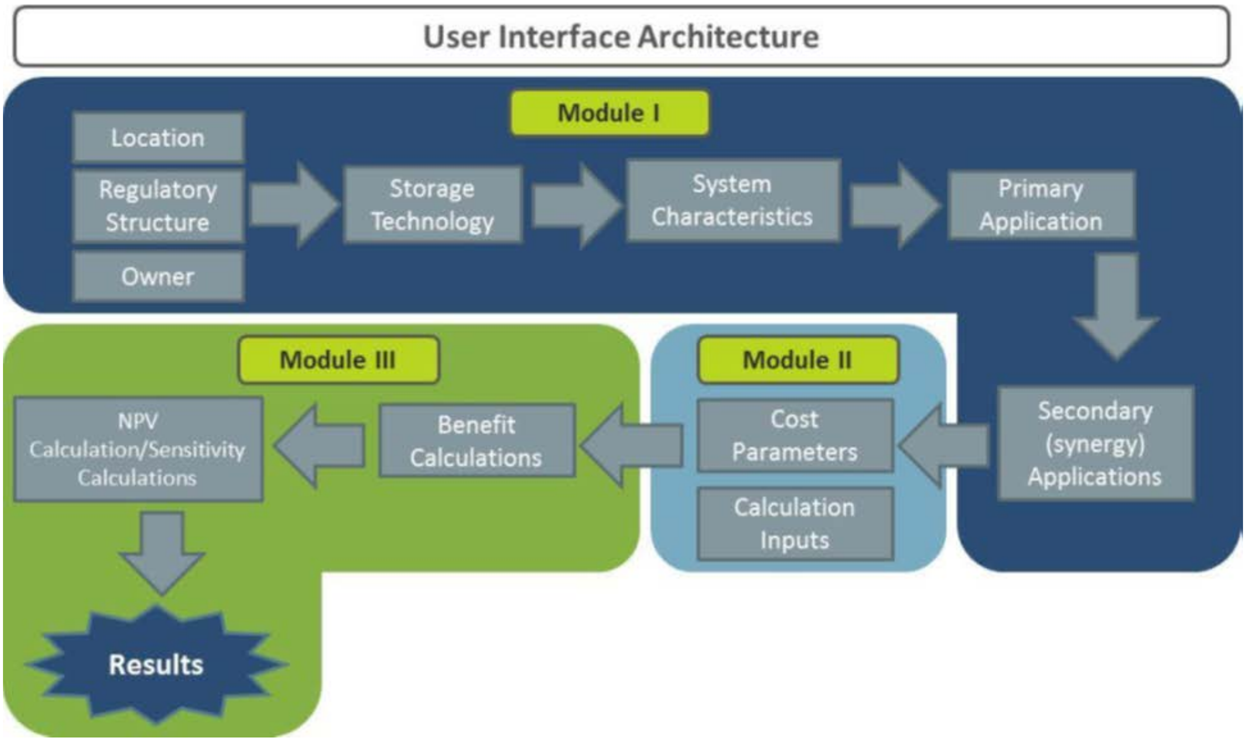


Figure 3.3: User Interface Architecture [U.S. Department of Energy, 2012]

Although the user experiences the ESCT in a linear fashion, there are many non-linear interdependencies among the various inputs, which are illustrated in Figure 3.4. For example, project characteristics specified in the Asset Characterization Module such as location, market, and owner, influence the type of benefit calculations used later on in the Computational Module.

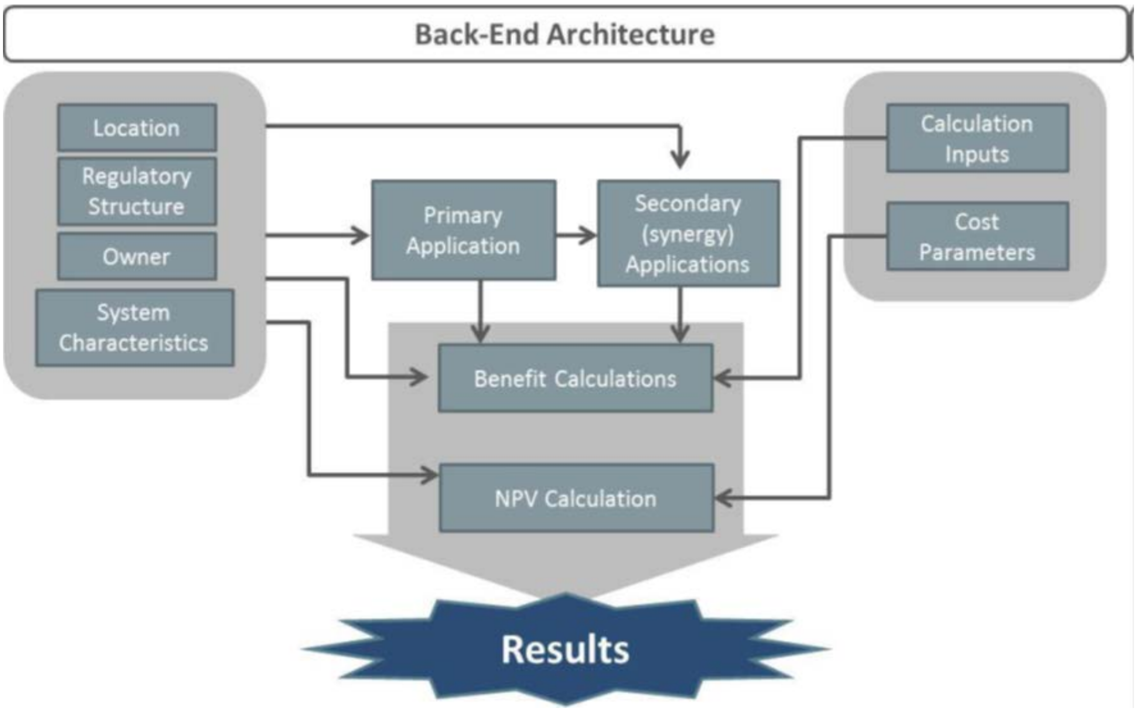


Figure 3.4: Back-End Architecture [U.S. Department of Energy, 2012]

Asset Characterization Module (ACM)

The ACM utilizes a series of graphic user interface screens to collect data and help the user navigate through the module. Figure 3.5 and Figure 3.6 depict 2 typical examples of screens that will appear in the ACM.

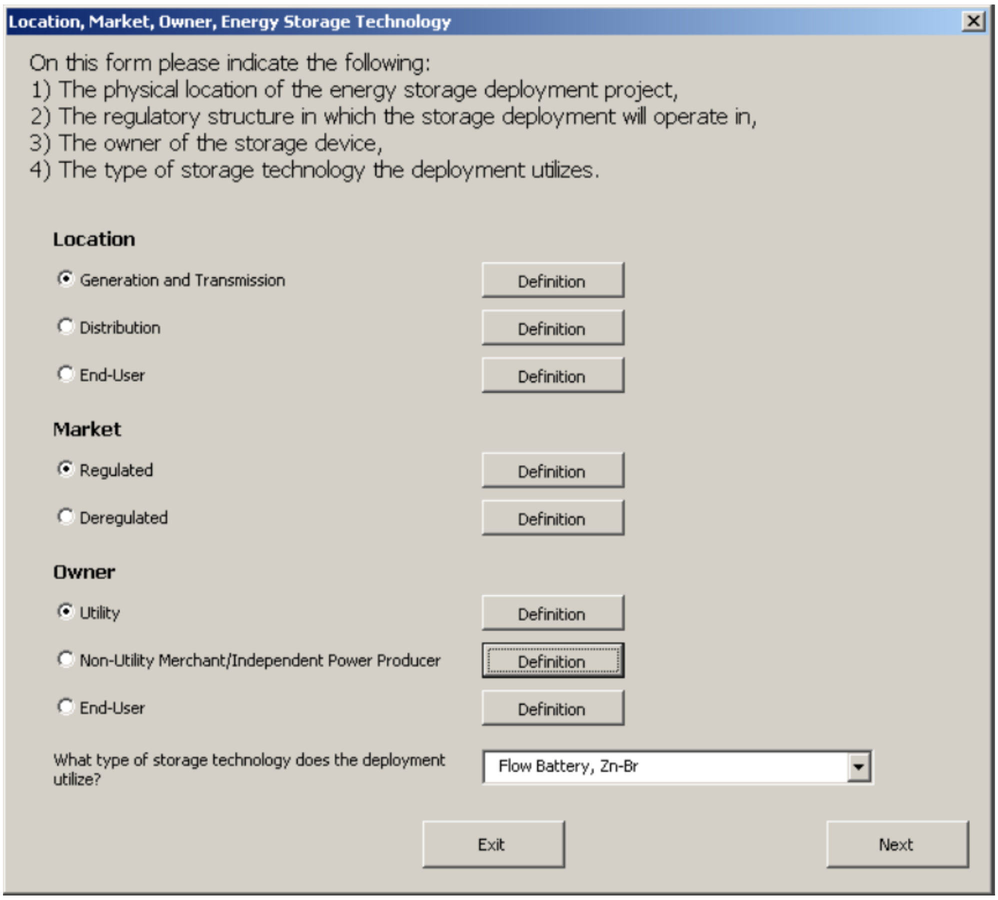


Figure 3.5: Typical ACM screen, Example 1 [U.S. Department of Energy, 2012]

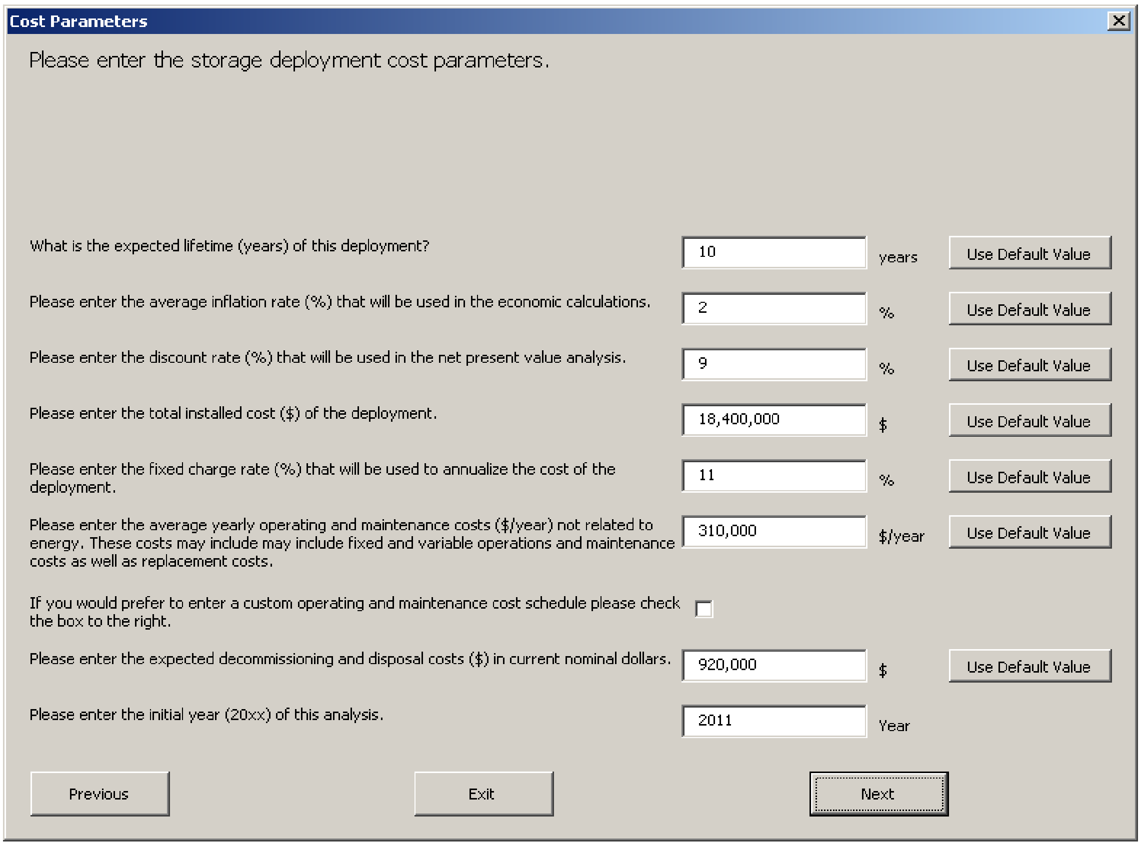


Figure 3.6: Typical ACM screen: Example 2 [U.S. Department of Energy, 2012]

Inputs for our project

Location

Case 1

Distribution: Storage located on this part of the electricity delivery system is located between a distribution step-down substation and the end-user. Storage is also located on this part of the system if it is located in the step-down substation and is located on the secondary side of the transformer. In addition, storage deployed in a ‚community energy storage' configuration is considered to be on this part of the system. This could include energy storage in the form of electric vehicles charging at stations owned by the utility.

Case 2

Generation & Transmission: This location describes any point between the generator and the power transformer at a step-down distribution substation.

Market

Regulated: A market in which utilities are vertically integrated, incorporating most elements of electric delivery and service into a single company.

Owner

Utility: An asset owner that maintains and operates a local transmission and or distribution grid, such as an investor-owned utility, municipal utility, or electricity cooperative.

Storage technology

In this step we enter many different energy storage technologies, searching for the most appropriate for our case. For each type of technology, we complete the following steps. Table 3.1 shows the parameters requested from the tool.

Table 3.1: ACM Input data [U.S. Department of Energy, 2012]

Parameters	Definition	Value
Nameplate power output (kW)	The upper range of the operating power output	Depends on the energy storage technology
Nameplate energy storage capacity (kWh)	The upper range of the operating energy storage capacity	Depends on the energy storage technology
Response time (s)	The time needed for the deployment to start storing energy	Depends on the energy storage technology
Nameplate round-trip efficiency (%)	The ratio of the output of an electricity storage system to the input required to restore it to the initial state of charge under specified conditions.	Depends on the energy storage technology
Nameplate cycle life (cycles)	The appropriate number of cycles can be completed by the device before it can no longer meet the specifications required by the application	Depends on the energy storage technology
Expected demand growth of electric system (%)	The expected rise in production and demand for energy	2%
Reactive capabilities	The ability of energy storage capacity to provide reactive power	Depends on the energy storage technology

NERC Region in which the energy storage deployment is located	NERC is a non-government organization which has a statutory responsibility to regulate bulk power system users, owners, and operators through the adoption and enforcement of standards for fair, ethical and efficient practices. More specifically; NERC has authority to enforce reliability standards with all users, owners, and operators of the bulk power system in the United States, and makes compliance with those standards mandatory and enforceable (NERC). **It affects the Inflation rate.**	NPCC Upstate NY
Expected lifetime (years)	The time period during which the deployment remains efficient.	Depends on the energy storage technology
Annual inflation rate (%)	Parameter used to escalate energy and capacity prices as well as any prices and costs used in the analysis (**Depends on the NERC region**)	3%
Discount rate (%)	Parameter used to discount future cash flows to account for the time value of money. One way to estimate this is to determine the highest low-risk interest rate one could expect from a capital investment.	5%
Total installed cost	The installed cost includes all equipment, delivery, installation, interconnection, and step-up transformation costs. For this benchmarking work it is assumed a specific site is available, so no land costs, permitting, and project planning costs are included.	Depends on the energy storage technology
Fixed charge rate (%)	The rate used to convert capital plant installed cost into an annuity equivalent (payment) representing annual carrying charges for capital equipment. It includes consideration of interest and equity return rates, annual interest payments and return of debt principal, dividends and return of equity principal, income taxes, and property taxes.	11%
Operating and maintenance cost schedule (figure)	Schedule that includes yearly operating and maintenance costs and decommissioning and disposal costs	Depends on the energy storage technology
Initial year of analysis	The first year of operation	2018

Parameters referring to the characteristics of each energy storage deployment are noted with green colour and are available in DOE/EPRI Electricity Storage Handbook (SAND2015-1002). For example table A.3 shows the characteristics of some advanced lead-acid batteries in utility T&D. Each column refers to a battery with specific characteristics and by using this table we create excel files that contain all the data we need to insert into the tool. For example, we create table 3.2 from the 4th column of table A.3 that refers to Advanced Lead-acid Battery 1MW in Utility T&D with 10 h of energy storage at rated capacity.

Table 3.2: Data referring to Advanced Lead-acid Battery 1MW in Utility T&D

Application	utility T&D
system parameters	
total nameplate output (kW)	1.000
total nameplate energy storage capacity (kWh/day) rated discharge	10.000
total nameplate energy storage capacity (kWh/year) rated discharge	3.650.000
response time of the energy storage device (sec)	0,0001
nameplate cycle life (cycles) of the energy storage device	5.475
Average or expected year over year demand growth of the electric system (%)	2%
does it have reactive capabilities (yes, no)	yes
NERC Region	NPCC Upstate NY
storage capacity (h/day)	10
efficiency of storage device(%)	90
number of cycles/year	365
cost parameters	
total plant cost($/kW)	5.023
expected lifetime (years)	15
Average inflation rate that will be used in economic calculations (%)	3%
Discount rate that will be used in net present value analysis (%)	5%
total installed cost ($)	5.026.000
Fixed charge rate that will be used to annualize the cost (%)	11%
yearly O&M fixed and variable costs not related to energy ($/year)	11.025
enter a custom O&M cost schedule (yes, no)	yes
expected decommissioning and disposal costs ($)	1.088.000
initial year of analysis	2018
operating and maintenance costs($/kW-y)(fixed)	9,2
operating and maintenance costs($/y)(fixed)	9.200
operating and maintenance costs($/kWh)(variable)	0,0005
operating and maintenance costs($/y)(variable)	1.825
periodic major maintenance ($/kW)	1.088
period between major maintenance (y)	8
Installed cost	
$/kW installed	1.036
installed cost per kWh of usable storage	399

Once we have entered all the required inputs for a screen we click the ‚Next' button to advance to the next screen where we choose primary and secondary applications of the energy storage deployment (tables 3.3, 3.4).

Case 1 (distribution)

Table 3.3: Applications and benefits for case 1

Application	primary benefits	secondary benefits
1.renewables energy time shift (primary)	Reduced Electricity Cost (Utility/Ratepayer)	Reduced CO_2 Emissions
2.wind generation grid integration-long duration (secondary)	Reduced Electricity Cost (Utility/Ratepayer)	Reduced CO_2 Emissions
3.electric service reliability (secondary)	Reduced Outages (Utility/Ratepayer)	-

Case 2 (generation)

Table 3.4: Applications and benefits for case 2

Application	primary benefits	secondary benefits
1.renewables capacity firming (primary)	Deferred Generation Capacity Investments	Reduced Emissions
2.wind generation grid integration-short duration (secondary)	Deferred Generation Capacity Investments	Reduced Emissions
3. renewables energy time shift (secondary)	Reduced Electricity Cost (Utility/Ratepayer)	Reduced CO2 Emissions

The primary application describes how the energy storage will be used for the majority of the year and it is assumed that this application will yield the highest value to the owner in terms of benefits. Secondary applications describe the ways in which the energy storage unit will be used when not being used for the primary application. There is a subset of applications that are especially appropriate given the primary application being pursued and given the technical characteristics of the energy storage technology. Finally, if applicable we choose a second secondary application that describes the ways in which the energy storage unit will be used when not being used for the primary application.

Depending on the applications that are being pursued by the ES deployment, a subset of benefits will be achievable. The benefits included in the ESCT are categorized as primary, secondary and additional. The ESCT quantifies the primary benefits that will represent a bulk of the total value derived from that application and the secondary benefits that will typically represent a significant part of the total value derived from that application. All the applications mentioned in tables 3.3, 3.4 and their benefits are described analytically in appendix D.

The final screen of the ACM, depicted in Figure 3.7, displays the benefits that the project is expected to yield based on all the inputs entered on the previous pages. We can review an explanation of each benefit by clicking the ‚Definition' buttons.

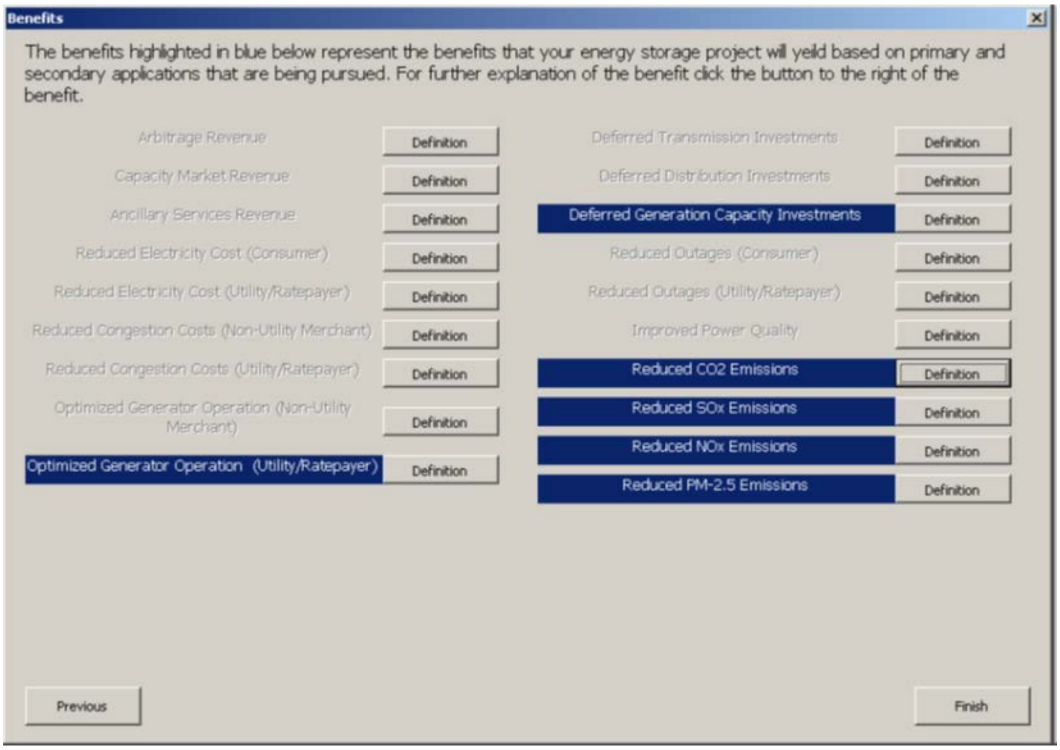


Figure 3.7: The final ACM Screen: The Benefits Summary Screen [U.S. Department of Energy, 2012]

We should carefully review the benefits the ESCT has selected before proceeding. In the next phase of the ESCT, the DIM, we enter the inputs required to quantify the benefits highlighted in blue.

The next Excel™ tab that the ESCT presents is the ‚Application Benefit Summary'. This tab displays an Application-Benefit summary map that is specific to the project under analysis. This map depicts a summary of how the applications of the project map to the benefits. This information provides deeper insight into how benefits and applications are linked. This tab also serves as a last visual check before moving into the Data Input Module phase of the ESCT. In case the highlighted applications or benefits in the chart fail to accurately represent your project, you can click the button at the top that reads ‚Return to the Assets Characterization Module (ACM). This returns you to the first screen of the ACM so you can review all inputs by revisiting each screen in sequence. The previously inserted data will still be preserved so you can review them and not waste time having to re-enter information that is correct.

Data Input Module (DIM)

The Data Input Module' tab provides you with a table to enter all the data required to calculate the benefits of the project. The input table contains the input name, the units of the input, and a definition of each input. Many inputs have a set of default values that can be leveraged in the event that user-provided estimates or actual project data are unavailable.

Our inputs

Case 1

Table 3.5: Inputs for case 1

Input Name	Units	Data	2018
Average Variable Peak Generation Costs	$/MWh	Table 8.2., Cost and Performance Characteristics of New Generating Technologies, Annual Energy Outlook 2018	3,54
CO_2 Emissions Factor for Generation on the Margin	lbs/MWh	Default	844,54
SOx Emissions Factor for Generation on the Margin	lbs/MWh	Default	0,07
NOx Emissions Factor for Generation on the Margin	lbs/MWh	Default	0,25
PM Emissions Factor for Generation on the Margin	lbs/MWh	Default	0,04
Value of CO_2	$/ton	Default	20
Value of SOx	$/ton	Default	520
Value of NOx	$/ton	Default	3.000
Value of PM	$/ton	Default	36.000
Average Variable Renewable Generation Costs	$/MW	Table 8.2., Cost and Performance Characteristics of New Generating Technologies, Annual Energy Outlook 2018	0
Total Renewable Energy Discharged for Arbitrage	MWh	Page 80, ES COMPUTATIONAL TOOL (ESCT) VERSION 1.2 – USER GUIDE	782 (h) × ES Power Capacity (MW)
Total Renewable Energy Discharged for Energy Time-Shift	MWh	Page 80,ES COMPUTATIONAL TOOL (ESCT) VERSION 1.2 – USER GUIDE	782 (h) × ES Power Capacity (MW)
Capital Cost of Conventional Electric Service Reliability Solution	$/kW	DOE/EPRI Electricity Storage Handbook in Collaboration with NRECA Appendix B: Storage System Cost Details)	156 (Combustion Turbine) 498 (Combined Cycle)
Annual Fixed Charge Rate for Electric Service Reliability Capital Investment	%	Custom	11

Case 2

Table 3.6: Inputs for case 2

Input Name	Units	Data	2018
Average Variable Peak Generation Costs	$/MWh	Table 8.2 Cost and performance characteristics of new generating technologies, Annual Energy Outlook 2018	3,54
CO_2 Emissions Factor for Generation on the Margin	lbs/MWh	Default	844,54
CO_2 Emissions Factor for Base Generation	lbs/MWh	Default	-
SOx Emissions Factor for Generation on the Margin	lbs/MWh	Default	0,07
SOx Emissions Factor for Base Generation	lbs/MWh	Default	-
NOx Emissions Factor for Generation on the Margin	lbs/MWh	Default	0,25
NOx Emissions Factor for Base Generation	lbs/MWh	Default	-
PM Emissions Factor for Generation on the Margin	lbs/MWh	Default	0,04
PM Emissions Factor for Base Generation	lbs/MWh	Default	0,20
Value of CO_2	$/ton	Default	20
Value of SOx	$/ton	Default	520
Value of NOx	$/ton	Default	3.000
Value of PM	$/ton	Default	36.000
Price of Conventional Capacity	$/MW	Page 76, ES COMPUTATIONAL TOOL (ESCT) VERSION 1.2 – USER GUIDE	133.610 (Combustion Turbine) 113.960 (Combined Cycle)
Average Variable Renewable Generation Costs	$/MW	Default	0
Total Renewable Energy Discharged for Arbitrage	MWh	Page 80, ES COMPUTATIONAL TOOL (ESCT) VERSION 1.2 – USER GUIDE	782 h × ES Power Capacity(MW)
Total Renewable Energy Discharged for Energy Time-Shift	MWh	Page 80,ES COMPUTATIONAL TOOL (ESCT) VERSION 1.2 – USER GUIDE	782 h × ES Power Capacity(MW)

Effective Load Carrying Capacity of Renewable Post-Firming	%	Default	90
Effective Load Carrying Capacity of Renewable Pre-Firming	%	Default	25
Nameplate Capacity of Renewable Resource	MW	Custom	0,0003 × ES Capacity (MWh/year)
Capacity Factor of Renewable Resource	%	Default	30

At this step we enter some default inputs such as the emission factors because we don't have specific data for these while for the rest we describe below the specific calculations.

Capital Cost of Conventional Electric Service Reliability Solution: The same with levelized cost of capacity which is the revenue per kW of discharge capacity needed to cover all life-cycle fixed and variable costs and give the target rate of return based on financing assumptions and ownership types. This metric is primarily of interest in comparing to capacity resources, such as a combustion turbine. This value was taken from table 3.7.

Average Variable Peak Generation Costs: The average variable generation costs for marginal generation units used to meet peak demand. According to table A.4, the variable O&M (2017$/MWh) is 3,54 for both combustion turbine and combined cycle.

Average variable renewable generation costs: The costs for renewable generation units used to charge ES devices and accomplish renewable energy time-shifting. According to the same table, the value is 0.

Total Renewable Energy Discharged for Arbitrage: The total amount of renewable energy discharged from the ES device and used for arbitrage purposes over a year. According to page 80, ES COMPUTATIONAL TOOL (ESCT) VERSION 1.2 – USER GUIDE, this value equals: 782 h × ES Power Capacity (MW).

The same is applicable to **Total Renewable Energy Discharged for Energy Time-Shift** which is the total amount of renewable energy discharged from the ES device for the purposes of shifting energy from a low-demand time to a high-demand time. This may allow an end user to avoid paying peak-prices for electricity or this may allow a utility to decrease their costs by offsetting the need to run less efficient, more expensive peaking units.

Price of Conventional Capacity: The annual price of conventional generation capacity. This can be estimated by assuming a base overnight cost of new generation and multiplying this cost by an annual fixed charge rate. According to page 76, ES COMPUTATIONAL TOOL (ESCT) VERSION 1.2 – USER GUIDE:

Price of Conventional Capacity = ((Overnight Capital Cost ($/kW) *11% fixed charge rate for utilities) + Fixed O&M Cost ($/kW))*1000.

Using the values of table A.4, we have:

<u>Combustion turbine</u>: Price of Conventional Capacity = ((1.054*0,11)+17,67)*1.000 = 133.610 $/MW

<u>Combined cycle</u>: Price of Conventional Capacity = ((935*0,11)+11,11)*1.000 = 133.610 $/MW

Table 3.7: Comparable Costs for a Combustion Turbine and Combined-Cycle Gas Turbine [Sandia National Laboratories, 2015]

Technology Option	Capacity (MW)	Heat Rate	Capacity Factor	Installed Cost ($/kW)	Present Value Life-cycle Cost ($/kW)	Levelized Cost of Capacity ($/kW-yr)	LCOE ($/MWh)
Combustion Turbine	100	11,000	5%	720	2225	156 (Total) 124 (Fixed Only)	357
Combined-Cycle Gas Turbine	500	6900	80%	1100	5152	498 (Total) 173 (Fixed Only)	71

Annual fixed charge rate for electric service reliability capital investment: The rate used to convert capital distribution installed cost into an annuity equivalent (payment) representing annual carrying charges for capital equipment. It includes consideration of interest and equity return rates, annual interest payments and return of debt principal, dividends and return of debt principal, dividends and return of equity principal, income taxes, and property taxes and we enter a value of 11% for this.

Nameplate Capacity of Renewable Resource: The nameplate capacity of the renewable resource(s) that were firmed with ES. From table 1.1 we have that 193,75 MW of the wind farms in Crete produced 512.832 MWh during 2017. So we need to find the power capacity (MW) of these wind farms that could produce the energy to be stored at the ES deployment we select.

Nameplate Capacity of Renewable Resource = (193,75 (MW)/512.832 (MWh)) *ES capacity (MWh) = 0,0003*ES capacity (MWh)

Computational Module (CM)

The CM Main page allows us to run the cost-benefit analysis with the inputs entered in the DIM, collectively referred to as the Reference Case, or it allows an analysis run with a variety of sensitivity case inputs, collectively referred to as the Sensitivity Case. When the analysis is complete, results can be reviewed by clicking the blue button labelled ‚View Reference Case Results.

Reference Case Results

Each results tab that corresponds to the Reference Case Results is explained below.

Result Tables: This page contains 2 tables that summarize the value of all the benefits and costs over the entire analysis period. The top table contains the annual benefit and cost values. The bottom table refers to cumulative benefit and cost values. Benefits are organized by benefit sub-category (e.g. Market Revenue, Improved Asset Utilization, etc.). All values are in present value terms.

Result Charts: This tab contains a pie chart and the underlying table that summarize the total cumulative benefits over the entire analysis period. All values are in present value terms. This page also contains a table and 2 graphs that visualize the project's benefits and costs in present value terms over the entire project lifetime. The tables contain the annual and cumulative costs and benefits in present value terms as well as the annual and cumulative net benefit of the project in present value terms. The top graph presents the annual values while the bottom graph shows the cumulative values.

Additional Benefits: This page contains a table that lists all of the additional benefits that might be achieved by the deployment along with an explanation of the rationale that could lead to that benefit. If after reading the explanation the user wishes to calculate the value of the benefit, they can click a link that will open an additional worksheet that will collect the additional inputs required to monetize these benefits. The ESCT does not quantify supplementary benefits in the main part of the tool. Instead, these benefits are initially presented qualitatively. The user then has the option to work through various worksheets in the Computational Module in order to quantify these types of benefits. These are not quantified by default for one or more of the following reasons:

1) The equations used for the calculation of these benefits would require inputs that are very difficult to measure.

2) These benefits may accrue to stakeholders that are not the owners of the ES assets.

3) The monetary value related with these benefits may be very small when only considering a single deployment as opposed to considering a system-wide deployment of ES.

4) The benefits only arise under specific circumstances.

5) The calculations use estimated inputs as opposed to measured data to monetize the benefits.

Any additional benefits an ES deployment may achieve are captured qualitatively in the ESCT. When reviewing the results of an analysis, a table will appear, which lists all of the additional benefits that might be achieved by the deployment along with a clarification of the reason that could lead to that benefit. If the user wishes to calculate the value of the benefit, they can click a link which will open a worksheet that will collect the additional inputs required to monetize these benefits.

3.4. ES Select methodology

Finding the right energy storage application for an electrical grid is a complex decision, due to the wide variety of technology choices and diverse applications along the electricity value chain. In this emerging sector, tools are required for evaluation and techno-economic analysis of grid-scale storage projects. In the U.S., an analytical tool called ES-Select™ was created by DNV-GL (formerly KEMA) in collaboration with Sandia National Labs, and licensed for public use. However, U.S. electric utility and market data are not directly transferable to Canada's electricity markets. Therefore, in response to industry need, NRC worked with the development team at DNV-GL to adapt ES-Select™ for Canadian markets and create a version of the tool that could be licensed through NRC for public use.

Currently, in beta testing, the ES-Select™ Canada tool allows users to compare and rank feasible technologies in selected Canadian jurisdictions for a range of grid services, at any given location on the electricity grid. The tool will allow users to screen technologies by calculating financial outputs that include cash flow, cumulative costs and benefits, and net present values. It can then be used to generate a variety of plots and charts for comparing technology options and final rankings based on total feasibility scores. Drawing on a Canadian database, the tool can perform specific evaluations for grid locations in Alberta, BC and Ontario, and provide average values for any other location in Canada.

At the center of ES-Select™ user interface is the home page where a user enters one or more grid applications and receives the list of prioritized feasible energy storage options to serve those applications. Figure 3.8 shows a diagram of the ES-Select™ design with the home page as the central hub of all its capabilities and functionalities.

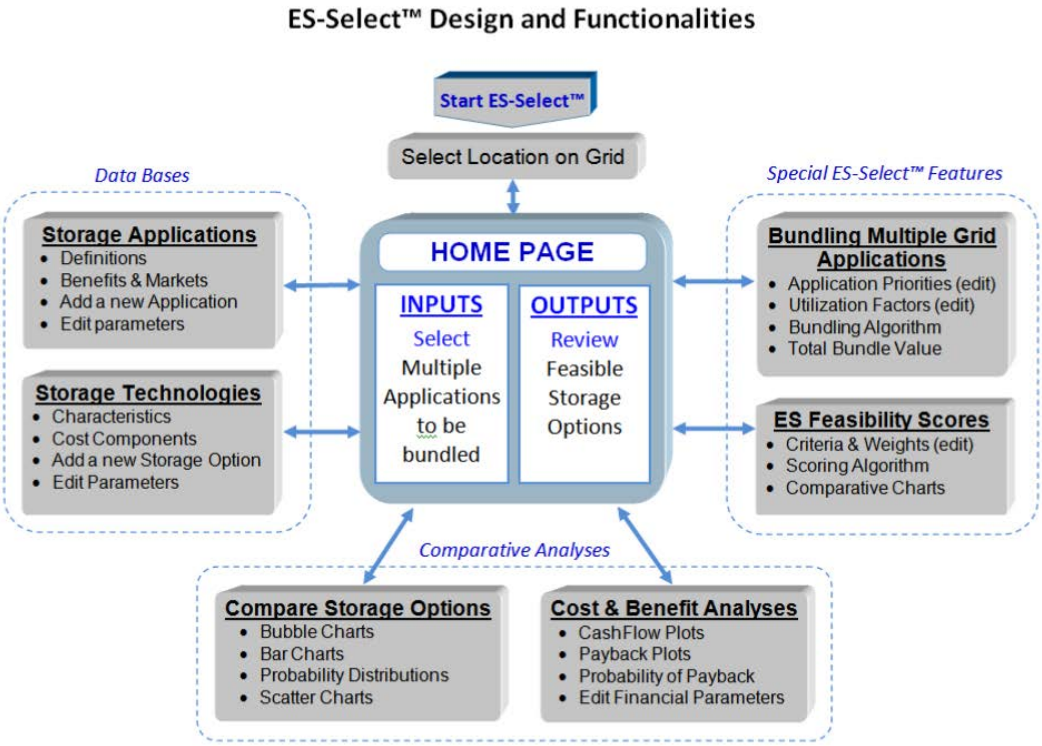


Figure 3.8: Overview of ES-Select™ Design and Functionalities [Sandia National Laboratories, 2012]

The only question the user will be asked before accessing the home page is the location where energy storage is (to be) connected to an electric grid. On the home page, the user can access the following features and capabilities of ES-Select™:

1. Energy storage technologies database (physical, operational, and economic parameters)

2. Storage applications database (benefits, market potentials, and storage requirements)

3. Multiple applications bundling (priorities, operational compatibilities, business compatibilities)

4. Feasibility score of energy storage options (criteria and their relative weights)

5. Cost and benefit analysis (cash flow, payback range, and probability of having a payback)

6. Comparison of energy storage options (economics, cycle life, efficiency, markets)

Location of Energy Storage on an Electric Grid

The first question that is asked of the ES-Select™ user before starting with the home page is the "location" of the storage application on the electric grid (Figure A.35). Knowing the asset location (or ownership) is important, because it impacts 3 critical factors:

• Installation cost
• Available grid applications
• Available energy storage options

Figure A.36 shows the limitations that any of the 5 grid locations would put on the available grid applications for the user to work with. Figure A.37 shows the limitations that any of the 5 grid locations would put on the available energy storage technologies or types for the user to choose from.

A user can access the above 2 restriction tables by clicking on the “location restrictions” button at the bottom of the location page.

ES-Select™ Home Page

The home page is the main interface for the ES-Select™ user. As shown in Figure 3.9, this page is divided into 2 halves. The left part is INPUT, where the user enters his or her one or more desired applications. The right part is OUTPUT, where the user can see all storage options listed in the order of their feasibility to serve the desired application(s). A horizontal bar graph on each side helps the user visualize, sort, and compare different options to support a better decision.

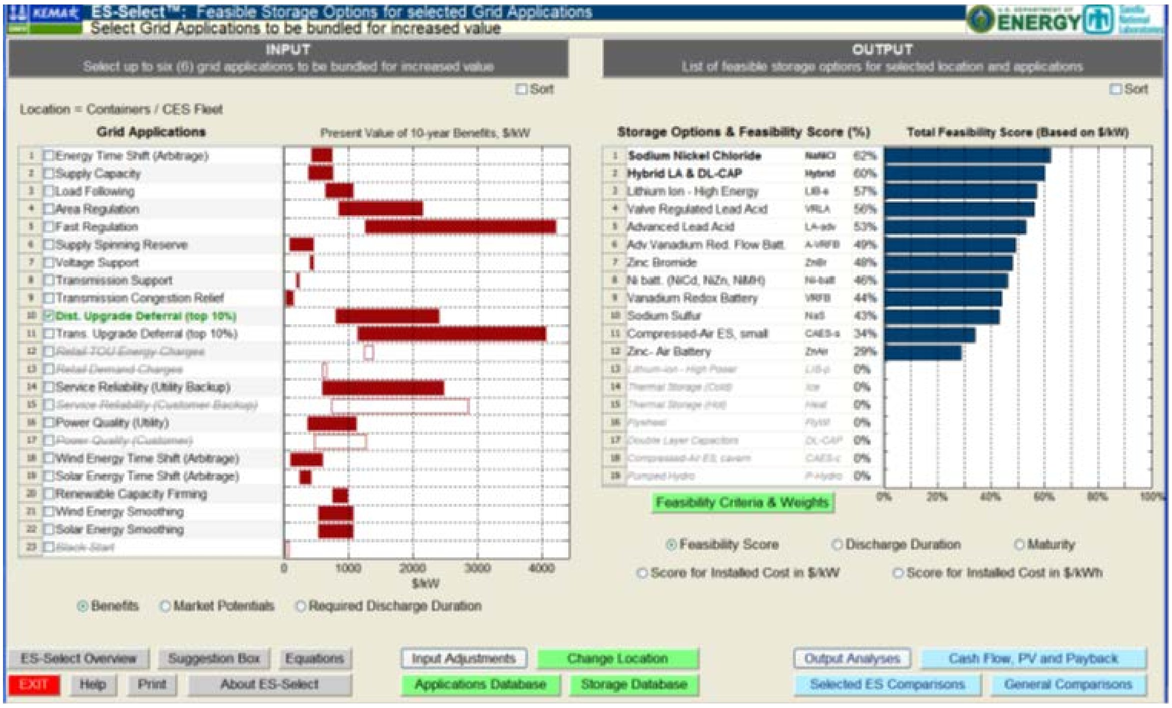


Figure 3.9: ES-Select™ Home Page for reviewing storage options for selected grid applications [Sandia National Laboratories, 2012]

On the INPUT side, 3 radio buttons below the left part allow the user to review the benefits, market potential, and required discharge duration for all applications before choosing one. The gray-colored applications are not available or recommended for the selected location on the grid. A checkbox on the top allows the user to sort the applications based on their selected characteristic. In case more than one application is used, the default priority of the application is the order in which they have been selected by the user. Energy storage technologies characteristics, which are part of the ES-Select technology database, are stated in Appendix B (ES-Select Database Inputs). The list of parameters and equations used from the model user manual can be found in Appendix C (ES-Select Parameters and Equations).

On the OUTPUT side, all energy storage technologies (options) considered in ES-Select are listed. The gray-colored ones with a feasibility score of zero mean that those storage options are not available due to failing to meet one or more of the feasibility criteria. Technologies that at least partially meet all of the feasibility criteria are listed in decreasing order of their total feasibility score. In order to help the user have a better insight into the listed storage options, 5 radio buttons below the right display area let the user review total feasibility scores, cost scores (based on $/kW or $/kWh), maturity, or discharge duration. A checkbox on the top allows the user to sort the storage options based on their selected characteristic (total feasibility score is always sorted). Selecting the green button under the energy storage list takes the user to the feasibility page, where more details on the feasibility scoring algorithm, criteria, and their relative weights are provided. The user can adjust the weights to obtain a scoring scheme that better matches the intended application(s).

The general methodology contains the steps below:

Step 1: Select location

Step 2: Select the applications (INPUT side)

Step 3: Set priority of Bundled Applications, change the priority of applications and select the one that gives the highest Total Bundle Value. (INPUT side)

Step 4: Extract charts that refer to ES options comparison, cash flow and payback analyses (OUTPUT side)

<u>Input side</u>

Definitions of Energy Storage Applications (Step 2)

Here are described all the applications selected. The definitions of different grid application of energy storage were originally adopted from the Sandia 2010-085 report “Energy Storage for the Electricity Grid: Benefits and Markets” published in Feb 2010. All storage applications available in the ES-Select database with their definitions according to the Electric Power and Research Institute and Sandia National Laboratories can be found in Appendix A.

Bundling multiple grid applications for increased value (Step 3)

An effective way to increase the value of an energy storage asset is to use it in multiple applications such that its capacity, power, or time could be “shared” among them in a coordinated, overlapping manner. In case the shared capacities are not overlapping, such as dedicating certain percentages of the capacity to different functions (for example, 20% for back up and 80% for peak shaving), the total value is not necessarily increased and almost the same result can be obtained by buying 2 smaller storage units. Overlapping capacity, power, or time, is what can help stack up different benefits, but proper controls are required to assure the priority of access.

The type and assigned priority of each application in a bundle can limit the access of the lower priority applications to the shared storage asset and, therefore, limit their contribution to the total bundle value. The total value is the weighted sum of the individual application values where the weight or utilization factor (UF) of each application corresponds to the availability of the storage to serve that application. For example, the total value for the 3 sample applications shown in Figure 3.10 may be calculated as:

Total Bundling Value = 100% V1 + 50% V2 + 75% V3

Where V1, V2 and V3 are the application values and the percentage factors are UFs. Note that the utilization factor of a lower priority application (like the 3rd one in this figure) could be larger than the utilization factor of a higher priority application (2nd application), if it has better compatibility with other applications in the bundle. In order to analyse business cases, utilization factors need to be calculated and averaged over a long period, such as a year.

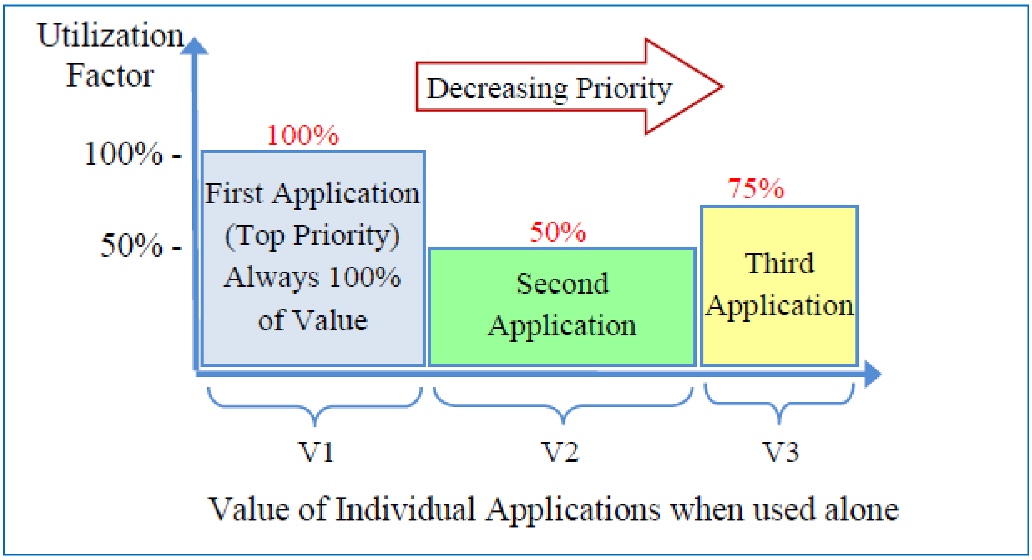


Figure 3.10: Individual Application Values and their Contribution to the total Bundle Value [Sandia National Laboratories, 2012]

When selecting more than one grid application, a green button appears below the applications list that would take the user to the bundling page where the user may change the default priority of selected applications in an effort to increase the total bundle value. When the user moves each application up or down the list of applications, the range of each application value (individual and in the bundle) can be reviewed in the bar chart at the middle. The distribution chart on the right side shows the range of the total bundle value. Selecting the radio button for Utilization Factors above the right side chart displays a table of the estimated range of utilization factors for each application. The user can adjust the utilization factors on this table.

Utilization Factor: It expresses how effectively a shared energy storage device can be “utilized” for a specific application. This is a multiplier, less than or equal to 1.00 (100%), that is multiplied by the nominal value of a storage application when it is offered or bundled with other applications that share a common storage asset. For example, in case a storage device is used to provide a diurnal energy shift at its full power, it just would not be available to be utilized for area regulation during that time. For this reason, doing area regulation during a limited number of hours each day will decrease the realizable value for area regulation. Utilization factor is influenced by 4 other factors:

1. Application priority
2. Application type (use pattern)
3. Peak time alignment
4. Asset availability (from prior applications)

Output side

Scoring feasibility of energy storage options for grid applications (Step 4)

At the homepage, selecting the green button, Feasibility Scores and Weights, below this list displays the feasibility page (Figure 3.11), where more details are available about how the feasibility of different storage options are calculated.

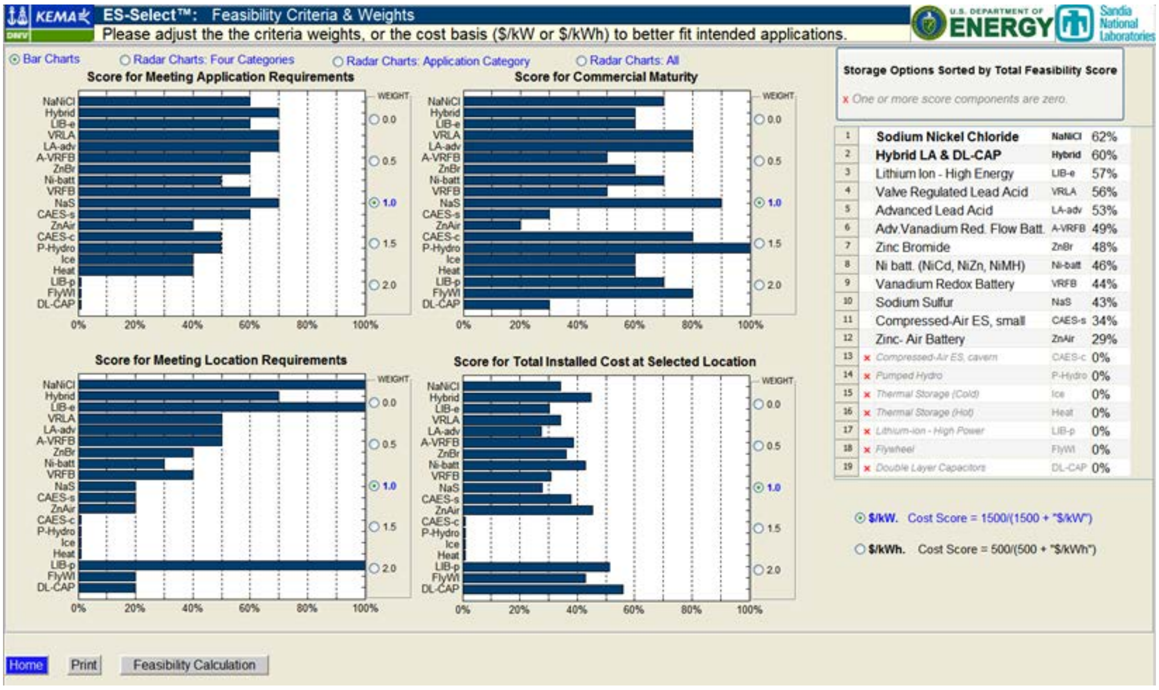


Figure 3.11: Feasibility Page listing storage option with their individual Feasibility Scores [Sandia National Laboratories, 2012]

In order to select an energy storage option that would be appropriate for the intended grid application(s), ES-Select™ attempts to score the feasibility of each storage option based on the following 4 criteria:

- **Maturity** or readiness for commercial deployment
- Suitability for the selected grid **location** (considers availability, mobility, size, weight, scalability, etc.)
- Satisfying application **requirements** (considers discharge duration, cycle life, efficiency, etc.)
- Installed **cost** in either $/kW or $/kWh basis (user's choice)

The 4 horizontal bar charts on the feasibility score page compare the feasibilities of different storage options for each of the above 4 criteria. To the right side of each bar chart is a 5-level weighting scale where, by default, all 4 criteria have an equal weight of 1.0. The weights may be modified to obtain a more balanced feasibility score for the intended application(s). The appropriate energy storage option is the one with the highest feasibility score.

ES-Select™ displays what appears to be feasible storage options for user's selected applications at the right side or OUTPUT side of the home page. At this step we find the beneficial storage options by selecting "Cash Flow, PV and Payback Analyses" -> "horizontal bar charts**".**

Comparison of Energy Storage Options

Once a list of feasible energy storage options is suggested for the selected application(s), a user may compare the storage options based on a variety of factors, such as size, cost, discharge duration, cycle life, payback time, etc. There are 2 buttons at the bottom of the home page for this purpose:

• Selected ES Comparisons
• General Comparisons

Figure 3.12 shows the Selected ES Comparison page. The drop box list in the top left corner shows the most common type of X-Y parameter pairs that a user may select to see the storage comparisons based on those pairs of parameters. A user might also include or exclude different storage options from the chart by using the check list of the storage options at the left side. The gray-colored options are those that are not acceptable for one or more criteria, such as using CAES at a residential site. Above the chart area, there are some options for enhancing the chart. The storage name labels can be moved to desirable locations by click and dragging them.

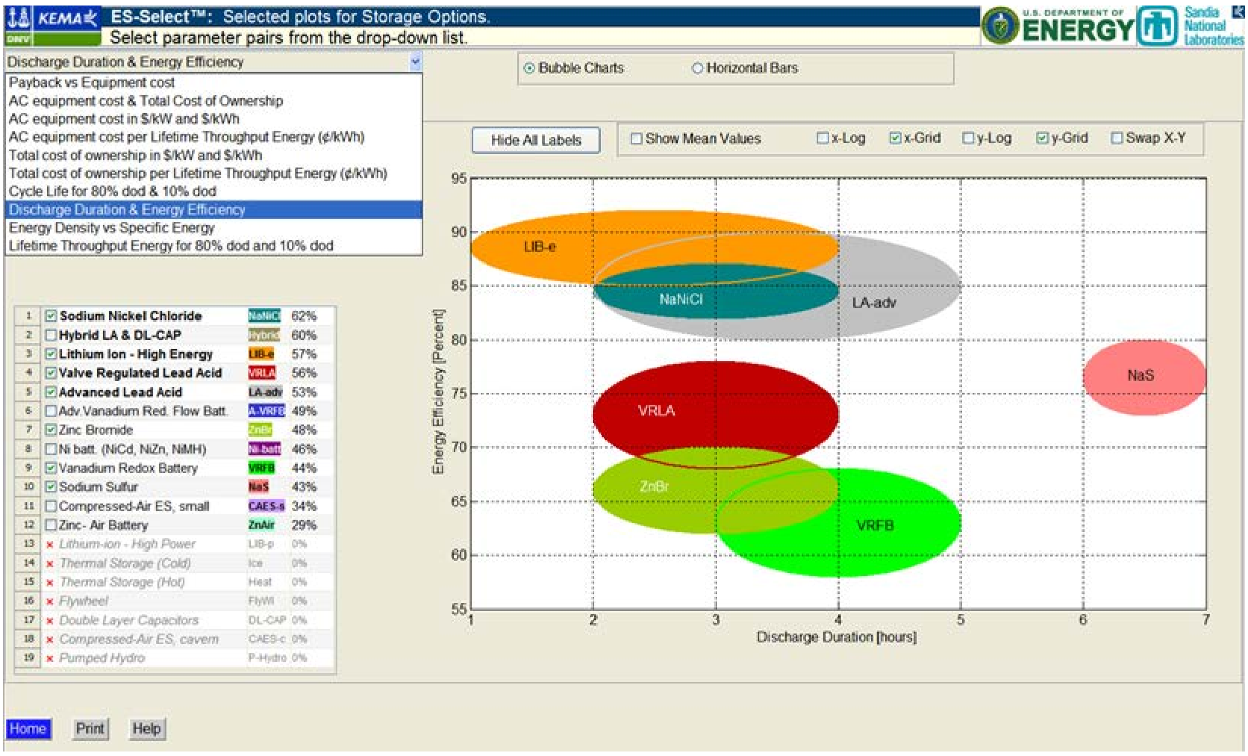


Figure 3.12: Page for displaying select ES Comparisons [Sandia National Laboratories, 2012]

There are 2 chart types available for better comparison of the storage options. The radio buttons near the top of the page will help a user choose one of these chart types. Figure 3.12 shows a sample of bubble chart and Figure 3.13 shows a sample of horizontal bars chart.

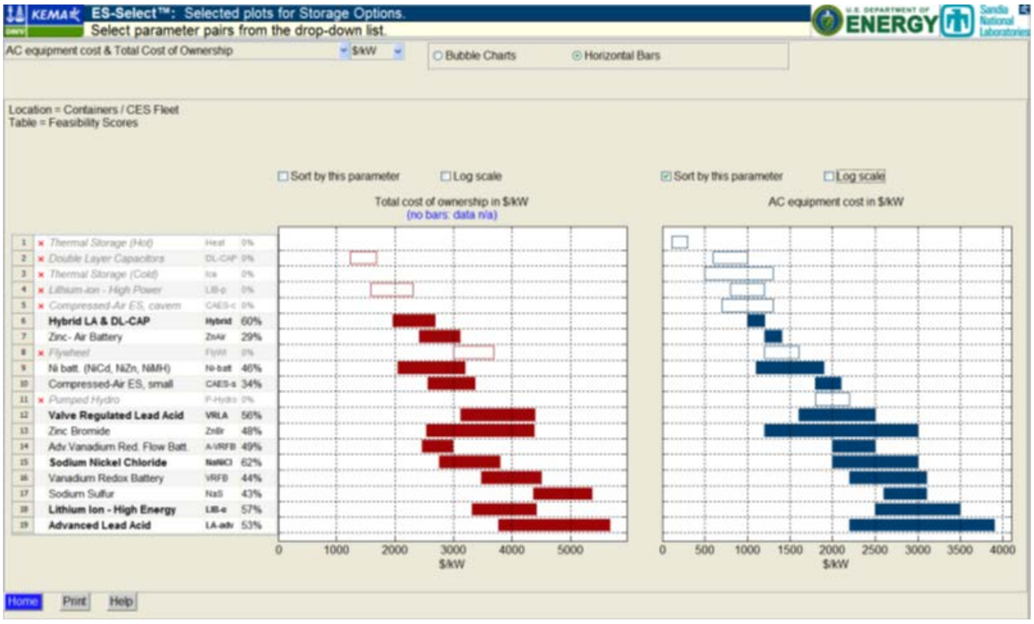


Figure 3.13: Sample of Horizontal Bars chart for comparing energy storage options [Sandia National Laboratories, 2012]

The page referred as General Comparison is very similar to the Selected ES Comparison page. The only difference is that on this page more parameters are available for comparative plotting and an experienced user can choose to plot any parameter versus any other one from the 2 dropdown lists of parameters.

Cash Flow and Payback Analyses

The current version of ES-Select™ provides some unique cash flow and payback analyses that take into account the uncertainty in both the cost of ownership of a storage device, as well as its benefits over the years. Selecting the Costs / Benefits button at the bottom of the home page opens the page for cash flow and payback analysis as shown in Figure 3.14 below.

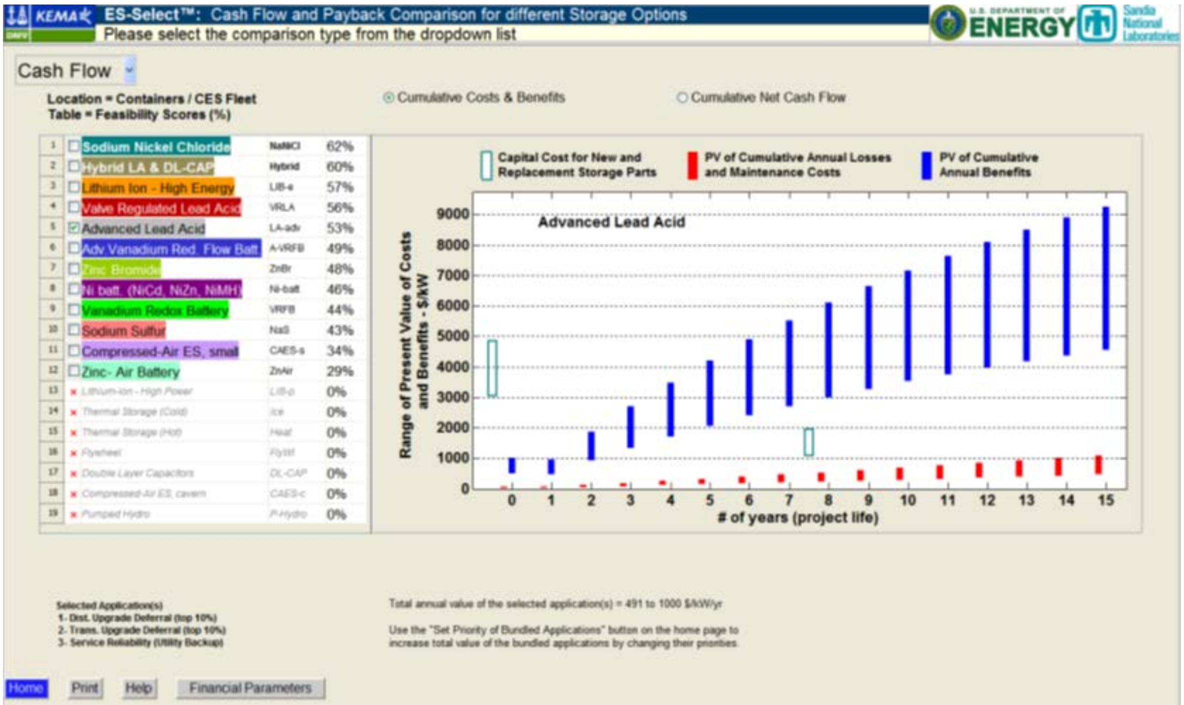


Figure 3.14: Page for Cash Flow and Payback Analyses [Sandia National Laboratories, 2012]

In addition, there are other options like the charts referring to: Range of Present Value of the Net Cash Flow, Comparison of the Ranges of Payback years in bars, Comparison of the Statistical Distribution of Payback Years, Probability of having a payback within the project lifetime.

Last but not least, the project lifetime and the financial parameters used in calculating cash flows and paybacks may be viewed by selecting the Financial Parameters button on the bottom of the page. These parameters are adjustable to better fit a particular project (see Figure 3.15).

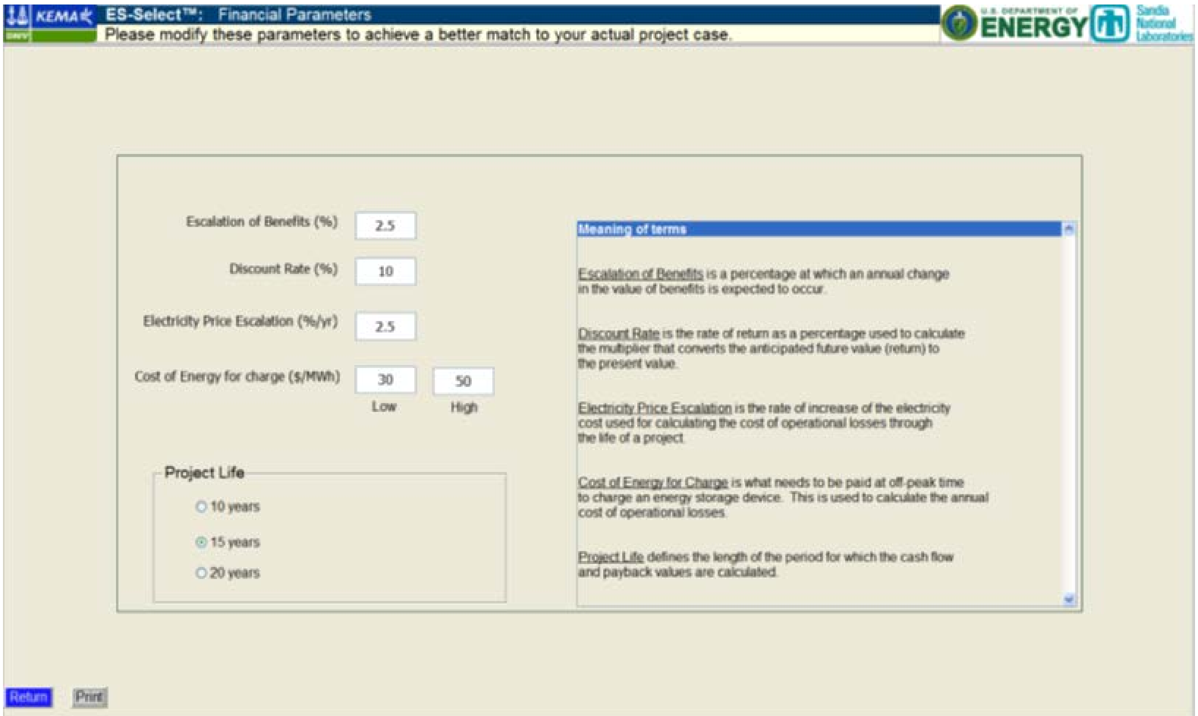


Figure 3.15: ES-Select™ Financial Parameters [Sandia National Laboratories, 2012]

We use the same economic parameters as for the ESCT.
Escalation of benefits: 3%
Discount rate: 5%
Electricity price escalation: 3%/year
Cost of energy for charge: We assume that the energy stored is produced from wind farms so the cost of this production is about 99$/MWh according to table 1.1. Therefore, we assume the following values: Low: 90$/MWh, High: 100$/MWh.

We choose to run the ES Select for 4 different locations:
Case 1: Bulk storage / Up to 50 MW
Case 2: Transmission & distribution / Up to 10 MW (substation)
Case 3: Distribution / Up to 2 MW (container/CES fleet)
Case 4: Commercial-industrial / Up to 1 MW

In each case, we choose the same 2 "sets" of applications we chose for our calculations with ESCT for comparison reasons. Those are:

	Application
Set 1	1. electric service reliability
	2. wind generation grid integration-long duration
	3. renewables energy time shift
Set 2	1. renewables capacity firming
	2. wind generation grid integration-short duration
	3. renewables energy time shift

4. Results

4.1. Possible additional energy - results

By the following methodology, described in chapter 3.1., we calculate the possible additional energy. Diagram 4.1. refers to the wind farm ROKAS and describes the relationship between real produced energy vs wind speed for set point =1 while the results are shown in table 4.1.

Diagram 4.1. Real produced energy vs wind speed for set-point = 1 for the wind farm ROKAS (equation 1)

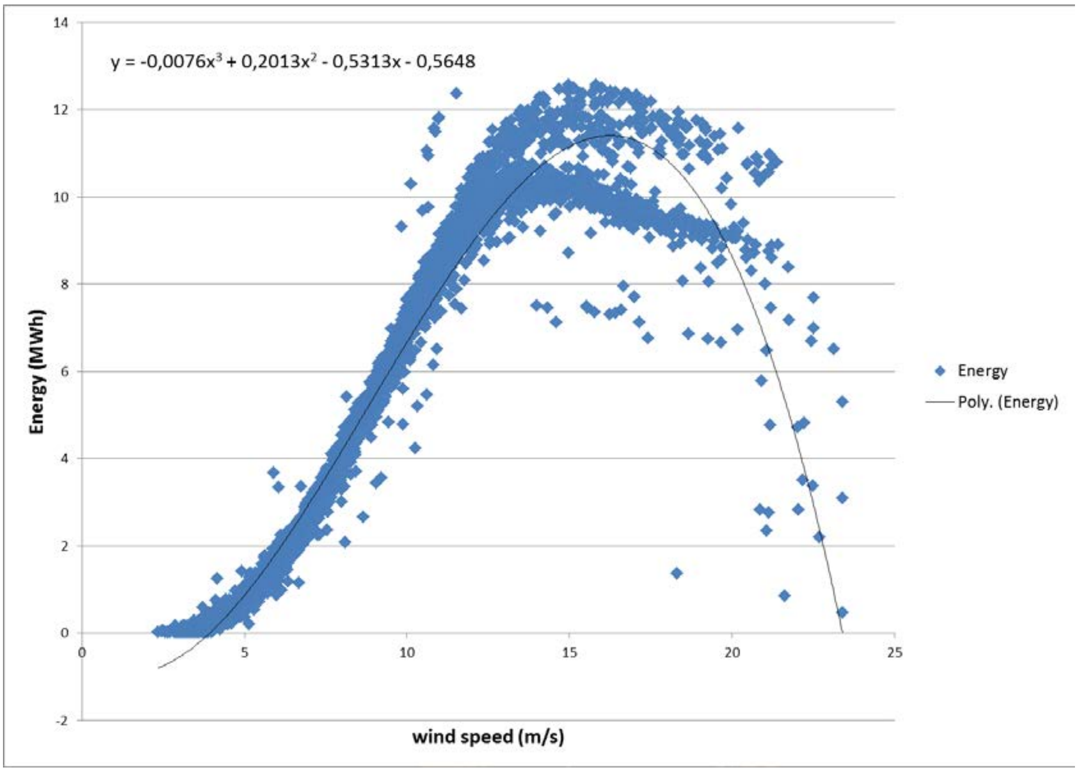


Table 4.1: Possible additional energy calculation for the wind farm Rokas during 2017

wind farm	ROKAS
real produced energy (MWh)	37.928,58
equation 1	$y= -0,0076x^3+0,2013x^2-0,5313x-0,5648$
max theoretical energy (MWh)	40.401,28
possible additional energy (MWh)	2.472,70
Curtailment ratio (%)	6,52

Equation 1 is a 3rd degree equation as that describing the relationship between power (Pmech) and wind speed (V).

$P_{mech} = c_p*(1/2)*\rho*A*V^3$
$P_{gen}= n*c_p = c_p*n_{mech\text{-}elec}$
$E_{el} = P_{gen}*\Delta t$

We follow the same process for the rest wind farms in order to calculate the total possible additional energy (energy curtailment) (table 4.2).

Table 4.2: Wind farms operating on Crete during 2017 and possible additional energy calculation [HEDNO, 2017]

wind farm	capacity (MW)	real produced energy (MWh)	possible additional energy (MWh)	Curtailment ratio (%)
ROKAS	12,9	37.928,58	2.472,70	6,52
AIOLOS	10,0	22.772,52	651,75	2,86
AHLADIA	10,0	19.659,66	2.179,59	11,09
KRYA	10,0	27.033,36	1.403,52	5,19
ANEMOESA	5,0	10.864,00	1.229,88	11,32
PLASTIKA	11,9	40.194,25	2.326,07	5,79
PLATYBOLA	3,0	5.103,67	317,13	6,21
ENERCON	2,5	5.575,19	408,27	7,32
XONOS-IWECO	4,5	14.665,03	1.377,53	9,39
YDROAIOLIKI	9,4	33.523,90	1.951,46	5,82
XIROLIMNI-DEI	3,0	10.149,79	712,88	7,02
ENVITEC-BATALI	5,4	15.985,10	897,16	5,61
DIETHNIS AIOLIKI	7,2	11.470,20	3.233,06	28,19
AHLADIA EPEKTASI	1,2	2.374,15	1.038,54	43,74
KRYA EPEKTASI	1,2	3.350,46	1.489,23	44,45
AKOUMIA	7,2	15.298,90	5.018,88	32,81
ROKAS-MODI 2	4,8	12.202,72	3.571,74	29,27
ROKAS-KALOGEROS	3,6	4.556,25	717,88	15,76
ΟΑΣ ΣΗΤΕΙΑΣ	1,2	3.902,98	421,38	10,80
ANEMOS-ALKIONIS	6,3	18.417,38	4.053,43	22,01
ΜΟΥΣΟΥΡΩΝ	2,6	7.992,55	655,18	8,20
ΚΟΥΛΟΥΚΟΝΑΣ	4,8	7.706,64	2.097,70	27,22
ΑΝΕΜ/ΕΣΣΑ ΕΠΕΚ	1,2	1.501,65	574,10	38,23
ENVITEC ΒΑΡΔΙΑ	5,4	12.051,31	613,13	5,09
KOPRINO	7,2	20.072,78	1.209,48	6,03
OAS 500 kW	0,5	1.951,49	223,00	11,43
ΜΟΙΡΩΝ Α/Π	5,3	8.387,69	2.482,67	29,60
ΑΣΙΔΕΡΩΤΑΣ	2,4	5.353,88	1.988,45	37,14
ΤΕΡΝΑ ΑΓ.ΒΑΡΒΑΡΑ	14,5	23.092,05	6.682,71	28,94
EPANOSIFI	6,0	16.281,71	1.141,42	7,01
IWECO ΜΕΓ. ΒΡΥΣΗ	5,0	7.945,60	2.281,56	28,71
ΞΗΡΟΛ 1&2	10,2	34.509,29	2.994,77	8,68
ΒΟΣΚΕΡΟ ENEL	6,0	9.514,85	2.881,68	30,29
ΕΝΤΕΚΑ	2,7	6.025,66	74,89	1,24
MEAN VALUE	5,7	14.041,62	1.805,08	17,03
TOTAL	**193,75**	**477.415,23**	**61.372,82**	

The possible additional energy was estimated about 61.372 MWh per year so based on this we need to find an energy storage technology that could store this amount of energy. As mentioned in previous pages we use Energy Storage Computational Tool and ES Select for our calculations.

4.2. ESCT results

We run the ESCT with many different technologies in order to find which fits best for our case taking into account the energy that can be stored annually and the cost of the deployment. We run the programme for 2 different locations (case1, case 2) assuming for each case that 2 different conventional energy units are being replaced by the ES deployment: combined cycle and combustion turbine.

4.2.1. Case 1 (distribution)

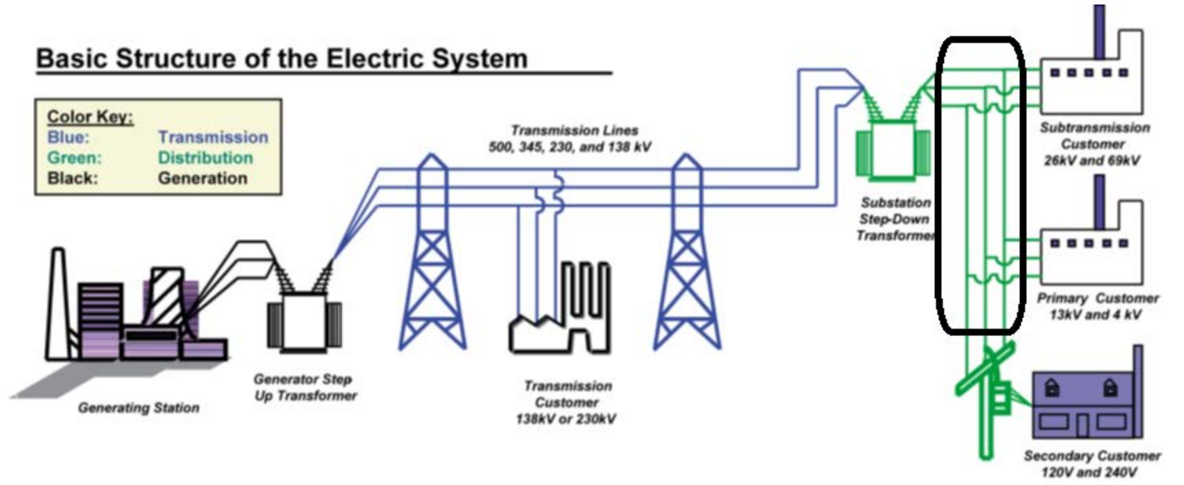


Figure 4.1: Location of ES deployment in case 1 [http://www.ee.teihal.gr]

Table 4.3: ESCT results for different energy storage technologies in case the ES deployment is located between Substation Step-Down Transformer and customer

Distribution				
adv lead acid (1.000 kW)				
energy capacity (kWh)	3.650.000			
conventional unit for replacement	**combined cycle**		**combustion turbine**	
	costs	benefits	costs	benefits
capital expenditure	5.934.500		5.934.500	
operating costs	1.253.000		1.253.000	
Reduced Outages (Utility/Ratepayer)		500		0
Total	7.187.500	500	7.187.500	0
benefit/cost ratio	7,00E-05		0,00E+00	
adv lead acid (12.000 kW)				
energy capacity (kWh)	17.520.000			
conventional unit for replacement	**combined cycle**		**combustion turbine**	
	costs	benefits	costs	benefits
capital expenditure	61.763.100		61.763.100	
operating costs	12.748.500		12.748.500	
Reduced Electricity Cost (Utility/Ratepayer)		2.500		2.500

Reduced Outages (Utility/Ratepayer)		8.500		3.000
Reduced CO_2 Emissions		5.100		5.100
Total	74.511.600	16.100	74.511.600	10.600
benefit/cost ratio	2,20E-04		1,40E-04	
adv lead acid (20.000 kW)				
energy capacity (kWh)	43.800.000			
conventional unit for replacement	**combined cycle**		**combustion turbine**	
	costs	benefits	costs	benefits
capital expenditure	138.809.900		138.809.900	
operating costs	29.768.500		29.768.500	
Reduced Electricity Cost (Utility/Ratepayer)		4.000		4.000
Reduced Outages (Utility/Ratepayer)		14.100		4.500
Reduced CO_2 Emissions		8.700		8.700
Total	168.578.400	26.800	168.578.400	17.200
benefit/cost ratio	1,60E-04		1,00E-04	
NaS (1.000 kW)				
energy capacity (kWh)	2.628.000			
conventional unit for replacement	**combined cycle**		**combustion turbine**	
	costs	benefits	costs	benefits
capital expenditure	6.875.000		6.875.000	
operating costs	169.500		169.500	
Reduced Outages (Utility/Ratepayer)		500		
Reduced Electricity Cost (Utility/Ratepayer)				2.100
Total	7.044.500	500	7.044.500	2.100
benefit/cost ratio	7,10E-05		3,00E-04	
NaS (12.000 kW)				
energy capacity (kWh)	31.536.000			
conventional unit for replacement	**combined cycle**		**combustion turbine**	
	costs	benefits	costs	benefits
capital expenditure	53.627.200		6.875.000	
operating costs	1.053.000		169.500	
Reduced Electricity Cost (Utility/Ratepayer)		2.500		2.100
Reduced Outages (Utility/Ratepayer)		8.500		
Reduced CO_2 Emissions		5.100		
Total	54.680.200	16.100	7.044.500	2.100
benefit/cost ratio	2,90E-04		3,00E-04	
VRB (10.000 kW)				
energy capacity (kWh)	18.250.000			
conventional unit for replacement	**combined cycle**		**combustion turbine**	
	costs	benefits	costs	benefits
capital expenditure	44.361.100		44.361.100	
operating costs	8.616.500		8.616.500	
Reduced Electricity Cost (Utility/Ratepayer)		1.700		1.700
Reduced Outages (Utility/Ratepayer)		7.000		2.200
Reduced CO_2 Emissions		4.500		4.500

Total	52.977.600	13.200	52.977.600	8.400
benefit/cost ratio	2,50E-04		1,60E-04	
FeCr (1.000 kW)				
energy capacity (kWh)	1.460.000			
conventional unit for replacement	**combined cycle**		**combustion turbine**	
	costs	benefits	costs	benefits
capital expenditure	1.791.300		1.791.300	
operating costs	362.000		362.000	
Reduced Outages (Utility/Ratepayer)		500		
Total	2.153.300	500	2.153.300	0
benefit/cost ratio	2,30E-04		0,00E+00	
FeCr (10.000 kW)				
energy capacity (kWh)	18.250.000			
conventional unit for replacement	**combined cycle**		**combustion turbine**	
	costs	benefits	costs	benefits
capital expenditure	18.856.800		18.856.800	
operating costs	3.096.500		3.096.500	
Reduced Electricity Cost (Utility/Ratepayer)		1.700		1.700
Reduced Outages (Utility/Ratepayer)		7.000		2.200
Reduced CO_2 Emissions		4.500		4.500
Total	21.953.300	13.200	21.953.300	8.400
benefit/cost ratio	6,00E-04		3,80E-04	
$ZnBr_2$ (1.000 kW)				
energy capacity (kWh)	1.825.000			
conventional unit for replacement	**combined cycle**		**combustion turbine**	
	costs	benefits	costs	benefits
capital expenditure	2.426.400		2.426.400	
operating costs	97.500		97.500	
Reduced Outages (Utility/Ratepayer)		500		
Reduced Electricity Cost (Utility/Ratepayer)				1.900
Total	2.523.900	500	2.523.900	1.900
benefit/cost ratio	2,00E-04		7,50E-04	
$ZnBr_2$ (10.000 kW)				
energy capacity (kWh)	18.250.000			
conventional unit for replacement	**combined cycle**		**combustion turbine**	
	costs	benefits	costs	benefits
capital expenditure	21.312.600		21.312.600	
operating costs	1.074.000		1.074.000	
Reduced Electricity Cost (Utility/Ratepayer)		1.700		21.700
Reduced Outages (Utility/Ratepayer)		7.000		2.200
Reduced CO_2 Emissions		4.500		4.500
Total	22.386.600	13.200	22.386.600	28.400
benefit/cost ratio	5,90E-04		1,30E-03	
Li-ion (1.000 kW)				
energy capacity (kWh)	492.750			

conventional unit for replacement	**combined cycle**		**combustion turbine**	
	costs	benefits	costs	benefits
capital expenditure	2.532.600		2.532.600	
operating costs	1.418.000		1.418.000	
Reduced Outages (Utility/Ratepayer)		500		
Total	3.950.600	500	3.950.600	0
benefit/cost ratio	1,30E-04		0,00E+00	
Li-ion (3.000 kW)				
energy capacity (kWh)	1.095.000			
conventional unit for replacement	**combined cycle**		**combustion turbine**	
	costs	benefits	costs	benefits
capital expenditure	4.916.600		4.916.600	
operating costs	385.500		385.500	
Reduced Electricity Cost (Utility/Ratepayer)				200
Reduced Outages (Utility/Ratepayer)		2.000		
Reduced CO_2 Emissions		1.500		1.500
Total	5.302.100	3.500	5.302.100	1.700
benefit/cost ratio	6,60E-04		3,20E-04	
Li-ion (10.000 kW)				
energy capacity (kWh)	10.950.000			
conventional unit for replacement	**combined cycle**		**combustion turbine**	
	costs	benefits	costs	benefits
capital expenditure	62.155.200		62.155.200	
operating costs	83.670.500		83.670.500	
Reduced Electricity Cost (Utility/Ratepayer)		1.700		1.700
Reduced Outages (Utility/Ratepayer)		7.000		2.200
Reduced CO_2 Emissions		4.500		4.500
Total	145.825.700	13.200	145.825.700	8.400
benefit/cost ratio	9,10E-05		5,80E-05	

According to table 4.3, $ZnBr_2$ (10.000 kW) replacing combustion turbine seems to have the highest benefit/cost ratio (0,0013) but this is still below 1 so this choice is not going to be beneficial. Table 4.4 depicts total net benefit calculation for the whole deployment period and diagramme 4.2. depicts the net present value per year. Both have been extracted from the ESCT.

Table 4.4: Result table for $ZnBr_2$ (10.000 kW) replacing combustion turbine in distribution grid location

	Annual Benefit and Cost Table				
	Benefits	**Additional Benefits - Total Present Value over the Deployment Period**	+ **Primary and Secondary Benefits - Total Present Value over the Deployment Period**	=	**Total Benefit - Present Value over the Deployment Period**
Market Revenue	Arbitrage Revenue	$ -	$ -		$ -
	Capacity Market Revenue	$ -	$ -		$ -
	Ancillary Services Revenue	$ -	$ -		$ -
Improved Asset Utilization	Optimized Generator Operation (Non-Utility Merchant)	$ -	$ -		$ -
	Optimized Generator Operation (Utility/Ratepayer)	$ -	$ -		$ -
	Deferred Generation Capacity Investments	$ -	$ -		$ -
	Reduced Congestion Costs (Non-Utility Merchant)	$ -	$ -		$ -
	Reduced Congestion Costs (Utility/Ratepayer)	$ -	$ -		$ -
T&D Capital Savings	Deferred Transmission Investments	$ -	$ -		$ -
	Deferred Distribution Investments	$ -	$ -		$ -
Energy Efficiency	Reduced Electricity Losses	$ -	$ -		$ -
Electricity Cost Savings	Reduced Electricity Cost (Consumer)	$ -	$ -		$ -
	Reduced Electricity Cost (Utility/Ratepayer)	$ -	$ 21.700		$ 21.700
Power Interruptions	Reduced Outages (Consumer)	$ -	$ -		$ -
	Reduced Outages (Utility/Ratepayer)	$ -	$ 2.200		$ 2.200
Power Quality	Improved Power Quality	$ -	$ -		$ -
Air Emissions	Reduced CO2 Emissions	$ -	$ 4.500		$ 4.500
	Reduced SOx Emissions	$ -	$ -		$ -
	Reduced NOx Emissions	$ -	$ -		$ -
	Reduced PM Emissions	$ -	$ -		$ -
	Total Gross Benefit	**$ -**	**$ 28.400**		**$ 28.400**
	Costs				
	Capital Cost of Deployment (fixed charge rate)				$ 21.312.600
	Operating and maintenance costs not related to energy (labor for operation, plant maintenance, equipment wear leading to loss-of-life)				$ 1.074.000
	Decommissioning and Disposal Costs				$ -
	Total Annual Cost of Deployment				**$ 22.386.600**
	Total Net Benefit				**$ (22.358.200)**

Diagram 4.2. Result chart for $ZnBr_2$ (10.000 kW) replacing combustion turbine in distribution grid location

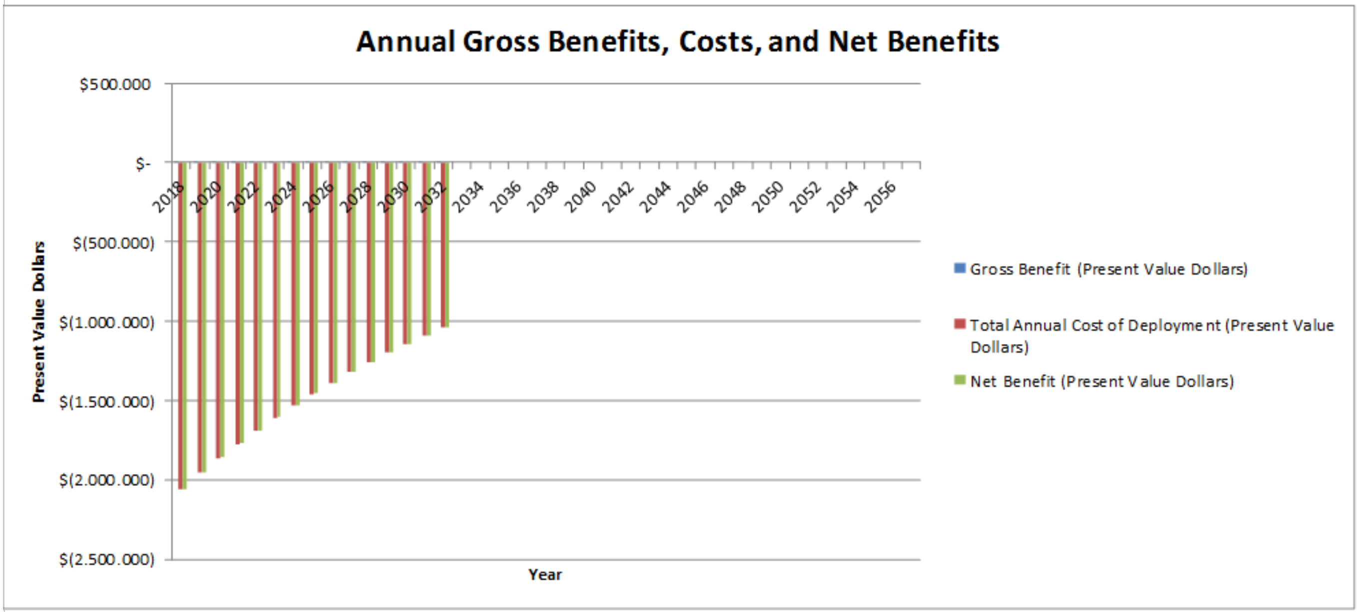
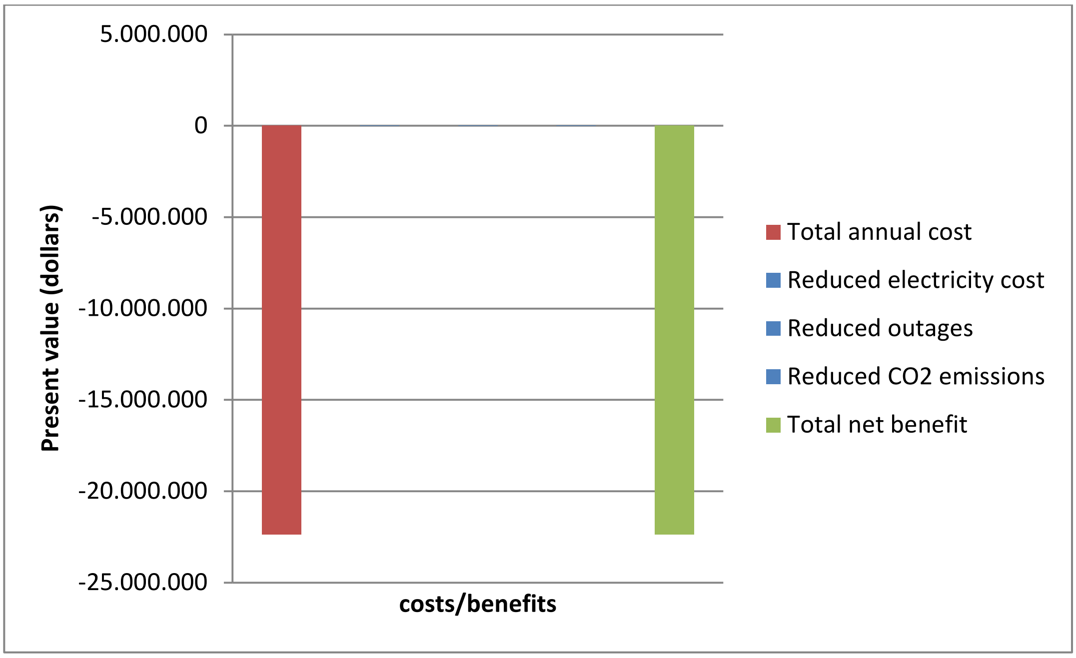


Diagram 4.3. Total costs and benefits for $ZnBr_2$ (10.000 kW) replacing combustion turbine in distribution grid location



4.2.2. Case 2 (generation and transmission)

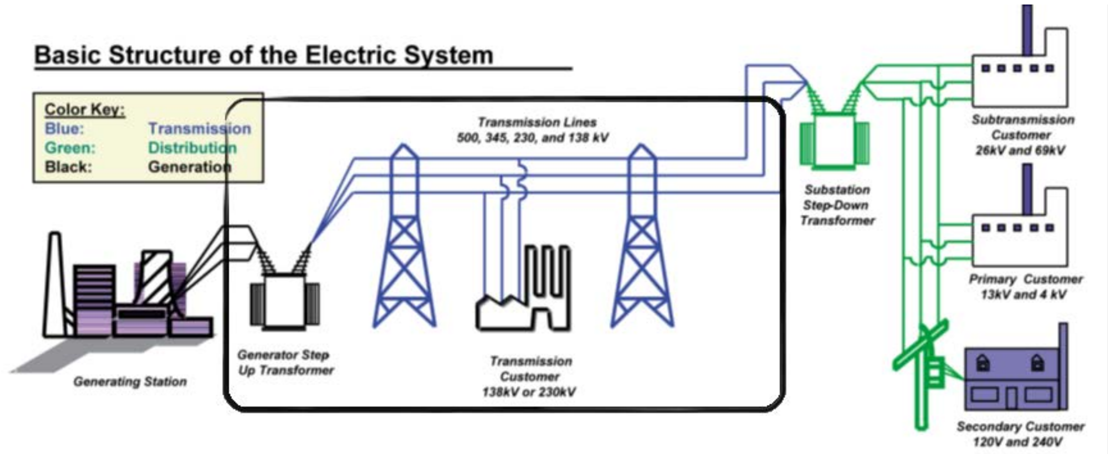


Figure 4.2: Location of ES deployment in case 2 [http://www.ee.teihal.gr]

Table 4.5: ESCT results for different energy storage technologies in case the ES deployment is between generation station and Substation Step-Down Transformer

Generation and Transmission				
adv lead acid (1.000 kW)				
energy capacity (kWh)	3.650.000			
conventional unit for replacement	**combined cycle**		**combustion turbine**	
	costs	benefits	costs	benefits
capital expenditure	5.934.500		5.934.500	
operating costs	1.253.000		1.253.000	
Deferred Generation Capacity Investments		1.849.800		1.123.900
Reduced PM Emissions		144.700		72.400

Total	7.187.500	1.994.500	7.187.500	1.196.300
benefit/cost ratio	0,277		0,166	
adv lead acid (12.000 kW)				
energy capacity (kWh)	17.520.000			
conventional unit for replacement	**combined cycle**		**combustion turbine**	
	costs	benefits	costs	benefits
capital expenditure	61.763.100		61.763.100	
operating costs	12.748.500		12.748.500	
Deferred Generation Capacity Investments		5.549.100		5.625.800
Reduced Electricity Cost (Utility/Ratepayer)		200		200
Reduced CO_2 Emissions		1.800		1.800
Reduced PM Emissions		434.400		434.400
Total	74.511.600	5.985.500	74.511.600	6.062.200
benefit/cost ratio	0,08		0,081	
adv lead acid (20.000 kW)				
energy capacity (kWh)	43.800.000			
conventional unit for replacement	**combined cycle**		**combustion turbine**	
	costs	benefits	costs	benefits
capital expenditure	138.809.900		138.809.900	
operating costs	29.768.500		29.768.500	
Deferred Generation Capacity Investments		12.948.200		15.732.900
Reduced Electricity Cost (Utility/Ratepayer)		700		700
Reduced CO_2 Emissions		2.100		2.100
Reduced PM Emissions		1.013.000		1.013.000
Total	168.578.400	13.964.000	168.578.400	16.748.700
benefit/cost ratio	0,083		0,099	
NaS (1.000 kW)				
energy capacity (kWh)	2.628.000			
conventional unit for replacement	**combined cycle**		**combustion turbine**	
	costs	benefits	costs	benefits
capital expenditure	6.875.000		6.875.000	
operating costs	169.500		169.500	
Deferred Generation Capacity Investments		1.747.000		1.123.900
Reduced Electricity Cost (Utility/Ratepayer)		2.100		
Reduced PM Emissions		137.800		72.400
Total	7.044.500	1.886.900	7.044.500	1.196.300
benefit/cost ratio	0,268		0,17	
NaS (12.000 kW)				
energy capacity (kWh)	31.536.000			
conventional unit for replacement	**combined cycle**		**combustion turbine**	
	costs	benefits	costs	benefits
capital expenditure	53.627.200		53.627.200	
operating costs	1.053.000		1.053.000	

Deferred Generation Capacity Investments		9.298.100		11.237.900
Reduced Electricity Cost (Utility/Ratepayer)		28.400		2.500
Reduced CO_2 Emissions		5.100		5.100
Reduced PM Emissions		265.800		265.800
Total	54.680.200	9.597.400	54.680.200	11.511.300
benefit/cost ratio	0,176		0,211	
VRB (10.000 kW)				
energy capacity (kWh)	18.250.000			
conventional unit for replacement	**combined cycle**		**combustion turbine**	
	costs	benefits	Costs	benefits
capital expenditure	44.361.100		44.361.100	
operating costs	8.616.500		8.616.500	
Deferred Generation Capacity Investments		5.549.100		6.742.800
Reduced Electricity Cost (Utility/Ratepayer)		1.700		1.700
Reduced CO_2 Emissions		4.500		4.500
Reduced PM Emissions		159.500		159.500
Total	52.977.600	5.714.800	52.977.600	6.908.500
benefit/cost ratio	0,108		0,13	
FeCr (1.000 kW)				
energy capacity (kWh)	1.460.000			
conventional unit for replacement	**combined cycle**		**combustion turbine**	
	costs	benefits	costs	benefits
capital expenditure	1.791.300		1.791.300	
operating costs	362.000		362.000	
Deferred Generation Capacity Investments		479.200		561.900
Reduced PM Emissions		13.300		13.300
Total	2.153.300	492.500	2.153.300	575.200
benefit/cost ratio	0,229		0,267	
FeCr (10.000 kW)				
energy capacity (kWh)	18.250.000			
conventional unit for replacement	**combined cycle**		**combustion turbine**	
	costs	benefits	costs	benefits
capital expenditure	18.856.800		18.856.800	
operating costs	3.096.500		3.096.500	
Deferred Generation Capacity Investments		5.570.200		5.625.800
Reduced Electricity Cost (Utility/Ratepayer)		1.700		1.700
Reduced CO_2 Emissions		4.500		4.500
Reduced PM Emissions		159.500		159.500
Total	21.953.300	5.735.900	21.953.300	5.791.500
benefit/cost ratio	0,261		0,264	
$ZnBr_2$ (1.000 kW)				
energy capacity (kWh)	1.825.000			
conventional unit for replacement	**combined cycle**		**combustion turbine**	
	costs	benefits	costs	benefits

capital expenditure	2.426.400		2.426.400	
operating costs	97.500		97.500	
Deferred Generation Capacity Investments		958.400		1.123.900
Reduced PM Emissions		72.400		72.400
Total	2.523.900	1.030.800	2.523.900	1.196.300
benefit/cost ratio	0,408		0,474	
$ZnBr_2$ (10.000 kW)				
energy capacity (kWh)	18.250.000			
conventional unit for replacement	**combined cycle**		**combustion turbine**	
	costs	benefits	costs	benefits
capital expenditure	21.312.600		21.312.600	
operating costs	1.074.000		1.074.000	
Deferred Generation Capacity Investments		5.549.100		6.742.800
Reduced Electricity Cost (Utility/Ratepayer)		200		200
Reduced CO_2 Emissions		1.100		1.100
Reduced PM Emissions		434.400		434.400
Total	22.386.600	5.984.800	22.386.600	7.178.500
benefit/cost ratio	0,267		0,321	
Li-ion (1.000 kW)				
energy capacity (kWh)	492.750			
conventional unit for replacement	**combined cycle**		**combustion turbine**	
	costs	benefits	costs	benefits
capital expenditure	2.532.600		2.532.600	
operating costs	1.418.000		1.418.000	
Deferred Generation Capacity Investments		924.900		1.123.900
Reduced Outages (Utility/Ratepayer)		500		1.500
Reduced PM Emissions		72.200		72.200
Total	3.950.600	997.600	3.950.600	1.197.600
benefit/cost ratio	0,253		0,303	
Li-ion (3.000 kW)				
energy capacity (kWh)	1.095.000			
conventional unit for replacement	**combined cycle**		**combustion turbine**	
	costs	benefits	costs	benefits
capital expenditure	4.916.600		4.916.600	
operating costs	385.500		385.500	
Deferred Generation Capacity Investments		924.900		1.123.900
Reduced CO_2 Emissions		100		100
Reduced PM Emissions		72.400		72.400
Total	5.302.100	997.400	5.302.100	1.196.400
benefit/cost ratio	0,188		0,226	
Li-ion (10.000 kW)				
energy capacity (kWh)	10.950.000			
conventional unit for replacement	**combined cycle**		**combustion turbine**	
	costs	benefits	costs	benefits
capital expenditure	62.155.200		62.155.200	

operating costs	83.670.500		83.670.500	
Deferred Generation Capacity Investments		3.719.200		4.495.200
Reduced Electricity Cost (Utility/Ratepayer)		4.200		200
Reduced CO_2 Emissions		800		1.100
Reduced PM Emissions		289.500		289.500
Total	145.825.700	4.013.700	145.825.700	4.786.000
benefit/cost ratio	0,028		0,033	

Case 2 where the ES deployment is located between generation station and Substation Step-Down Transformer seems much better as far as the benefit/cost ratios are concerned. According to table 4.5, $ZnBr_2$ (1.000 kW) replacing combustion turbine has the highest benefit/cost ratio (0,474) comparing to other technologies but this is also under 1 which means it is not going to have a payback the next 15 years. Table 4.6 depicts total net benefit calculation for the whole deployment period and diagramme 4.4. depicts the net present value per year. Both have been extracted from the ESCT.

Table 4.6: Result table for $ZnBr_2$ (1.000 kW) replacing combustion turbine in generation and transmission grid location

	Annual Benefit and Cost Table Benefits	Additional Benefits - Total Present Value over the Deployment Period	+	Primary and Secondary Benefits - Total Present Value over the Deployment Period	=	Total Benefit - Present Value over the Deployment Period
Market Revenue	Arbitrage Revenue	$ -		$ -		$ -
	Capacity Market Revenue	$ -		$ -		$ -
	Ancillary Services Revenue	$ -		$ -		$ -
Improved Asset Utilization	Optimized Generator Operation (Non-Utility Merchant)	$ -		$ -		$ -
	Optimized Generator Operation (Utility/Ratepayer)	$ -		$ -		$ -
	Deferred Generation Capacity Investments	$ -		$ 1.123.900		$ 1.123.900
	Reduced Congestion Costs (Non-Utility Merchant)	$ -		$ -		$ -
	Reduced Congestion Costs (Utility/Ratepayer)	$ -		$ -		$ -
T&D Capital Savings	Deferred Transmission Investments	$ -		$ -		$ -
	Deferred Distribution Investments	$ -		$ -		$ -
Energy Efficiency	Reduced Electricity Losses	$ -		$ -		$ -
Electricity Cost Savings	Reduced Electricity Cost (Consumer)	$ -		$ -		$ -
	Reduced Electricity Cost (Utility/Ratepayer)	$ -		$ -		$ -
Power Interruptions	Reduced Outages (Consumer)	$ -		$ -		$ -
	Reduced Outages (Utility/Ratepayer)	$ -		$ -		$ -
Power Quality	Improved Power Quality	$ -		$ -		$ -
Air Emissions	Reduced CO2 Emissions	$ -		$ -		$ -
	Reduced SOx Emissions	$ -		$ -		$ -
	Reduced NOx Emissions	$ -		$ -		$ -
	Reduced PM Emissions	$ -		$ 72.400		$ 72.400
	Total Gross Benefit	**$ -**		**$ 1.196.300**		**$ 1.196.300**
	Costs					
	Capital Cost of Deployment (fixed charge rate)					$ 2.426.400
	Operating and maintenance costs not related to energy (labor for operation, plant maintenance, equipment wear leading to loss-of-life)					$ 97.500
	Decommissioning and Disposal Costs					$ -
	Total Annual Cost of Deployment					**$ 2.523.300**
	Total Net Benefit					**$ (1.327.000)**

Diagram 4.4. Result chart for $ZnBr_2$ (1.000 kW) replacing combustion turbine in generation and transmission grid location

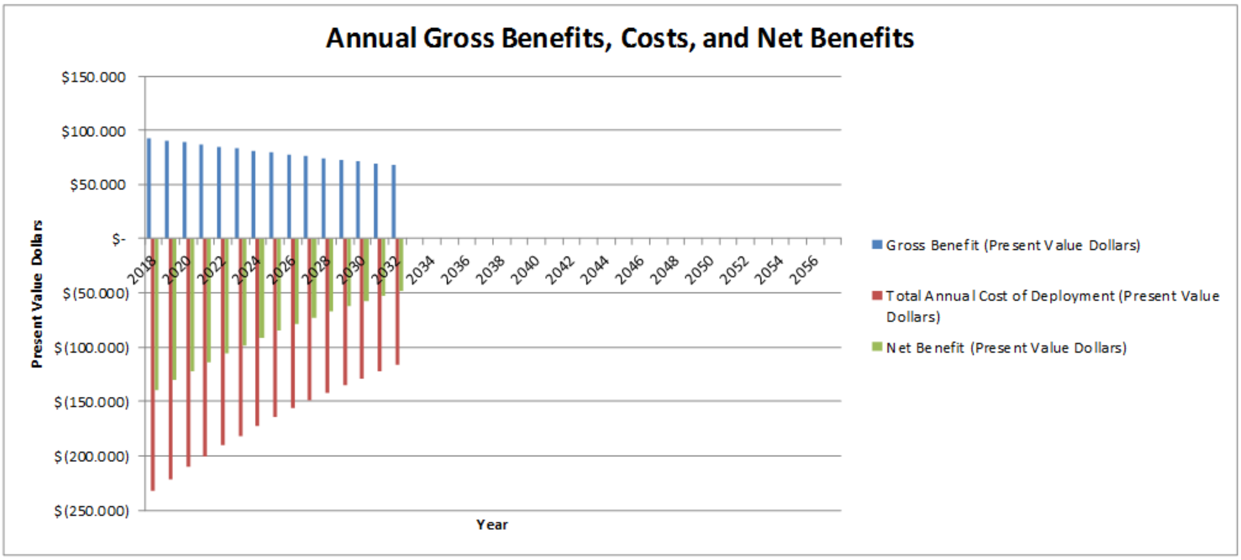
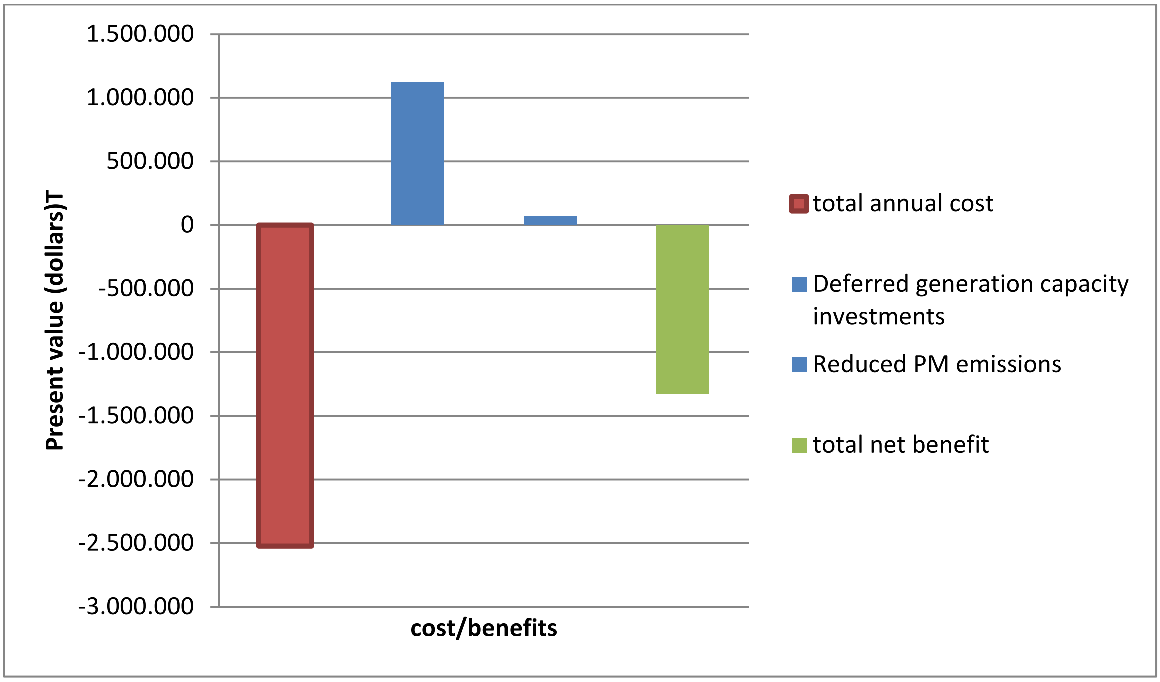


Diagramme 4.5. depicts total costs and benefits over the whole deployment period.

Diagram 4.5. Total costs and benefits for $ZnBr_2$ (1.000 kW) replacing combustion turbine in generation and transmission grid location



4.3. ES Select results

4.3.1. Case 1.1

Step 1: Bulk storage / Up to 50 MW

Step 2

Application
1. electric service reliability
2. wind generation grid integration-long duration
3. renewables energy time shift

Step 3

The Total bundle value that comes from this set of applications is 181 to 441 $/MWh.

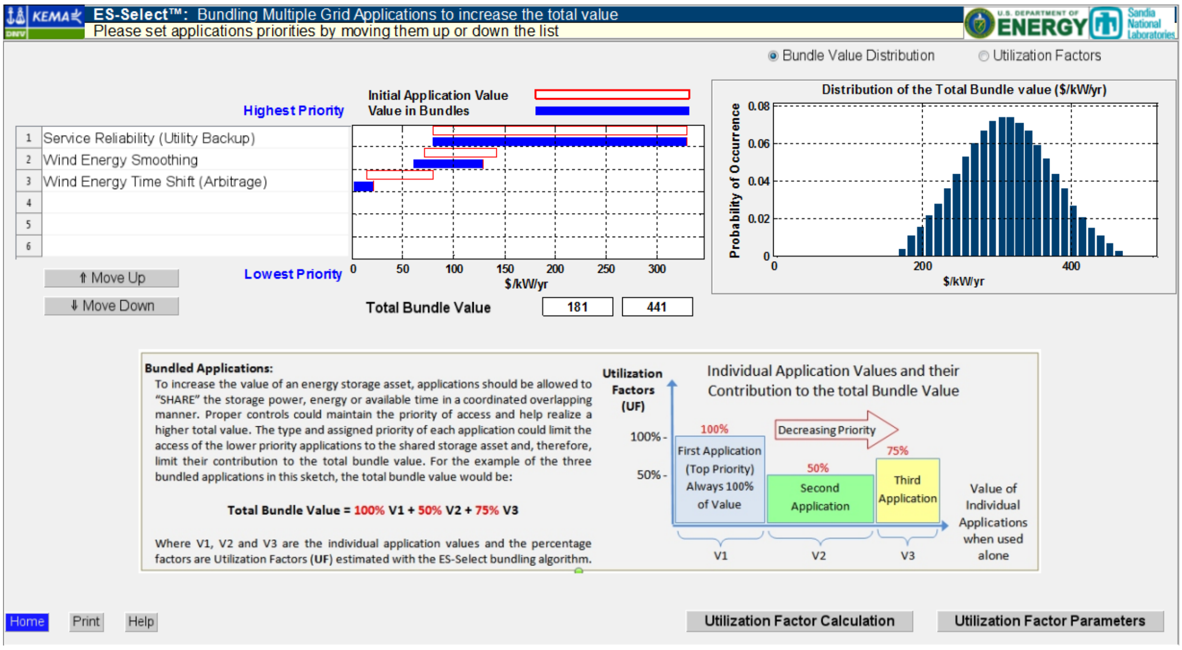


Figure 4.3: Total bundle value calculation for case 1.1

Step 4

The best-fit energy storage technology located next to bulk storage (up to 50MW), is NaS with a total feasibility score of 71%. Figure 4.4 illustrates the individual scores of meeting application and location requirements, commercial maturity and total cost, which form the total feasibility score.

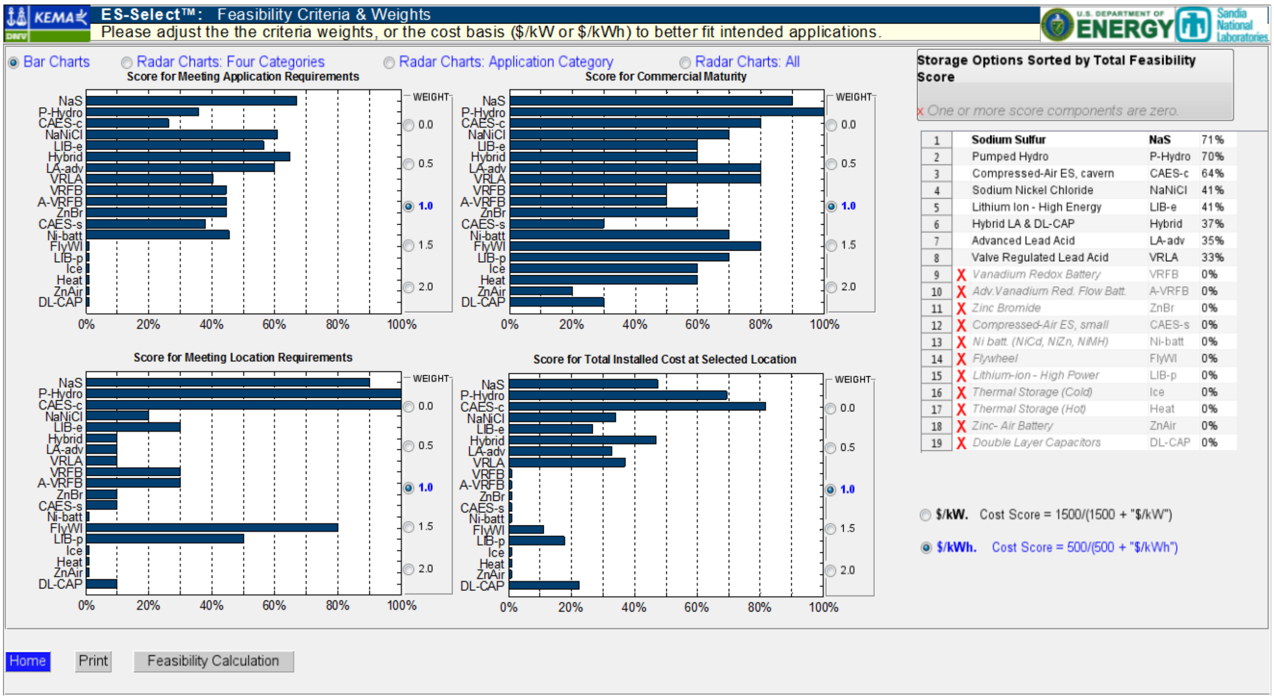


Figure 4.4: Feasibility criteria analysis of various ESTs' for case 1.1

All storage options sorted by total feasibility score shown in Figure 4.5.

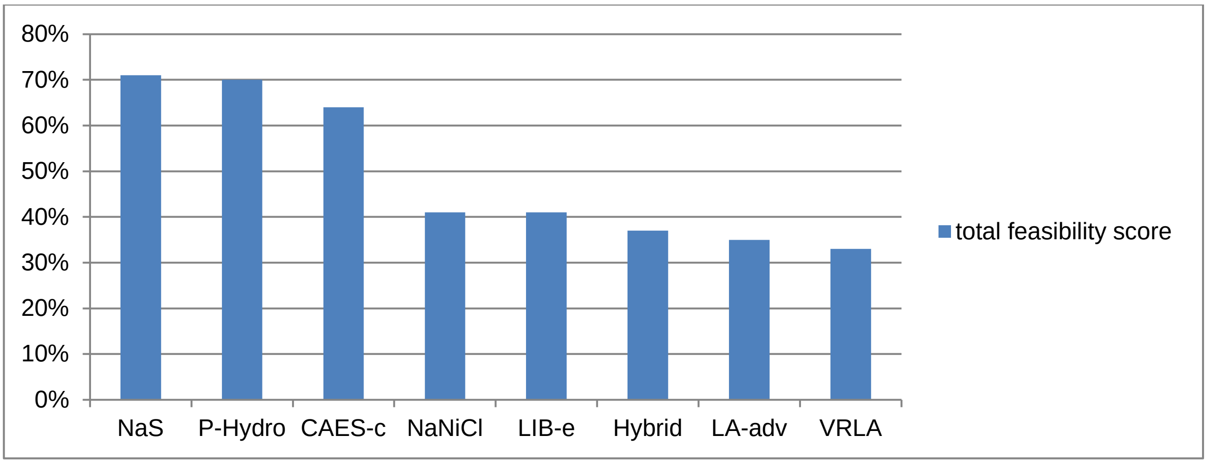


Figure 4.5: Storage options sorted by total feasibility score for case 1.1

CAES-c and Hybrid are likely to have a payback in the next 15 years when located on bulk storage grid location. ES Select estimates the probability of having a payback for this technology over 85% as illustrated in the following figure.

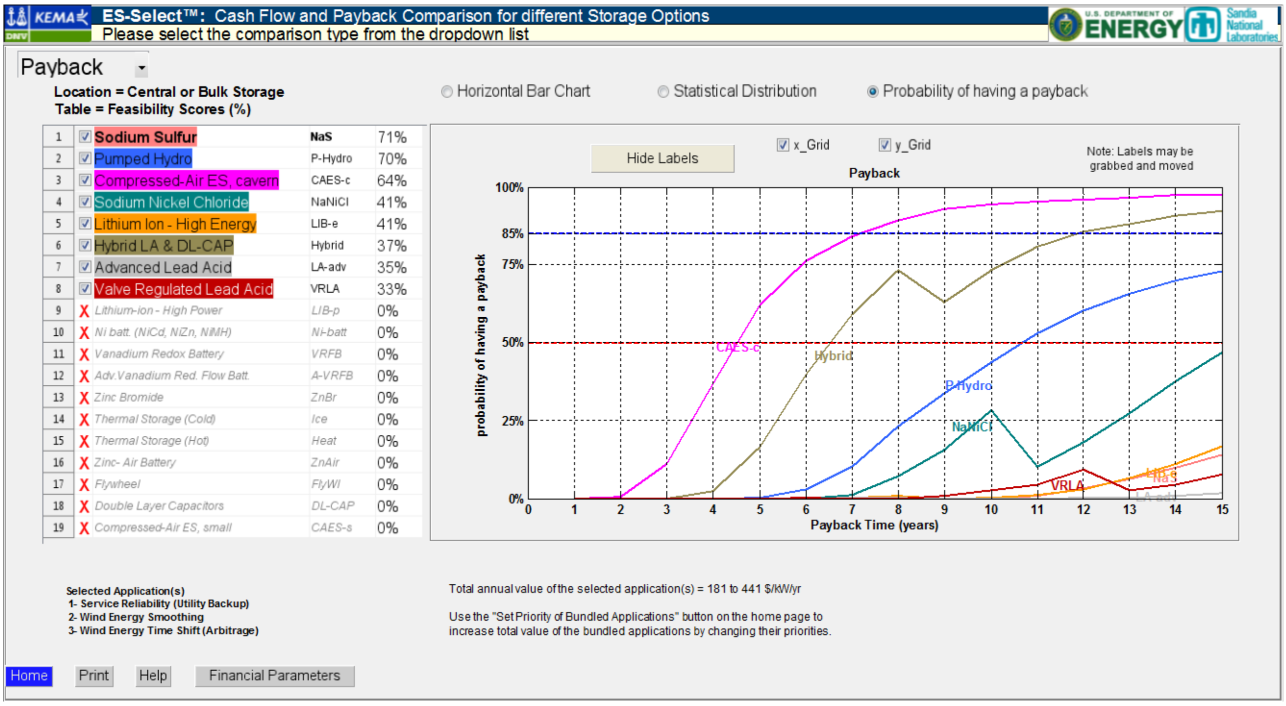


Figure 4.6: The probability of having a payback in any given year within the storage lifetime time for case 1.1

There is a high probability of payback time occurrence for CAES-c already between years 5-7 and for Hybrid between years 8-10 as illustrated in Figure 4.7.

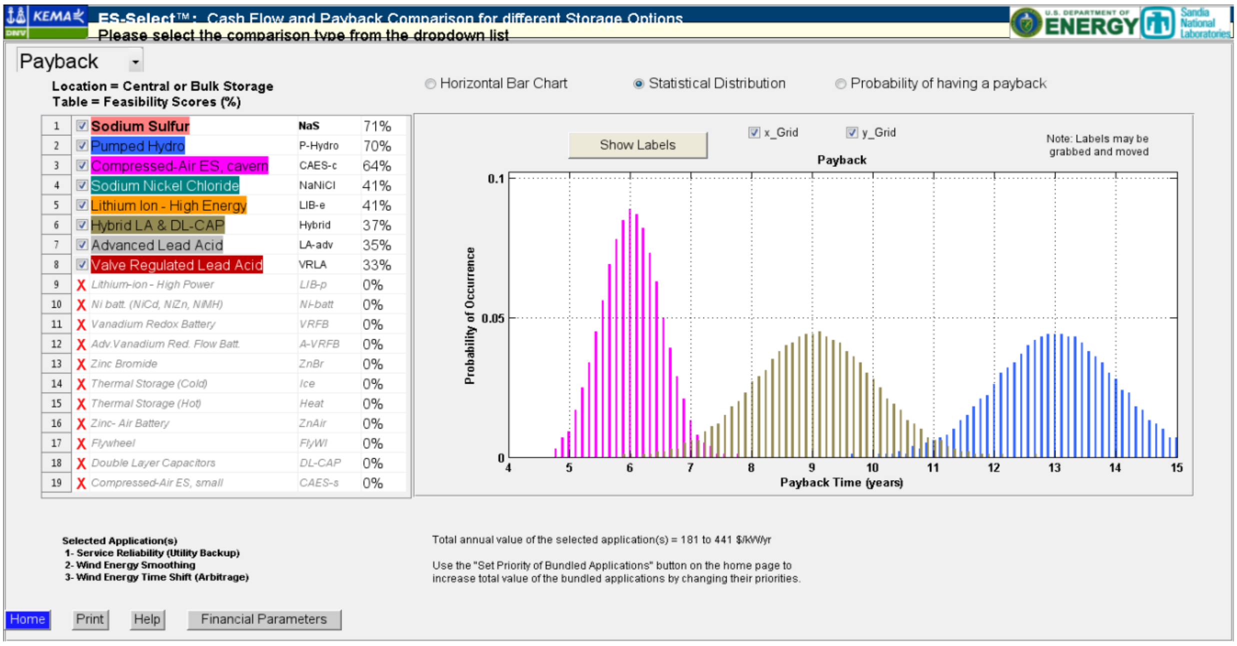


Figure 4.7: Statistical distribution of payback years of storage options for case 1.1

Considering the above figures for energy storage options up to 50MW, CAES-c seems to be the best-fit storage option as it has above 85% probability of having a payback in the next 15 years and 64% feasibility score.

We follow the same process for other cases as depicted in Appendix E.

4.4. Results comparison between ESCT and ES Select

Table 4.7: ESCT results

Applications	Location	Payback
Case 1	Distribution	No payback
Case 2	Generation & transmission	No payback

Table 4.8: ES Select results

Applications	Location	Technology	Probability of payback	Feasibility score
Case 1.1	Bulk storage	CAES-c	95%	64%
Case 1.2	Bulk storage	-	No payback	-
Case 2.1	Transmission & distribution	CAES-c	95%	48%
Case 2.2	Transmission & distribution	CAES-c	60%	53%
Case 3.1	Distribution	Hybrid	85%	58%
Case 3.2	Distribution	-	No payback	-
Case 4.1	Commercial	Hybrid	90%	60%
Case 4.2	Commercial	Hybrid	15%	58%

Tables 4.7, 4.8 contain the cases and the results from each tool. Case 1 from table 4.7 refers to the same location as cases 3.1, 3.2, 4.1, 4.2 from table 4.8. The same happens with case 2 and cases 1.1, 1.2, 2.1, 2.2. It should be noted that No payback at ESCT means that none technology has a 100% probability of having a payback, the same as ES Select. For example, in cases 1.1 and 2.1 the ES technology shows 95% probability of having a payback (<100%) so both tools conclude that there is no beneficial energy storage technology for the island of Crete in the cases mentioned.

4.5. ES Select results - Other cases

At the previous chapter, we run ESCT and ES Select in order to find if an energy storage deployment could be beneficial for the island of Crete and therefore we inserted only 3 applications in each case. Contrary to ESCT, the ES Select gives us the ability to select up to 6 applications to be bundled for increased value, so we run again ES Select with sets of 6 applications.

4.5.1. Case A

Step 1: Bulk storage (Over 10 MW)

Step 2

Application
1. Service reliability (Utility backup)
2. Energy time shift (Arbitrage)
3. Black start

4. Renewable capacity firming	
5. Wind energy smoothing	
6. Wind energy time shift (Arbitrage)	

Step 3

The Total bundle value that comes from this set of applications is 307 to 571 $/kW/y.

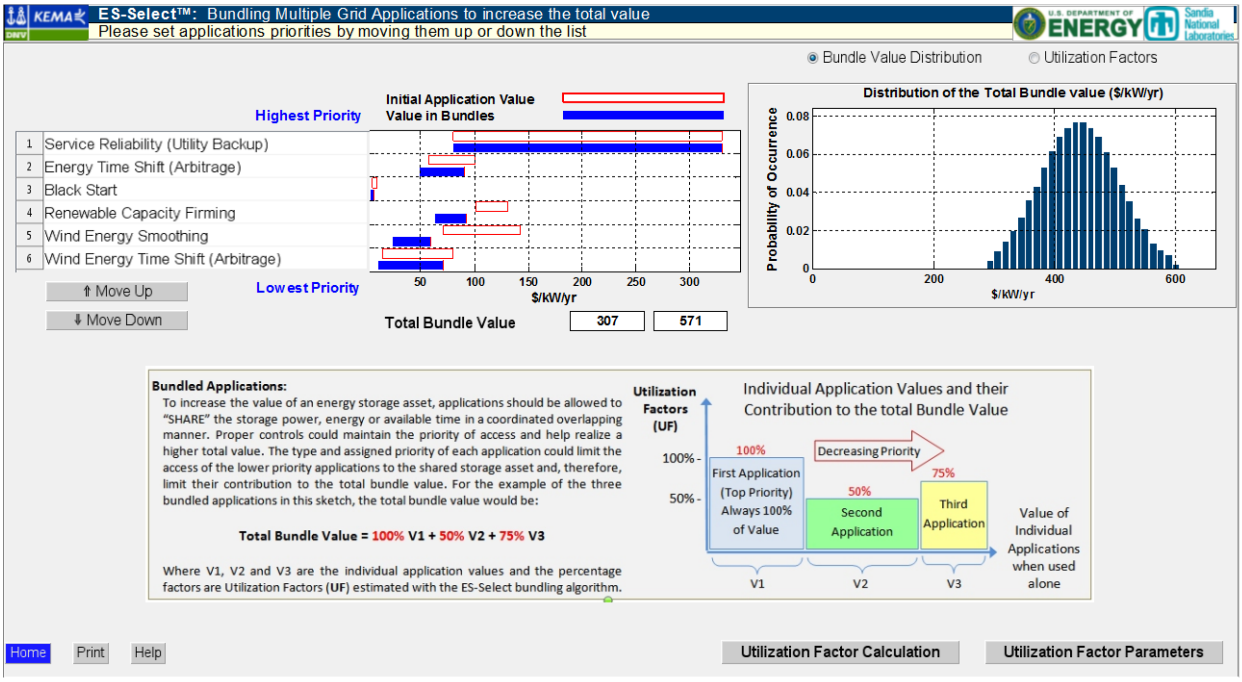


Figure 4.8: Total bundle value calculation for generation grid location

Step 4

The best-fit energy storage technologies located next to generation (over 10MW) are P-Hydro with a total feasibility score of 73%, CAES-c with 72% and NaS with 66%. Figure 4.9 illustrates the individual scores of meeting application and location requirements, commercial maturity and total cost on commercial and industrial grid location, which form the total generation feasibility score.

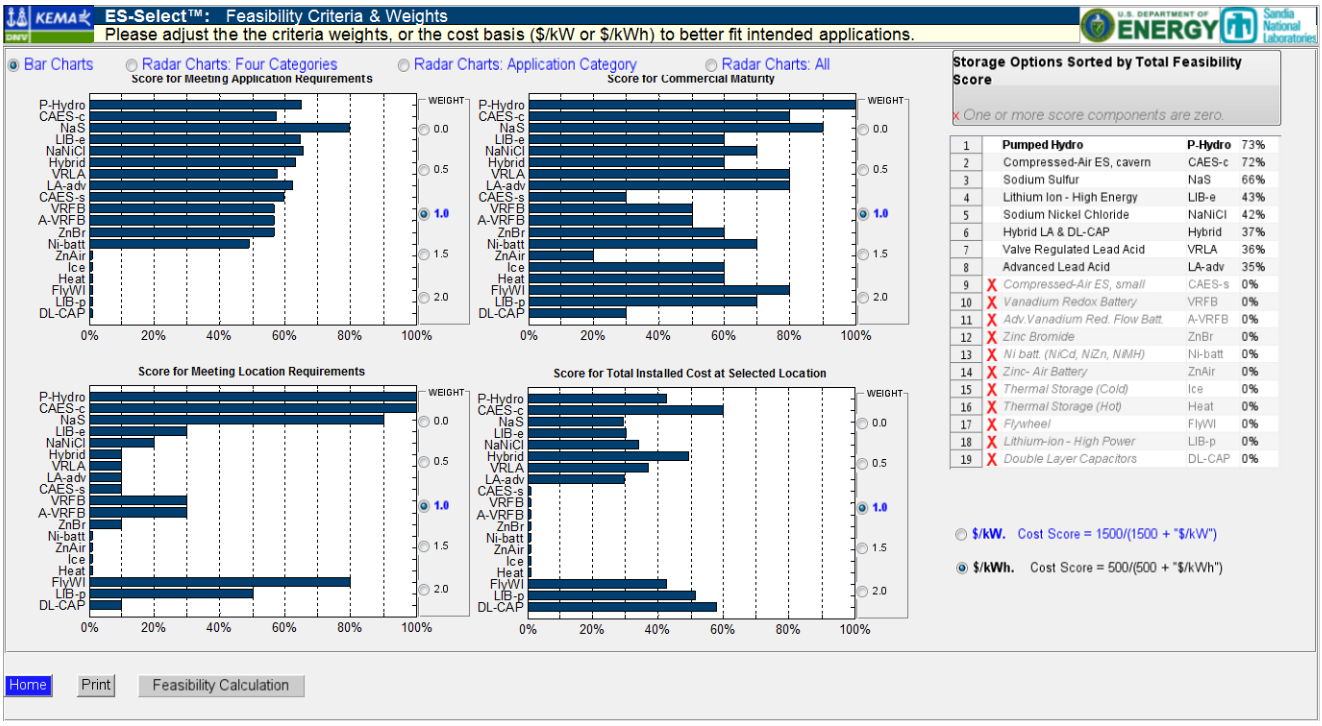


Figure 4.9: Feasibility criteria analysis of various ESTs' with the central or bulk storage

All storage options sorted by total feasibility score shown in Figure 4.10.

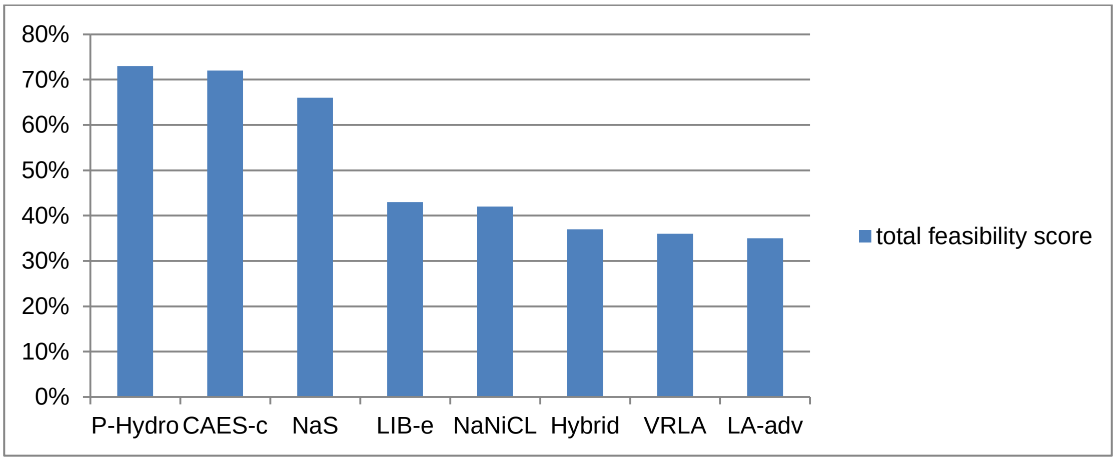


Figure 4.10: Storage options sorted by total feasibility score on generation grid location

CAES-c, Hybrid, P-Hydro and NaNiCl are likely to have a payback in the next 15 years when located on generation grid. ES Select estimates the probability of having a payback for these technologies over 85% as illustrated in the following figure.

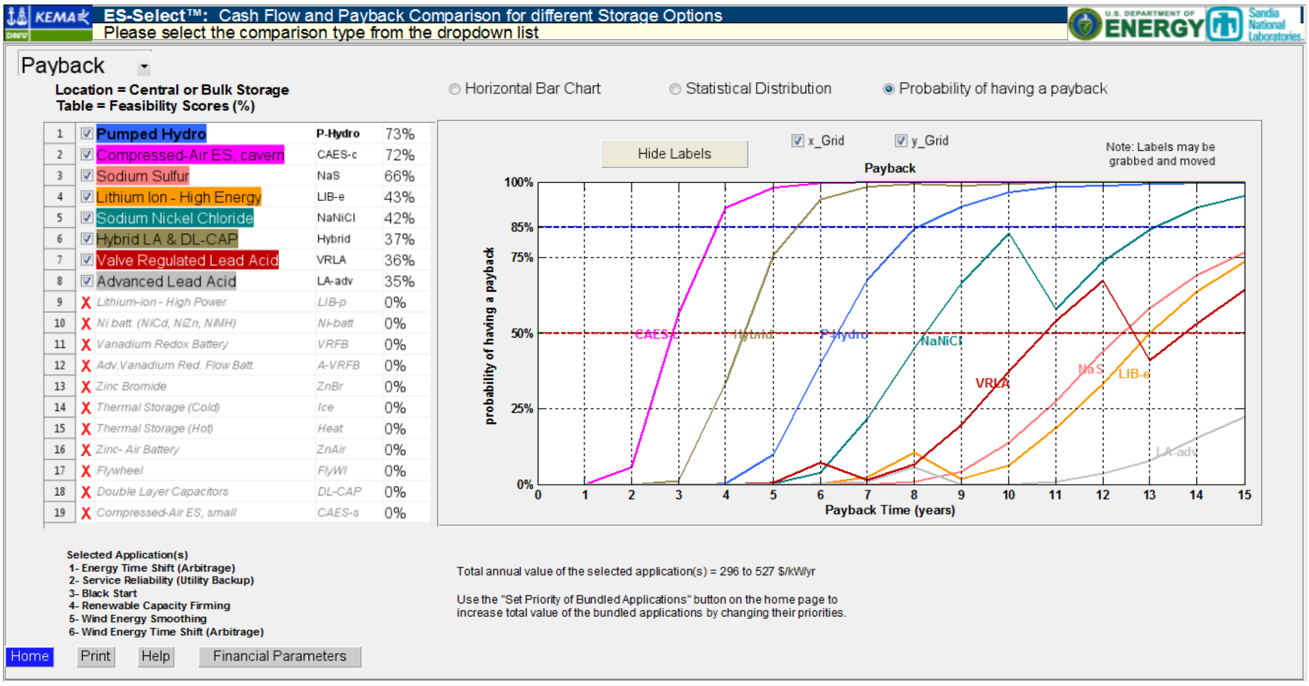


Figure 4.11: The probability of having a payback in any given year within the storage lifetime time on generation grid location

There is a high probability of payback time occurrence of CAES-c already between years 3-4, for Hybrid between years 5-6, for P-Hydro between years 6-7 and for NaNiCl between years 9-11as illustrated in figure 4.12.

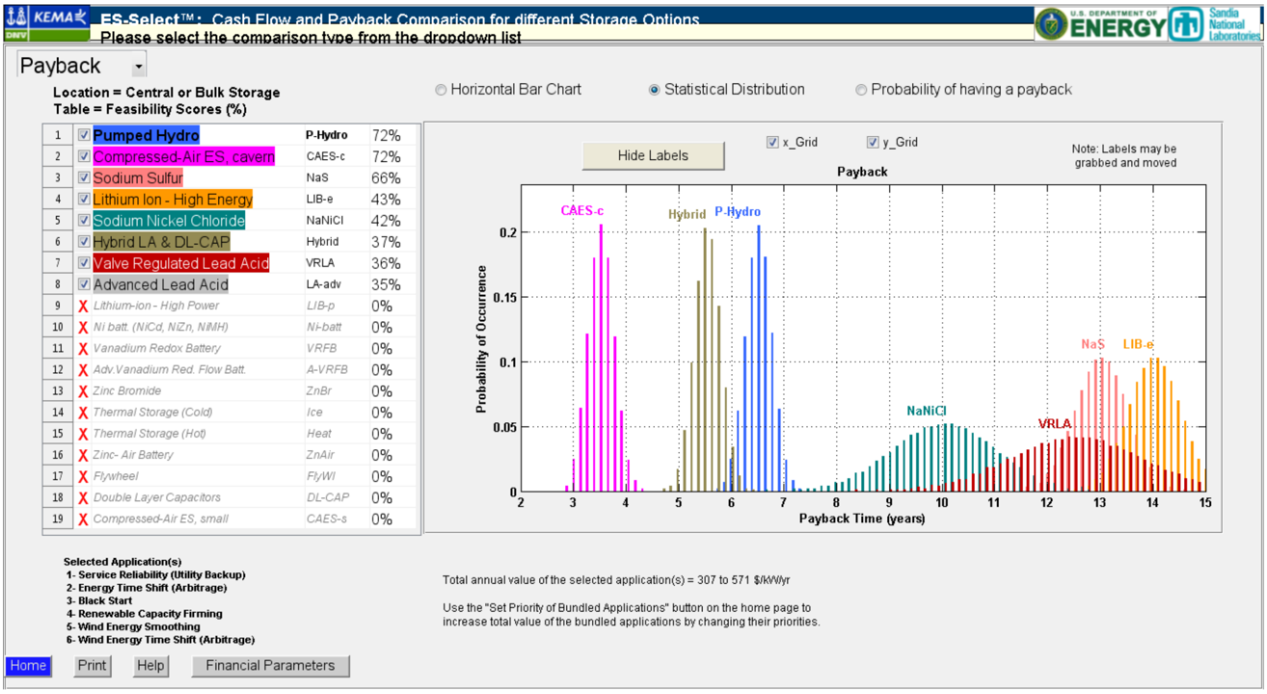


Figure 4.12: Statistical distribution of payback years of storage options on generation grid location

Considering the above figures, for energy storage options above 10MW, P-Hydro seems to be the storage option that has the highest feasibility score (73%) and above 85% probability of having a payback in the next 15 years. P-Hydro is capable of discharge times in tens of hours, with correspondingly high sizes (above 280MW) and has the ability to store more than 800.000 MWh/year. This amount of energy exceeds our needs for the island of Crete and the same happens with CAES-c and NaS for bulk storage applications. LIB-e coming 4th shows a low probability of having a payback. NaNiCl, the technology coming fifth, is available at the size of 10,6 MW for bulk storage with a capacity of 19.345 MWh/year. So 3 batteries of this type could be a solution.

4.5.2. Case B

Step 1: Transmission / Up to 10 MW (substation)

Step 2

Application
1. Energy time shift (Arbitrage)
2. Black start
3. Service reliability (Utility backup)
4. Renewable capacity firming
5. Wind energy smoothing
6. Wind energy time shift (Arbitrage)

Step 3

The Total bundle value that comes from this set of applications is 294 to 521 $/kW/y.

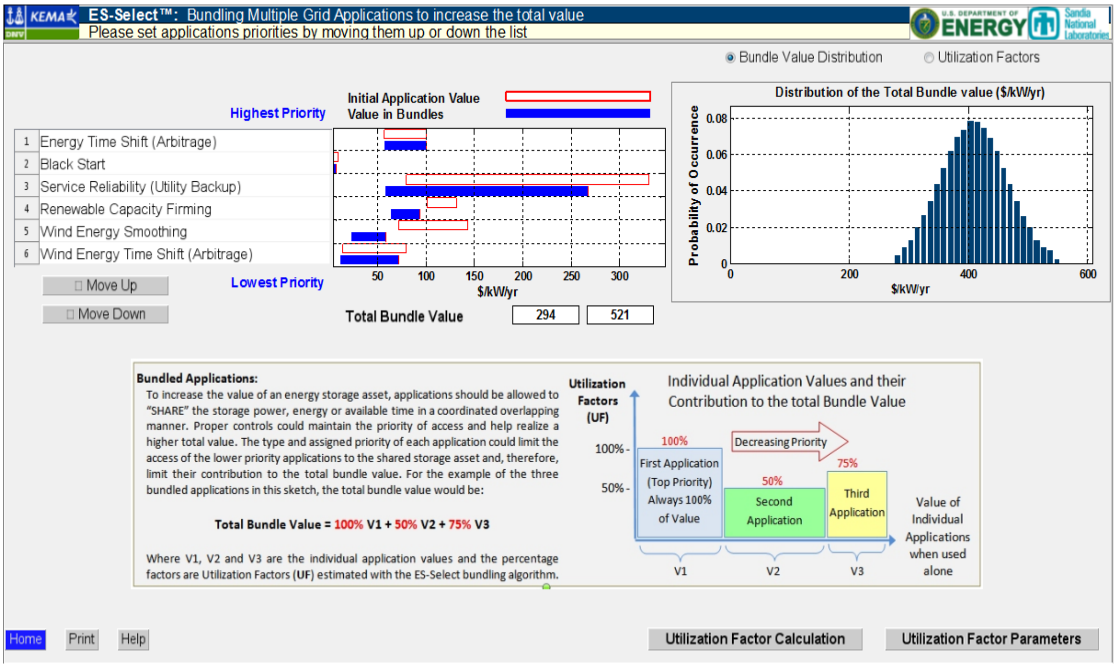


Figure 4.13: Total bundle value calculation for transmission grid location

Step 4

The best-fit energy storage technologies located next to transmission (up to 10MW) are NaS with a total feasibility score of 76%, NaNiCl with 59% and CAES-c with 58%. Figure 4.14 illustrates the individual scores of meeting application and location requirements, commercial maturity and total cost on commercial and industrial grid location, which form the total transmission feasibility score.

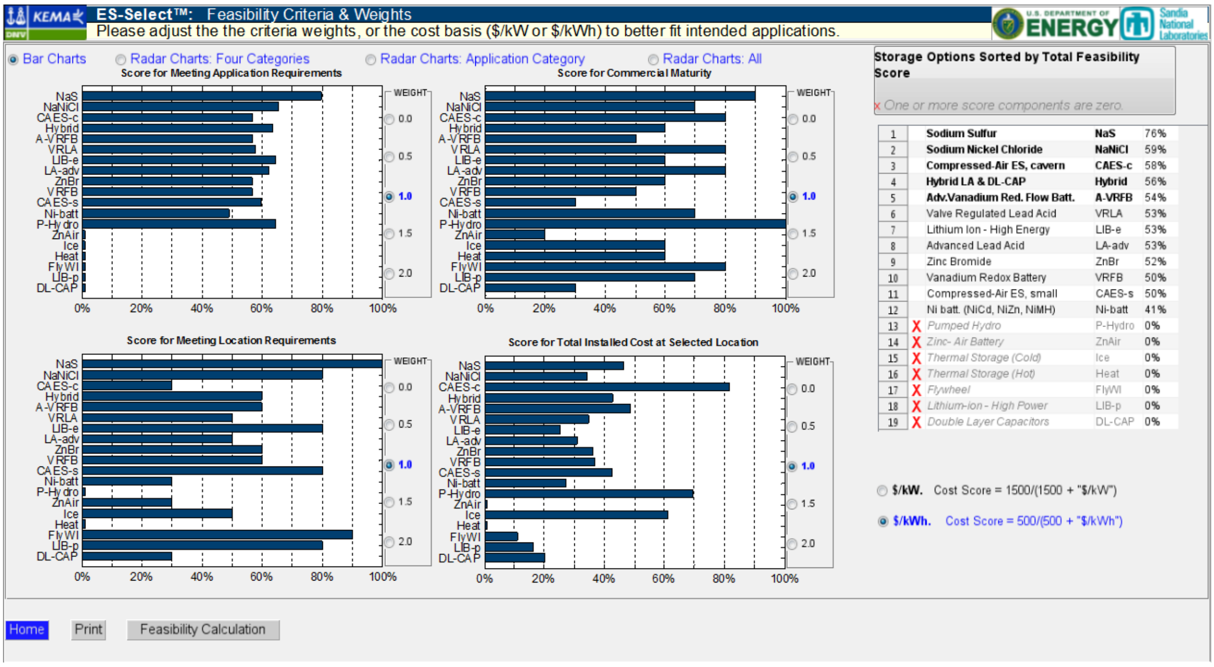


Figure 4.14: Feasibility Page listing storage option with their individual Feasibility Scores for transmission grid location

All storage options sorted by total feasibility score shown in Figure 4.15.

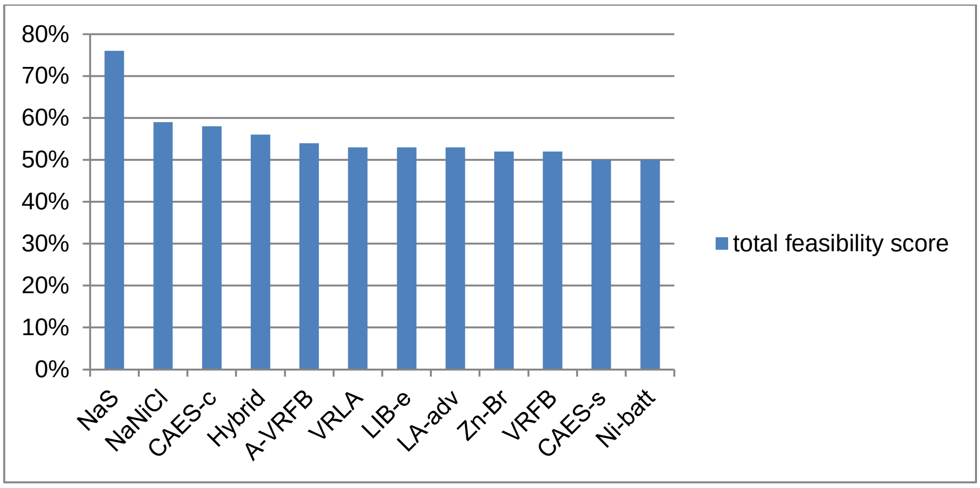


Figure 4.15: Storage options sorted by total feasibility score on transmission grid location

Many technologies are likely to have a payback in the next 15 years as ES Select estimates the probability of having a payback for these technologies over 85% as illustrated in the following Figure. NaS shows a 50% probability of having a payback between years 14-15 despite having the highest feasibility score.

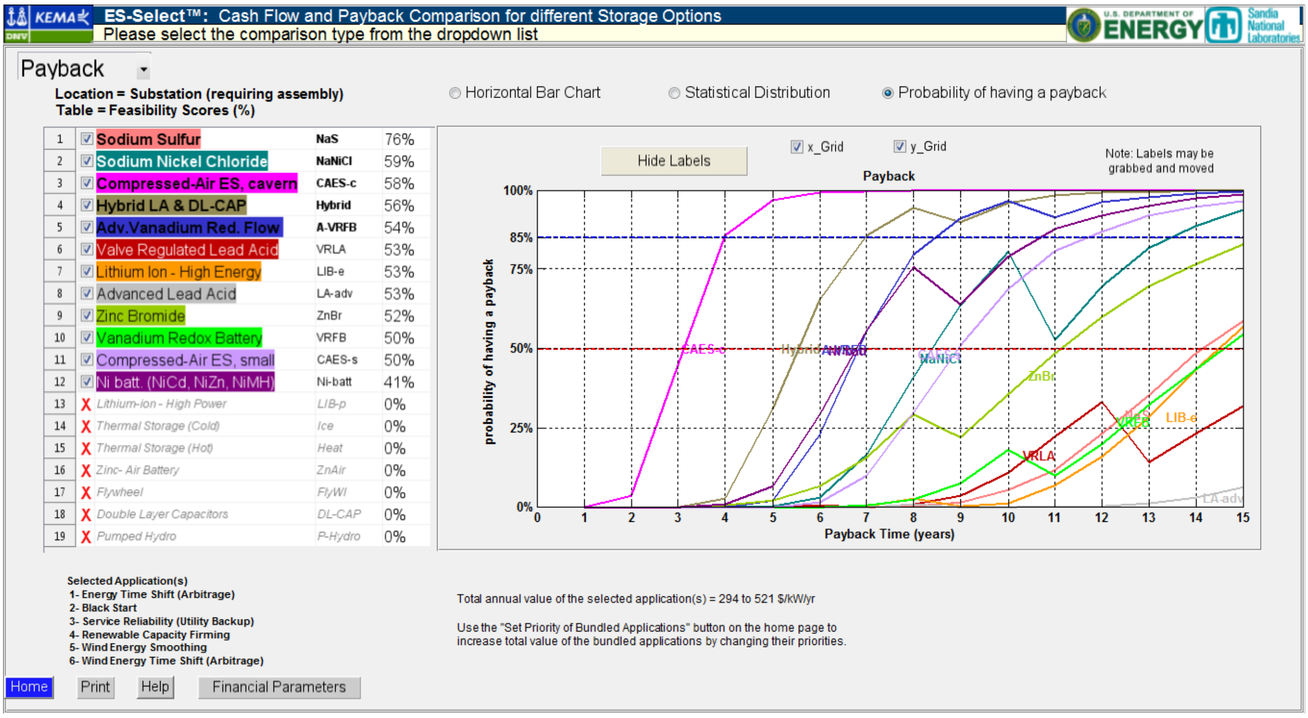


Figure 4.16: The probability of having a payback in any given year within the storage lifetime time on transmission grid location

There is a high probability of payback time occurrence of CAES-c already between years 4-5, for Hybrid between years 6-7 and for P-Hydro between years 7-8 as illustrated in Figure 4.17. NaNiCl shows a probability of payback time occurrence between years 10 and 12.

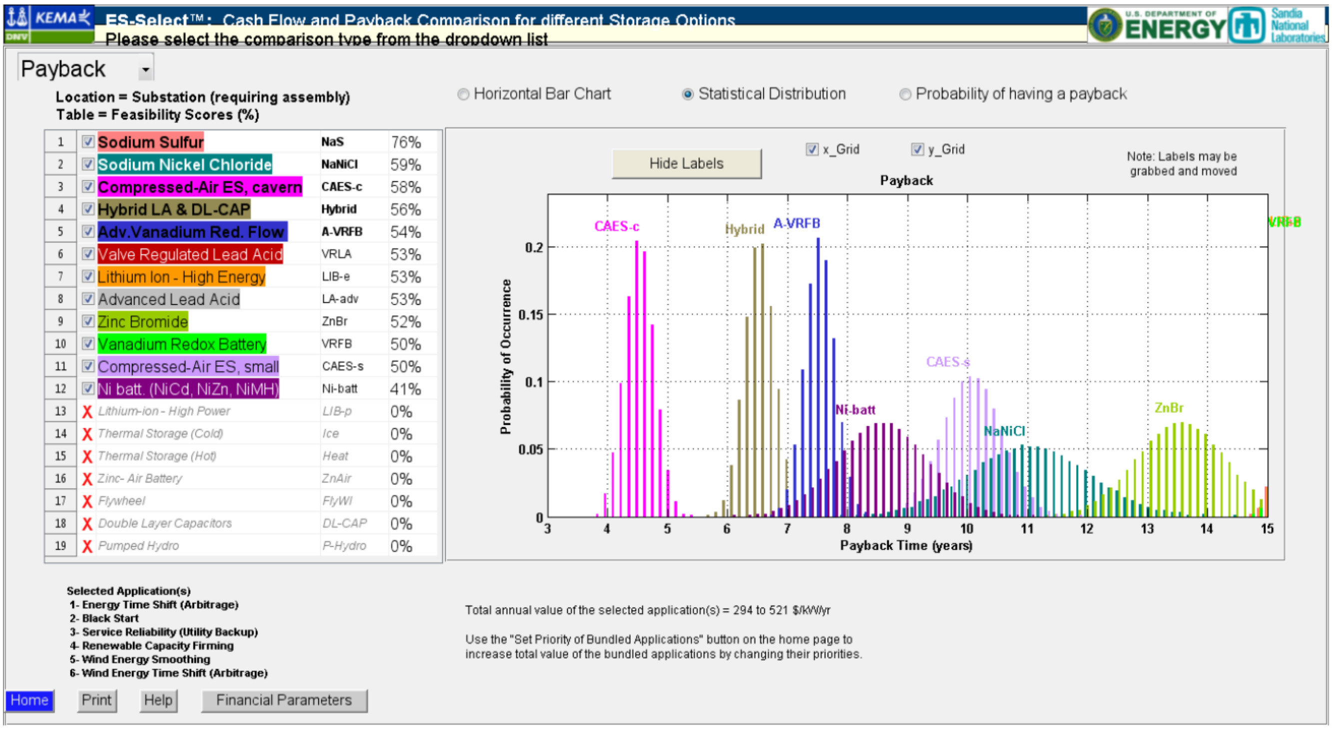


Figure 4.17: Statistical distribution of payback years of storage options on transmission grid location

Considering the above figures, for energy storage options up to 10MW, NaS is rejected due to the low probability of having a payback. NaNiCl, coming second, seems to be the best-fit storage option as it has a 59% feasibility score and above 85% probability of having a payback in the next 15 years. The storage capacity of a 1,06 MW NaNiCl battery is 1.934 MWh / year and the energy we need to store is about 61.372 MWh/year so 31 batteries of this type seem to be the best option.

4.5.3. Case C

Step 1: Distribution / Up to 2 MW (container/CES fleet)

Step 2

Application
1. Power quality (Utility)
2. Energy time shift (Arbitrage)
3. Service reliability (Utility backup)
4. Renewable capacity firming
5. Wind energy smoothing
6. Wind energy time shift (Arbitrage)

Step 3

The Total bundle value that comes from this set of applications is 363 to 602 $/kW/y.

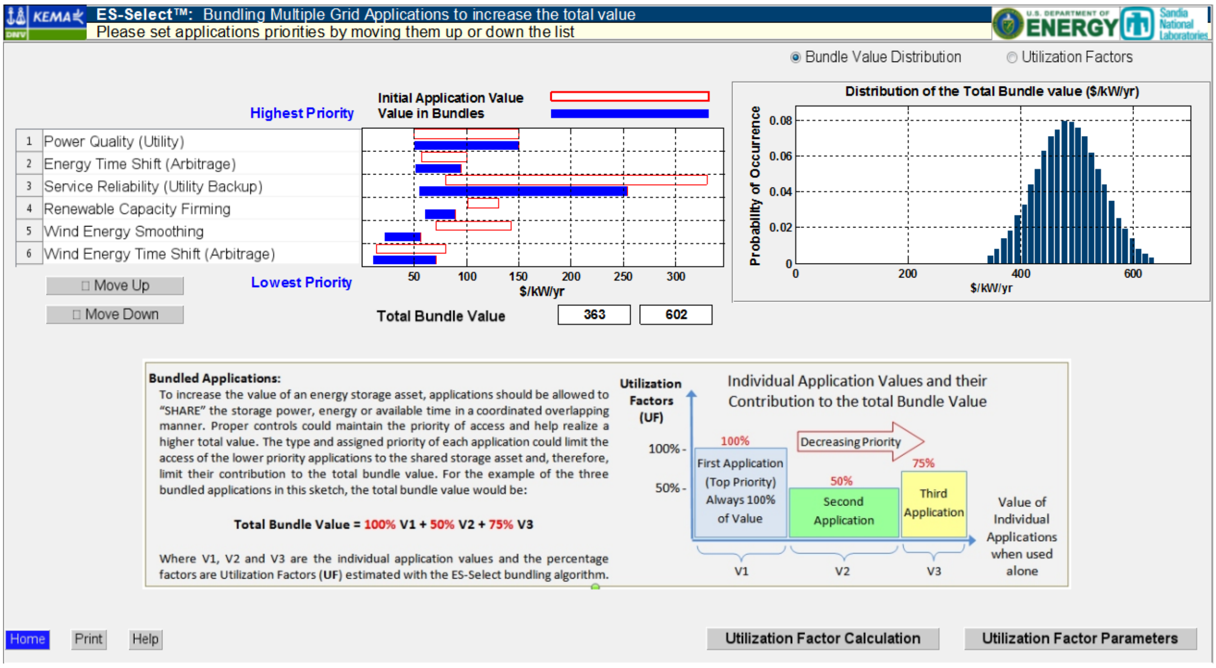


Figure 4.18: Total bundle value calculation for distribution grid location

Step 4

The best-fit energy storage technologies located next to distribution (up to 2MW) are NaNiCl with a total feasibility score of 63%, Hybrid with 58% and LIB-e with 55%. Figure 4.19 illustrates the individual scores of meeting application and location requirements, commercial maturity and total cost on commercial and industrial grid location, which form the total distribution feasibility score.

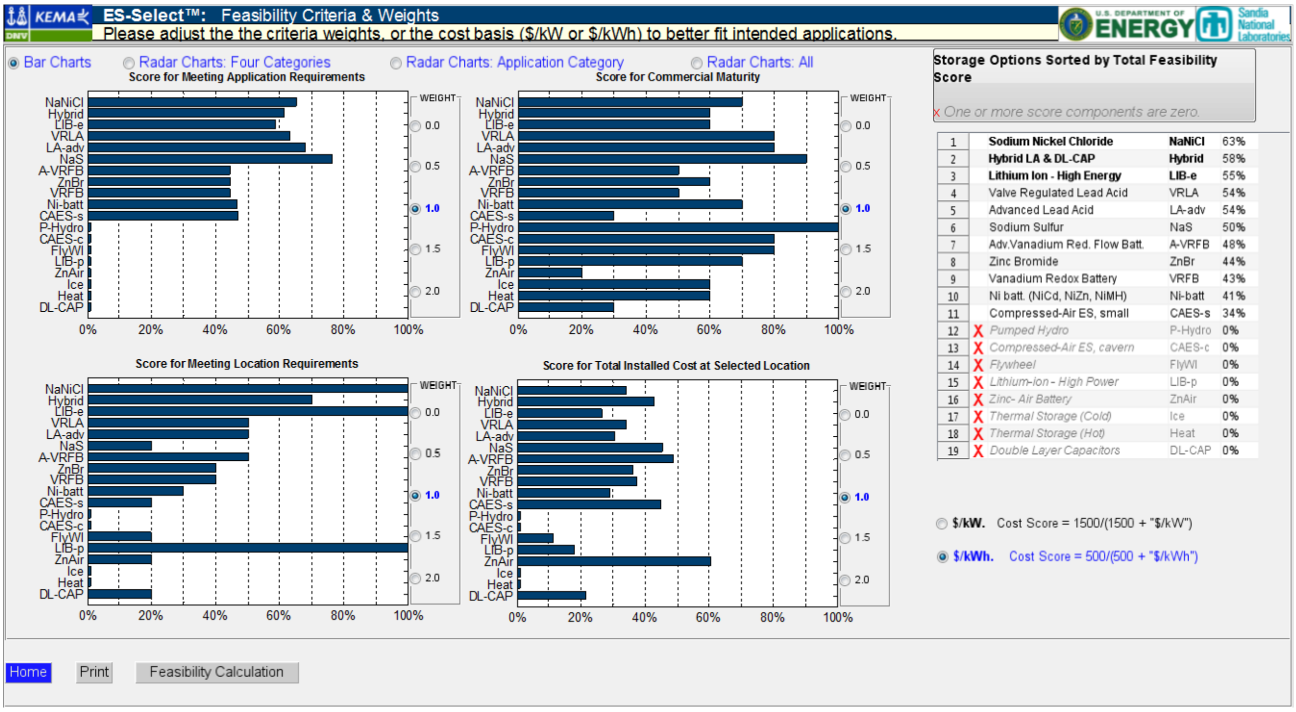


Figure 4.19: Feasibility Page listing storage option with their individual Feasibility Scores for distribution grid location

All storage options sorted by total feasibility score shown in Figure 4.20.

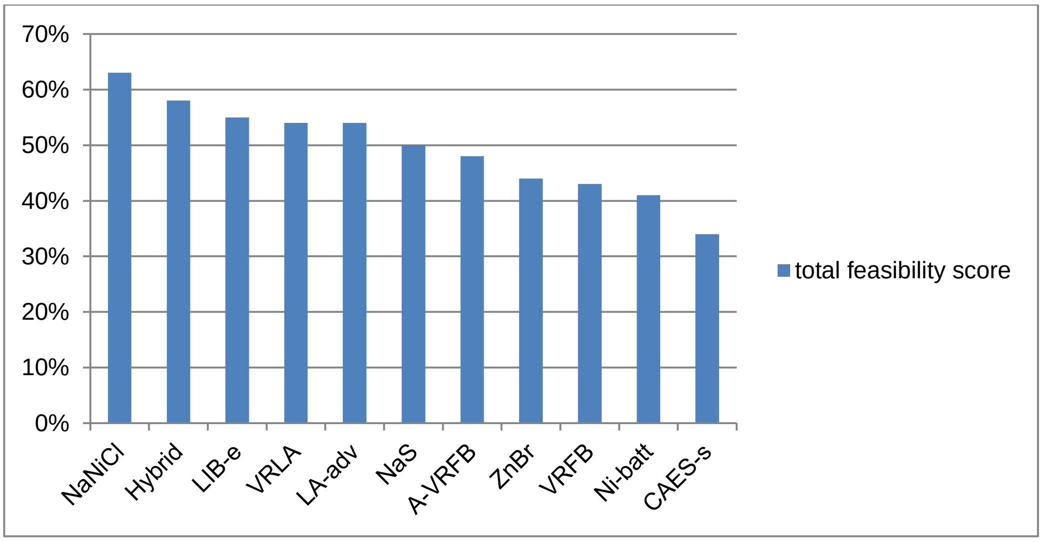


Figure 4.20: Storage options sorted by total feasibility score on distribution grid location

Many technologies are likely to have a payback in the next 15 years as ES Select estimates the probability of having a payback for these technologies over 85% as illustrated in the following figure.

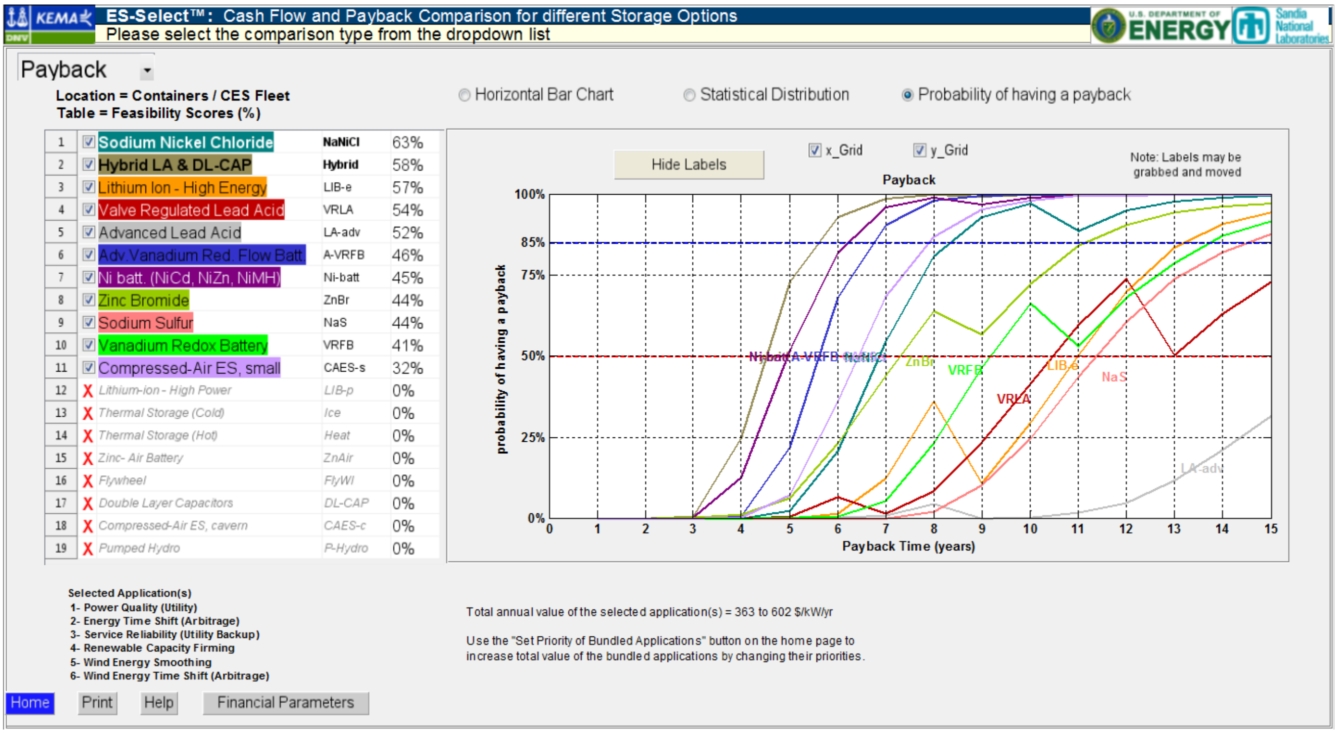


Figure 4.21: The probability of having a payback in any given year within the storage lifetime time on distribution grid location

There is a high probability of payback time occurrence of Hybrid already between years 5-6, for A-VRFB between years 6-7 and for NaNiCl, which has the highest feasibility score, between years 7-8 as illustrated in figure 4.22.

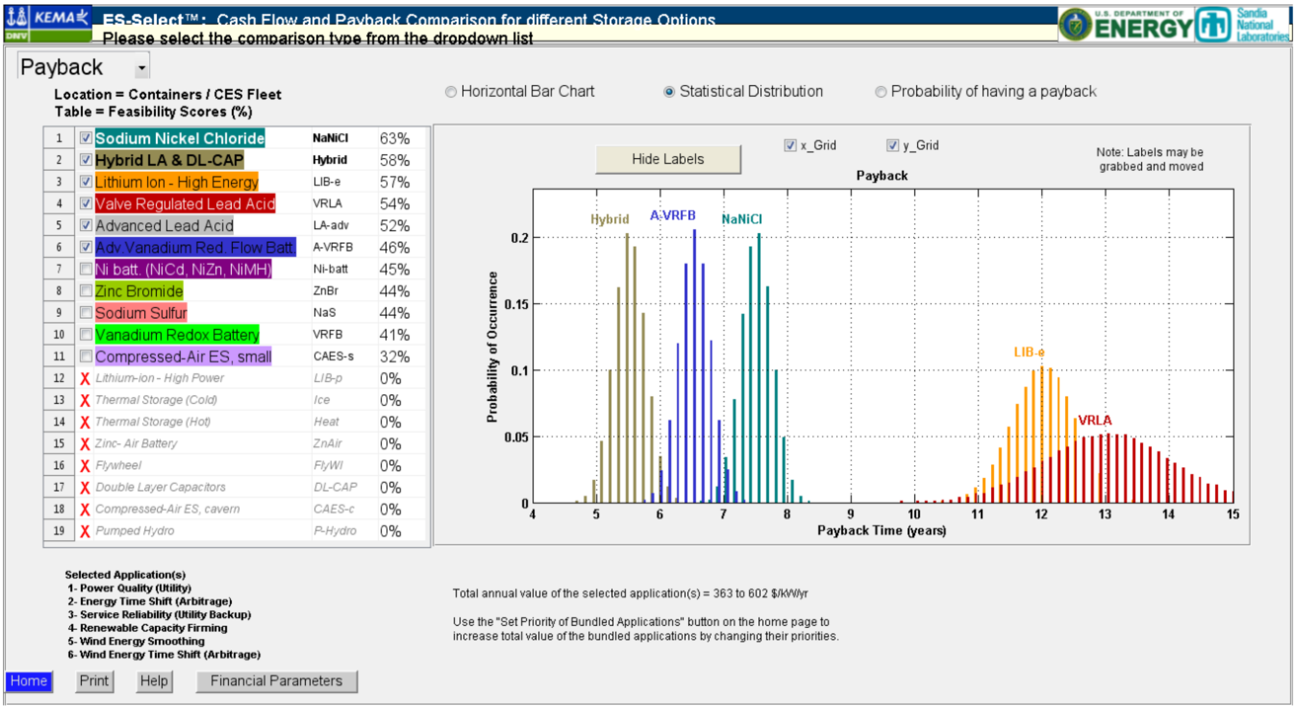


Figure 4.22: Statistical distribution of payback years of storage options on distribution grid location

Considering the above figures, for energy storage options up to 2MW, NaNiCl seems to be the best-fit storage option as it has 63% feasibility score and above 85% probability of having a payback in the next 15 years. The storage capacity of a 1,06MW NaNiCl battery is 1.934MWh / year, so 31 units storing 59.954 MWh/year could be a possible solution.

4.5.4. Case D

Step 1: Commercial-industrial / Up to 1 MW

Step 2

Application
1. Power quality (Customer)
2. Energy time shift (Arbitrage)
3. Renewable capacity firming
4. Retail TOU energy charges
5. Wind energy smoothing
6. Wind energy time shift (Arbitrage)

Step 3

The Total bundle value that comes from this set of applications is 455 to 597$/kW/y.

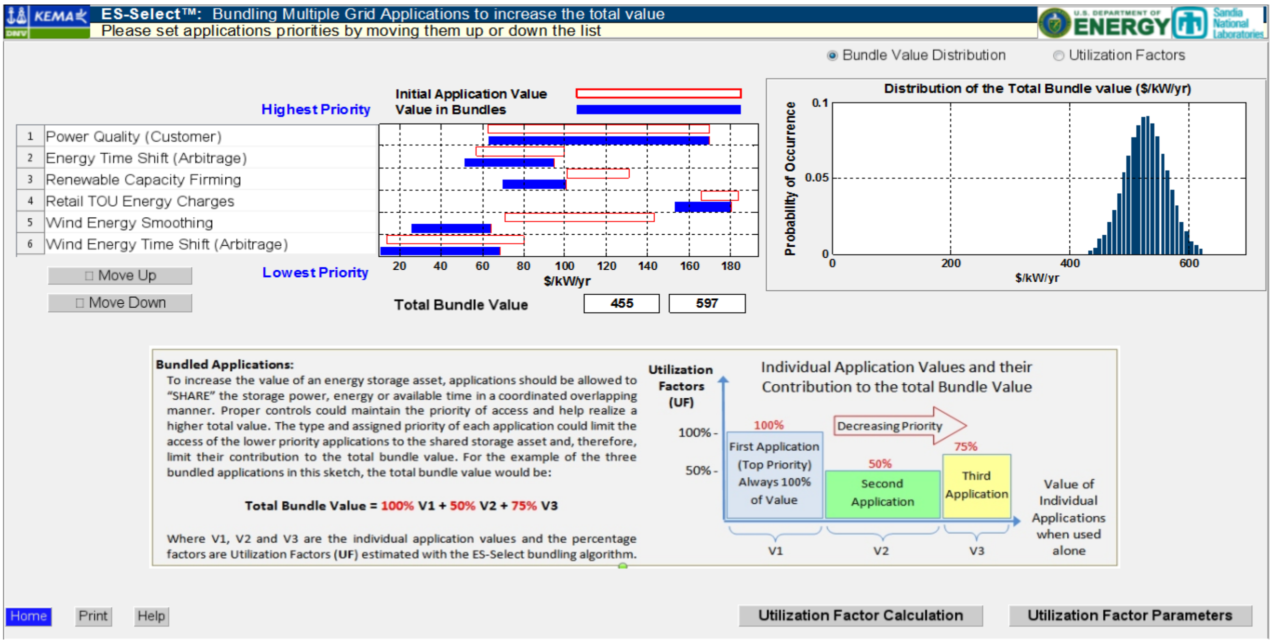


Figure 4.23: Total bundle value calculation for commercial-industrial grid location

Step 4

The best-fit energy storage technologies located for commercial use (up to 1MW) are NaS with a total feasibility score of 77%, NaNiCl with 63% and VRLA with 62%. Figure 4.24 illustrates the individual scores of meeting application and location requirements, commercial maturity and total cost on commercial and industrial grid location, which form the total feasibility score.

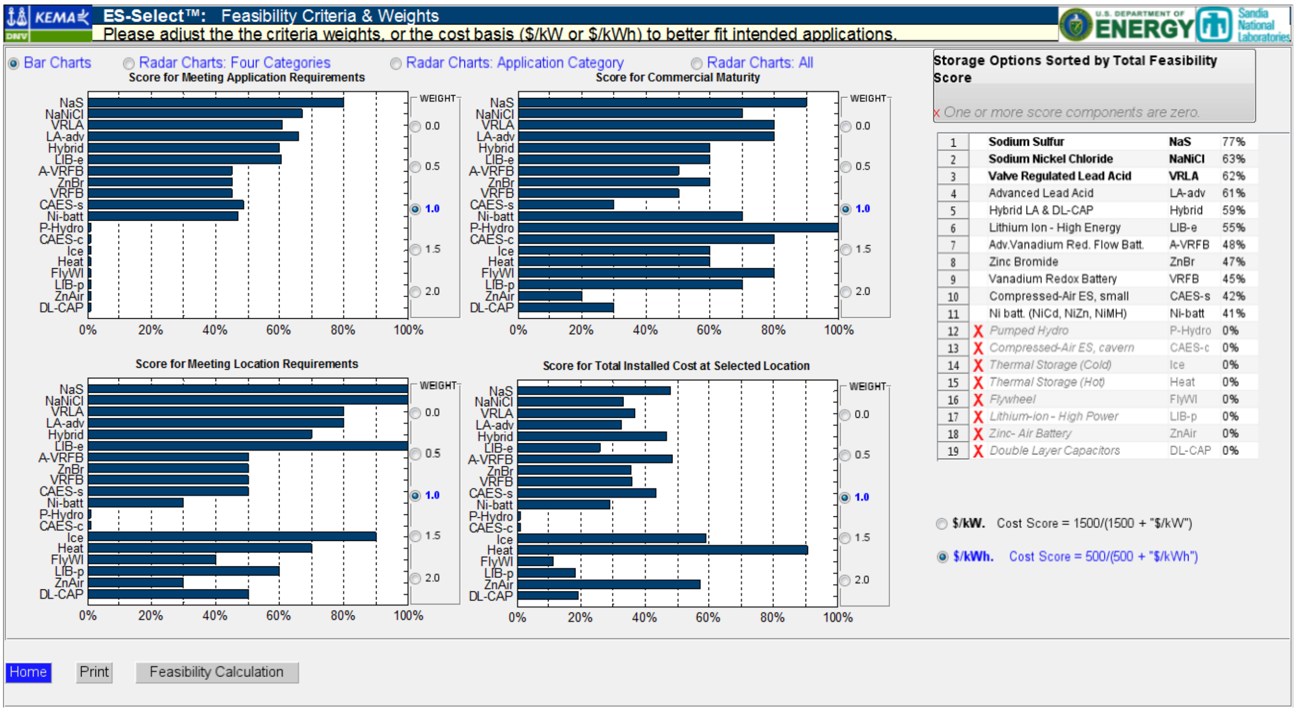


Figure 4.24: Feasibility Page listing storage option with their individual Feasibility Scores for commercial-industrial grid location

All storage options sorted by total feasibility score shown in Figure 4.25.

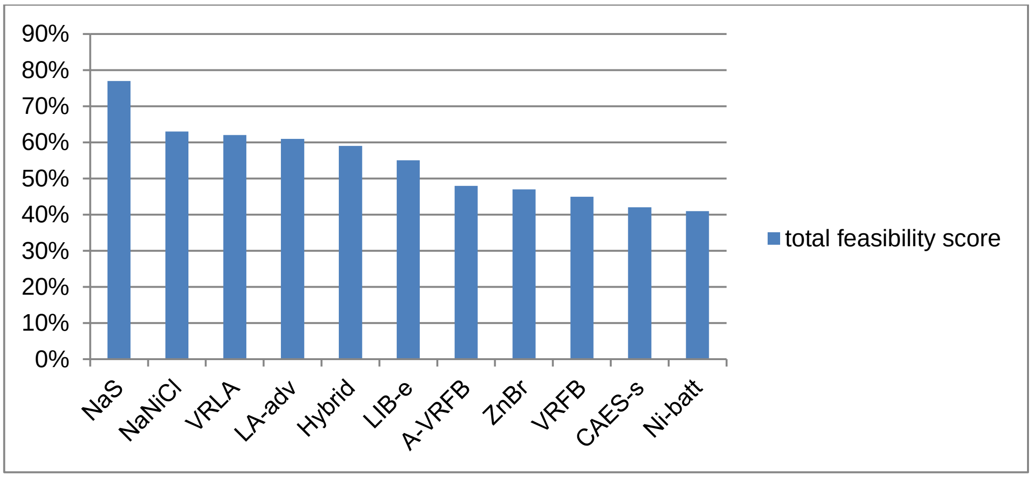


Figure 4.25: Storage options sorted by total feasibility score on commercial-industrial grid location

Many technologies are likely to have a payback in the next 15 years as ES Select estimates the probability of having a payback for these technologies over 85% as illustrated in the following figure.

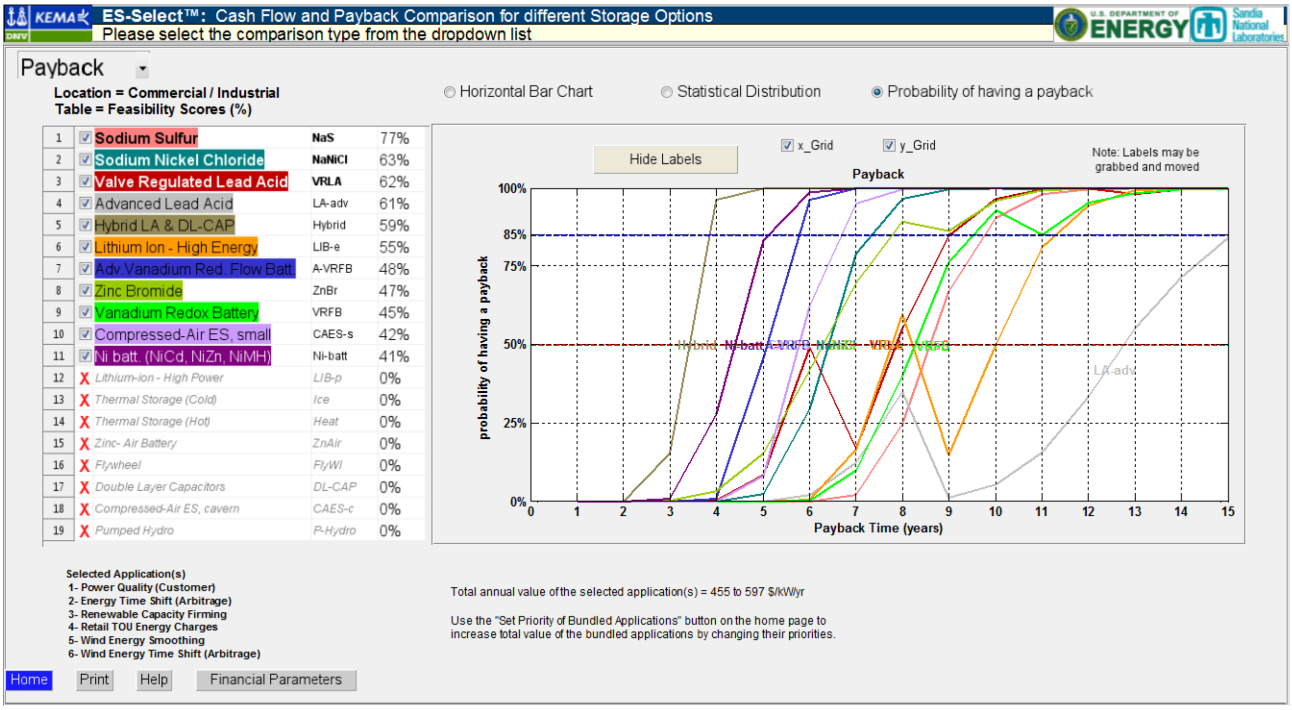


Figure 4.26: The probability of having a payback in any given year within the storage lifetime time on commercial-industrial grid location

There is a high probability of payback time occurrence of Hybrid already between years 4-5, for NaNiCl between years 7-8 and for NaS, which has the highest feasibility score, between years 9-10 as illustrated in figure 4.27.

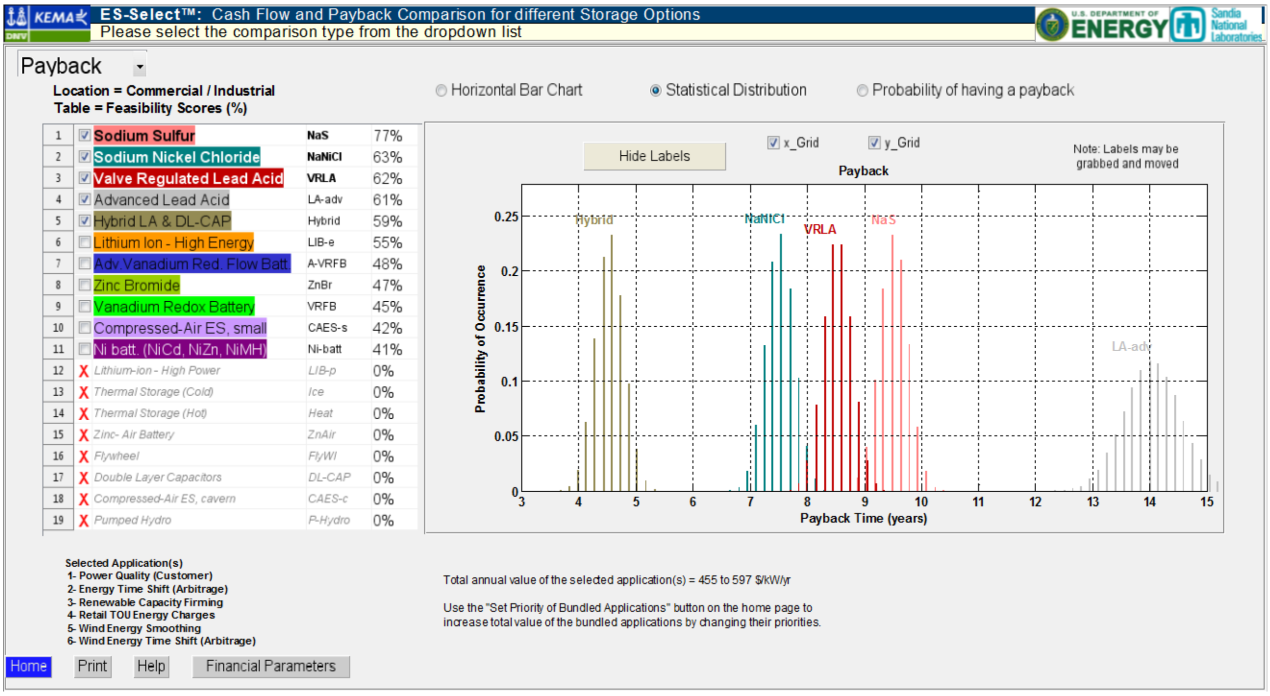


Figure 4.27: Statistical distribution of payback years of storage options on commercial-industrial grid location

Considering the above figures, for energy storage options up to 1MW, NaS seems to be the best-fit storage option as it has 77% feasibility score and above 85% probability of having a payback in the next 15 years. The storage capacity of an 1MW NaS battery is 2.628 MWh / year, so 23 units storing 60.444 MWh/year could be a possible solution.

4.5.5. Technology proposals for each case

All the results from chapter 4.5 are cited in table 4.9

Table 4.9: Proposed technologies' characteristics for each case

Case	Location	ES technology	Capacity (MW)	Number of Units	Energy Capacity (MWh/year)	Feasibility score (%)	Payback time (years)
A	**Central or bulk storage**	NaNiCl	10,6	3	58.035	43	9-11
B	**Transmission**	NaNiCl	1,06	31	59.954	59	10-12
C	**Distribution**	NaNiCl	1,06	31	59.954	63	7-8
D	**Commercial-industrial**	NaS	1,00	23	60.444	77	9-10

5. Conclusions

5.1 Summary

This thesis looks at the exploitation of the large wind potential of Crete by installing energy storage technologies which store wind energy replacing energy produced by fossil fuels. This results in cost-effective energy production and reduced emissions to the environment. The study is composed of 2 parts, the possible additional energy production and the selection of appropriate energy storage technology to store this energy.

In chapter 4.1 we calculate the possible additional energy that would be produced in case that the 34 wind farms installed on the island of Crete would operate 24 hours a day. Energy data and wind data are available for those wind farms so we calculate the possible additional energy during 2017 concluding that it would be about 61.372 MWh per year.

The next step is to find an energy storage technology that could store this amount of energy successfully. We choose 2 different tools, Energy Storage Computational Tool and ES Select tool so as to compare the results.

Energy Storage Computational Tool gives the user the ability to select between 3 different locations for the energy storage deployment and up to 3 applications are available. We run this tool for 2 different locations, generation and distribution, selecting the available set of applications and in each case. 13 different energy storage technologies are assessed in each case, with $ZnBr_2$ (10.000 kW) replacing combustion turbine having the highest benefit/cost ratio (0,003) in distribution grid location and $ZnBr_2$ (1.000 kW) replacing combustion turbine having the highest benefit/cost ratio (0,474) in generation grid location. In both cases, the benefit/cost ratio is under 1 which means that none technology would have a payback in the next 15 years.

ES Select gives the user the ability to select between 5 different locations for the energy storage deployment and up to 6 applications can be chosen in each case. We run this tool for 4 different locations (generation, transmission, distribution, commercial & industrial) selecting the same sets of 3 applications as for the corresponding locations in ESCT. Generation grid location in ESCT refers to the same location as generation and transmission grid locations in ES Select. The same happens with distribution grid location in ESCT and distribution and commercial&industrial grid locations in ES Select. ES Select also shows that none technology would be beneficial so we conclude that both tools end up to the same result.

As mentioned above, ES Select gives the user the ability to combine up to 6 applications, so in chapter 4.4 we run the tool for 4 different locations selecting sets of 6 applications in each case.

For energy storage devices with a capacity over 10 MW, located on the generation grid, the best fit storage technology is NaNiCl, with a total feasibility score of 43% and above 85% payback probability until 2032. P-Hydro seems to be the storage option that has the highest feasibility score (73%) and above 85% probability of having a payback in the next 15 years but it is capable of discharge times in tens of hours, with correspondingly high sizes (above 280MW) and has the ability to store more than 800.000 MWh/year. This amount of energy exceeds our needs for the island of Crete and the same happens with CAES-c and NaS for bulk storage applications. LIB-e coming 4th shows a low probability of having a payback so NaNiCl, the technology coming 5th, is available at the size of 10,6 MW for bulk storage with a capacity of 19.345 MWh/year. So 3 batteries of this type could be a solution.

For energy storage devices with a capacity under 10 MW, located on the transmission grid, the storage technology with the highest feasibility score is the NaS but it is rejected as it has no foreseen payback until 2032. Therefore, NaNiCl coming 2nd, seems to be the best-fit storage option as it has 59% feasibility score and above 85% probability of having a payback in the next 15 years. The reason for the decrease in the total feasibility is the high installation cost at the transmission grid. The storage capacity of a 1,06 MW NaNiCl battery is 1.934,5MWh / year and the energy we need to store is about 61.372 MWh/year so 31 batteries of this type seem to be the best option.

For energy storage devices with a capacity under 2 MW, located on the distribution grid, the best-fit storage technology is again NaNiCl as it has the highest feasibility score (63%) and above 85% probability of having a payback in the next 15 years. Hybrid LA & DL-CAP and LIB-e have lower total feasibility scores due to low scores for commercial maturity. The storage capacity of a 1,06MW NaNiCl battery is 1.934MWh / year, so 31 units storing 61.372 MWh/year could be a possible solution.

For energy storage devices with a capacity under 1 MW, located on the commercial grid, the best-fit storage technology is NaS with 77% feasibility score and above 85% probability of having a payback in the next 15 years. NaNiCl and VRLA, despite having a high probability of payback occurrence in the next 15 years, their feasibility score is lower due to lower scores for commercial maturity and total installed cost. The storage capacity of a 1MW NaS battery is 2.628 MWh / year, so 23 units storing 60.444 MWh/year could be a possible solution.

5.2 Comparison with other studies

There are other studies on energy storage systems, as mentioned in chapter 2, in which ES Select tool and ESCT are used for the techno-economic assessment of energy storage technologies. Of course, each study defers on the amount of energy for storage, economic assumptions, location restrictions and applications selected. Taking those into consideration, we cite the following tables with the results of some studies, including ours, utilizing ES Select.

Table 5.1 refers to the technologies with the highest feasibility score and table 5.2 refers to the technologies with the highest probability of having a payback in the lifetime of the deployment.

Table 5.1: Technologies with the highest feasibility score per study utilizing ES Select

Location	Electric Energy Storage Assessment in Crete	Techno-Economic Energy Storage Assessment in Denmark 2030	Potential of Energy Storage Technologies for Electrical Power System in Kuwait	Feasibility Analysis of Energy Storage Technologies in Power Systems for Arid Region
Central or bulk storage	P-Hydro	P-Hydro	P-Hydro	P-Hydro
Transmission	NaS	NaS	NaS	NaS
Distribution	NaNiCl	NaNiCl	NaNiCl	-
Commercial-industrial	NaS	NaS	NaS	-

Table 5.2: Technologies with the highest probability of having a payback per study utilizing ES Select

Location	Electric Energy Storage Assessment in Crete	Techno-Economic Energy Storage Assessment in Denmark 2030	Potential of Energy Storage Technologies for Electrical Power System in Kuwait	Feasibility Analysis of Energy Storage Technologies in Power Systems for Arid Region
Central or bulk storage	CAES-c	Hybrid	CAES-c	CAES-c
Transmission	CAES-c	Hybrid	NaS	NaS
Distribution	Hybrid	Hybrid	NaNiCl	-
Commercial-industrial	Hybrid	Thermal storage in heat	NaS	-

Table 5.1 shows that, despite the different limitations, all studies conclude to the same technologies according to the feasibility score criteria while table 5.2 shows some differentiations in the technologies preferred according to the probability of having payback criteria.

6. Final comments

6.1. Limitations

Given the generic nature of the benefit estimates, for particular projects or situations more circumstance-specific and detailed evaluation using new assumptions and data could be necessary. This may lead to minor deviations in the estimates, which are however, most likely covered in the assumed interval between low and high input values in the ES-Select database and handled through the Monte Carlo method.

The assessment does not take account of any possible extreme events and technology breakthroughs, as it is limited solely to the ES-Select and ESCT framework and input data. This means, for example, that rapid technological development causing the creation of new technologies with unpredictably decreased costs is not reflected in the presented results.

Furthermore, Pumped hydro, which is the most deployed globally energy storage technology and Compressed Air ES cavern which had high feasibility score in bulk storage, was omitted from the assessment, due to their high sizes (above 130MW) and their ability to store much more energy than our needs for the island of Crete.

Given the fact that the ES-Select algorithm is not publicly shared, in some cases it may be challenging to fully interpret the results from the model and especially their causes. The list of parameters and equations from the model user manual (Appendix C) does not seem to sufficiently cover all necessary computations for the estimation of the feasibility factor and payback probability.

The ES-Select model does not consider benefits that accrue to the society at large, as for example reduced need for equipment and land, reduced reliance on fossil fuels and increase in energy security, reduced air emissions, enabling superior value from Smart Grids, improved business productivity due to improved electric service reliability and power quality, etc. Robust consideration of the energy storage societal value proposition is as important as considering energy efficiency, demand side management, distributed resources and renewables.

6.2. Future work

In this Thesis, we investigate many cases combining different applications for increased value of the energy storage asset. All storage applications available in the ES-Select database with their definitions according to the Electric Power and Research Institute and Sandia National Laboratories can be found in Appendix A. Their relevance and best combination for the island of Crete could be further explored. When estimating the combined benefits for a value proposition, all potential operational conflicts and synergies between the combined applications must be considered. In addition, the fact that the benefits can accrue to different stakeholders simultaneously can be a challenge. For example, from the same storage application, benefits can accrue at specific electricity end users, utility ratepayers at large, utilities, merchant storage owners and the society. Moreover, the benefits of using bilateral contracts between wind generators and distributed storage owners, without using aggregators can be investigated.

ES-Select has the functionality of adding new storage applications and technologies, except for those included in the database, if data is available. This means that any unaddressed storage uses, not part of the database can be reflected. This function is particularly interesting in regards to the technology database, as it gives the opportunity to include also certainly relevant for Crete storage options with strategic importance not addressed in this assessment. Other benefits that could be addressed could be utility incentives, special tariffs and pricing approaches. Some utilities might provide incentives encouraging customers to install storage devices similar to those encouraging rooftop photovoltaic, demand response, and smart metering. Consequently, special tariffs might apply to customers reducing the utility costs.

For some cases, it might be needed to distinguish the benefits at different locations. Therefore, there are locational benefits that can be realized only if distributed storage is deployed. This is particularly relevant for areas where renewable energy is distributed (e.g. rooftop photovoltaic). Finally, the definition of the exact location of the energy storage deployment, which depends on the type of the energy storage technology, the analysis of the applications selected and the topography of Crete are issues that could be investigated in the future.

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8. Appendix

Appendix A: Definitions of Energy Storage Applications

Application 1 —Energy Time-shift (Arbitrage)

Price Arbitrage Electric energy time-shift means that storage can take advantage of the electricity price difference between on-peak and off-peak hour by purchasing and store energy at times when electricity price is low and selling it back to the grid when the price is higher.

Application 2 — Supply Capacity

System Capacity Energy storage could be used to defer the cost of installation of new power plant or to "rent" generation capacity in the wholesale electricity marketplace.

Application 3 — Load Following

Not modeled in the EPRI White Paper Energy storage could serve as load following capacity that adjusts its output to balance the generation and the load within a specific region or area.

Application 4 — Area Regulation

Area regulation is the use of on-line generation or storage which can change output quickly (MW/min) to track minute-to-minute fluctuations in loads and to correct for the unintended fluctuations in generation. It helps to maintain the grid frequency and to comply with Control Performance Standards (CPSs) 1 and 2 of the North American Reliability Council (NERC).

Application 5 — Fast Regulation

N/A Similar to "Area Regulation" with specific reference to FERC 755 for area regulation compensation.

Application 6 — Supply Spinning Reserve

Spinning Reserve capacity is the generation capacity that can be called upon in the event of a contingency such as the sudden, unexpected loss of a generator. 3 types of reserve capacities are: Spinning Reserve, Supplemental Reserve and Backup Supply.

Application 7 — Voltage Support

The purpose of voltage support is to maintain the grid voltage. Common method is to use resources like energy storage to inject or absorb reactive power (VAR) that offsets reactance in the grid.

Application 8 — Transmission VAR Support

VAR Support Energy storage could be used to enhance the transmission and distribution system performance by providing support during the event of electrical anomalies and disturbances such as voltage sag, unstable voltage, and sub-synchronous resonance.

Application 9 — Transmission Congestion Relief

Transmission congestion happens when shortage of transmission capacity to transmit power during periods of peak demand. When the transmission systems are becoming congested, congestion charges are usually applied and increased. Energy storage system would be installed to avoid the congestion related charges and cost. Energy could be stored during the off-peak hours, and be released during on-peak hours, when the transmission systems are congested.

Application 10 — Distribution Upgrade Deferral

Defer Distribution Investment Energy storage could be installed to defer the installation/upgrade of distribution lines and substations. The market is believed to be necessary due to the difficulty in siting power lines/substation, and then once sited, the cost of building the power lines/substation. Storage can be utilized to defer the need for the additional lines/substation.

Application 11 — Transmission Upgrade Deferral

Defer Transmission Investment Energy storage could be installed to defer the installation/upgrade of transmission lines and substations. The market is believed to be necessary due to the difficulty in siting transmission lines/substation, and then once sited, the cost of building the transmission lines/substation. Storage can be utilized to defer the need for the additional lines/substation.

Application 12 — Retail TOU Energy Charges

Retail TOU Energy Charges Energy storage could be used by end users (utility customers) to shift or reduce energy consumption at peak hours to reduce their overall cost for electricity. Energy is purchased at off-peak hours when electricity price is low, and then released at the on-peak hours when electricity price is high.

Application 13 — Retail Demand Charges

Retail Demand Charges Energy storage could be used by end users (utility customers) to reduce power consumption when demand charge is high to reduce their overall cost for electricity. Energy is purchased when demand charge do not apply or low, and then discharged when the demand charge do apply or high.

Application 14 — Service Reliability (Utility Backup)

This electric service reliability application focuses on the need for back-up power systems at the utility side of the electric meter. Usually, the facilities use a combination of batteries for ride-through of momentary outages and then have a diesel generator for longer duration outages.

Application 15 — Service Reliability (Consumer Backup)

This electric service reliability application focuses on the need for back-up power systems at Commercial and Industrial facilities. Usually, the facilities use a combination of batteries for ride-through of momentary outages and then have a diesel generator for longer duration outages.

Application 16 — Power Quality (Utility)

Power quality problem may cause a disoperation or failure of sensitive industrial equipment and critical commercial operations. Energy storage could be used at the utility side of the meter to improve power quality on the feeder for all customers against short-duration events such as harmonics, variation in voltage magnitude, and frequency and interruptions in service, et al.

Application 17 — Power Quality (Consumer)

Power quality problem may cause a disoperation or failure of sensitive industrial equipment and critical commercial operations. Energy storage could be used to improve power quality at end user side against short-duration events such as harmonics, variation in voltage magnitude, and frequency and interruptions in service et al.

Application 18 — Wind Energy Time Shift (Arbitrage)

This is a subset of Energy Time Shift (arbitrage). Renewable resources are unpredictable and do not align with typical peak load patterns. Wind production tends to peak during the evening and morning hours when load is at a low and ebbs during daytime hours when load is at a maximum. Having a storage device with durations of 4-6 hours can provide a tremendous advantage to renewable efficiencies, easing of grid impacts, and renewable production. The device will be able to (a) store and discharge renewable generation from low cost periods to high cost periods, (b) provide transmission relief for wind farms. Wind farms infrastructure is typically not sized to maximum output of the farm, storage can capture energy that would be typically dumped in these cases and increase wind farm capacity factor.

Application 19 — Solar Energy Time Shift (Arbitrage)

Price Arbitrage This is a subset of Energy Time Shift (arbitrage). Renewable resources are unpredictable and don't align with typical peak load patterns. Solar production tends to peak at or before noon when load is at a low and ebbs during the afternoon hours when load is at a maximum. Having a storage device with durations of 3-4 hours can provide a tremendous advantage to renewable efficiencies, easing of grid impacts, and renewable production. The device will be able to (a) store and discharge renewable generation from low cost periods to high cost periods, (b) provide transmission relief for solar farms.

Application 20 — Renewables Capacity Firming

The objective of renewable capacity firming is to make the generation output somewhat constant. Storage could be used to store wind and solar power during hours of peak production regardless of demand, and discharge to supplement traditional generation when renewable output reduces during expected generation time.

Application 21 — Wind Energy Smoothing

Renewable Energy Integration Short duration intermittency from wind generation is caused by variation of wind speed that occurs throughout the day. Storage could be used to manage or mitigate the less desirable effects from high wind generation penetration. For example, wind farms are beginning to be faced with specific requirements in order to interconnect their devices to the grid. This requirement comes from utility interconnections and well as the power purchase requirements, which can apply penalties to the developers if certain ramping (2%) requirements are not met. Storage can be applied to smooth wind output and offset these requirements.

Application 22 — Solar Energy Smoothing

Renewable Energy Integration Shading caused by terrestrial obstructions such as clouds and trees. As a cloud passes over solar collectors, power output from the affected solar generation system drops. This rate of change could be quite rapid. Solar farms, in some cases, are beginning to be faced with specific requirements in order to interconnect their devices to the grid. This requirement comes from utility interconnections and well as the power purchase requirements, which can apply penalties to the developers if certain ramping (2%) requirements are not met. Storage can be applied to smooth solar output and offset these requirements. Electric energy time-shift means that storage can take advantage of the electricity price difference between on-peak and off-peak hour by purchasing and store energy at times when electricity price is low and selling it back to the grid when the price is higher.

Application 23 — Black Start

A black start is the process of powering up a generating (power) plant when the grid power is not available such as in blackouts. Black start uses the power from the generators inside the plant that are often started by small diesel generators. These small diesel generators can be replaced with energy storage devices.

Appendix B: ES Select database inputs

ES-Select™: View and Edit Storage Database

You can view parameter groups from the drop-down list, or add a new technology to the database.

Characteristics

	Storage Technology	Abbreviations	Discharge Duration (hours) LO	Discharge Duration (hours) HI	Specific Energy (kWh/ton-metric) LO	Specific Energy (kWh/ton-metric) HI	Energy Density (kWh/m^3) LO	Energy Density (kWh/m^3) HI	Round Trip AC Energy Efficiency at Rated Power and 80% DoD LO	Round Trip AC Energy Efficiency at Rated Power and 80% DoD HI	Response time to full power	Footprint (m^2/MWh) LO	Footprint (m^2/MWh) HI
1	Lithium-ion - High Power	LIB-p	0.2500	1	60	90	60	90	0.8400	0.9100	ms	40	60
2	Lithium Ion - High Energy	LIB-e	1	4	80	120	90	130	0.8500	0.9200	ms	18	26
3	Ni batt. (NiCd, NiZn, NiMH)	Ni-batt	0.3000	3	50	90	40	210	0.7000	0.8000	ms	26	93
4	Advanced Lead Acid	LA-adv	2	5	18	30	30	70	0.8000	0.9000	ms	33	45
5	Valve Regulated Lead Acid	VRLA	2	4	18	25	30	60	0.6800	0.7800	ms	25	35
6	Vanadium Redox Battery	VRFB	3	5	8	11	15	21	0.5800	0.6800	ms	37	55
7	Adv.Vanadium Red. Flow Batt.	A-VRFB	3	6	17	21	25	30	0.6500	0.7000	ms	17	33
8	Zinc Bromide	ZnBr	2	4	30	50	30	45	0.6200	0.7000	ms	9	19
9	Sodium Sulfur	NaS	6	7	80	140	100	170	0.7300	0.8000	ms	4	5
10	Sodium Nickel Chloride	NaNiCl	2	4	100	150	170	190	0.8200	0.8700	ms	8	11
11	Thermal Storage (Cold)	Ice	4	7	10	20	10	20	0.9000	1	sec	108	135
12	Thermal Storage (Hot)	Heat	4	9	150	160	110	130	0.9100	0.9800	sec	11	13
13	Zinc- Air Battery	ZnAir	5	6	130	170	300	500	0.6500	0.7700	ms	5	6
14	Flywheel	FlyWl	0.0300	1	5	12	5	15	0.8400	0.8600	ms	530	670
15	Double Layer Capacitors	DL-CAP	0.0800	1.2000	2.3000	16	2.1000	15	0.9200	0.9700	ms	100	400
16	Hybrid LA & DL-CAP	Hybrid	0.5000	5	16	28	32	65	0.8200	0.8700	ms	65	150
17	Compressed-Air ES, cavern	CAES-c	8	10	NaN	NaN	NaN	NaN	0.6000	0.7000	min	NaN	NaN
18	Compressed-Air ES, small	CAES-s	3	5	NaN	NaN	NaN	NaN	0.6000	0.7000	sec	NaN	NaN

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Figure A.1: ES Select database inputs [Sandia National Laboratories, 2012]

ES-Select™: View and Edit Storage Database

You can view parameter groups from the drop-down list, or add a new technology to the database.

Cycles & Costs

	Storage Technology	Abbreviations	Cycle Life at 80% DoD (1,000 cycles) LO	Cycle Life at 80% DoD (1,000 cycles) HI	Cycle Life at 10% DoD (1,000 cycles) LO	Cycle Life at 10% DoD (1,000 cycles) HI	Annual Operational Losses over Equipment Rating (kWh/yr/kW) LO	Annual Operational Losses over Equipment Rating (kWh/yr/kW) HI	Annual maintenance or Warranty cost (often 0.5% - 1.5% of cost) ($/yr/kW) LO	Annual maintenance or Warranty cost (often 0.5% - 1.5% of cost) ($/yr/kW) HI	AC Storage Unit Price at Factory (Equipment Cost) ($/kW) LO	AC Storage Unit Price at Factory (Equipment Cost) ($/kW) HI
1	Lithium-ion - High Power	LIB-p	4	8	60	110	110	250	8	35	800	1200
2	Lithium Ion - High Energy	LIB-e	3.5000	7	50	100	120	250	7	25	2500	3500
3	Ni batt. (NiCd, NiZn, NiMH)	Ni-batt	1	3	1	3	150	500	2.2500	40.5000	1100	1900
4	Advanced Lead Acid	LA-adv	1.2000	2.4000	20	30	250	900	10	30	2200	3900
5	Valve Regulated Lead Acid	VRLA	0.6000	1	2	4	300	900	10	40	1600	2500
6	Vanadium Redox Battery	VRFB	6	8	160	200	300	875	9	15	2200	3100
7	Adv.Vanadium Red. Flow Batt.	A-VRFB	6	8	160	200	100	300	10	14	2000	2500
8	Zinc Bromide	ZnBr	1.5000	2.5000	15	25	570	670	10	30	1200	3000
9	Sodium Sulfur	NaS	5	6	40	50	200	625	15	60	2600	3100
10	Sodium Nickel Chloride	NaNiCl	3	5	50	100	85	145	10	22	2000	3000
11	Thermal Storage (Cold)	Ice	5.5000	11	5.5000	11	0	15	3	15	500	1300
12	Thermal Storage (Hot)	Heat	3.6000	3.8000	7.2000	7.5000	30	90	2	12	110	300
13	Zinc- Air Battery	ZnAir	5	10	10	20	540	750	15	40	1200	1400
14	Flywheel	FlyWl	100	200	170	200	750	850	35	50	1200	1600
15	Double Layer Capacitors	DL-CAP	100	200	100	200	80	250	8	10	600	1000
16	Hybrid LA & DL-CAP	Hybrid	5	17.5000	20	70	100	700	5	15	1000	1200
17	Compressed-Air ES, cavern	CAES-c	6	12	6	12	300	1000	3	12	700	1300
18	Compressed-Air ES, small	CAES-s	10	20	100	200	300	1000	1	4	1800	2100

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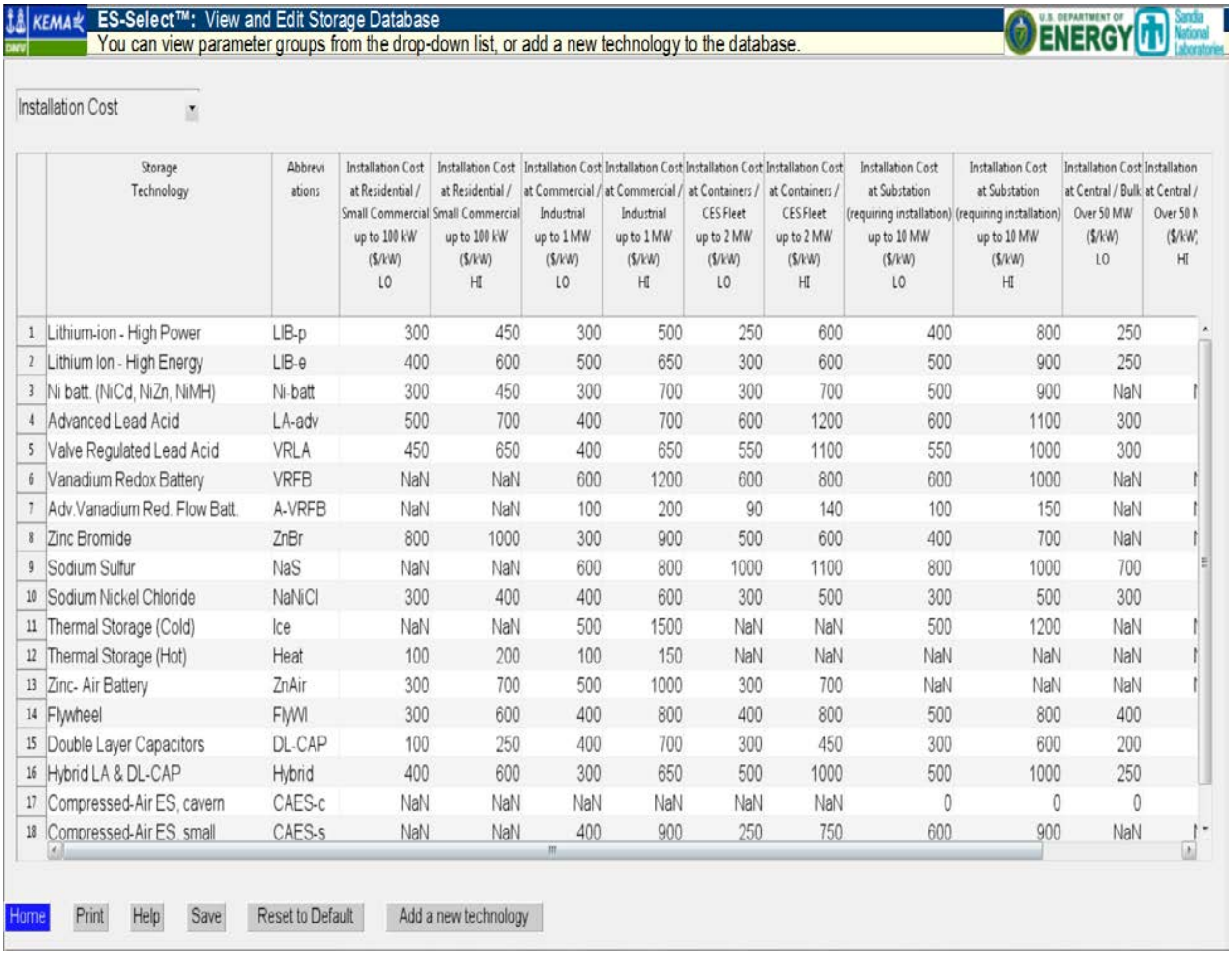
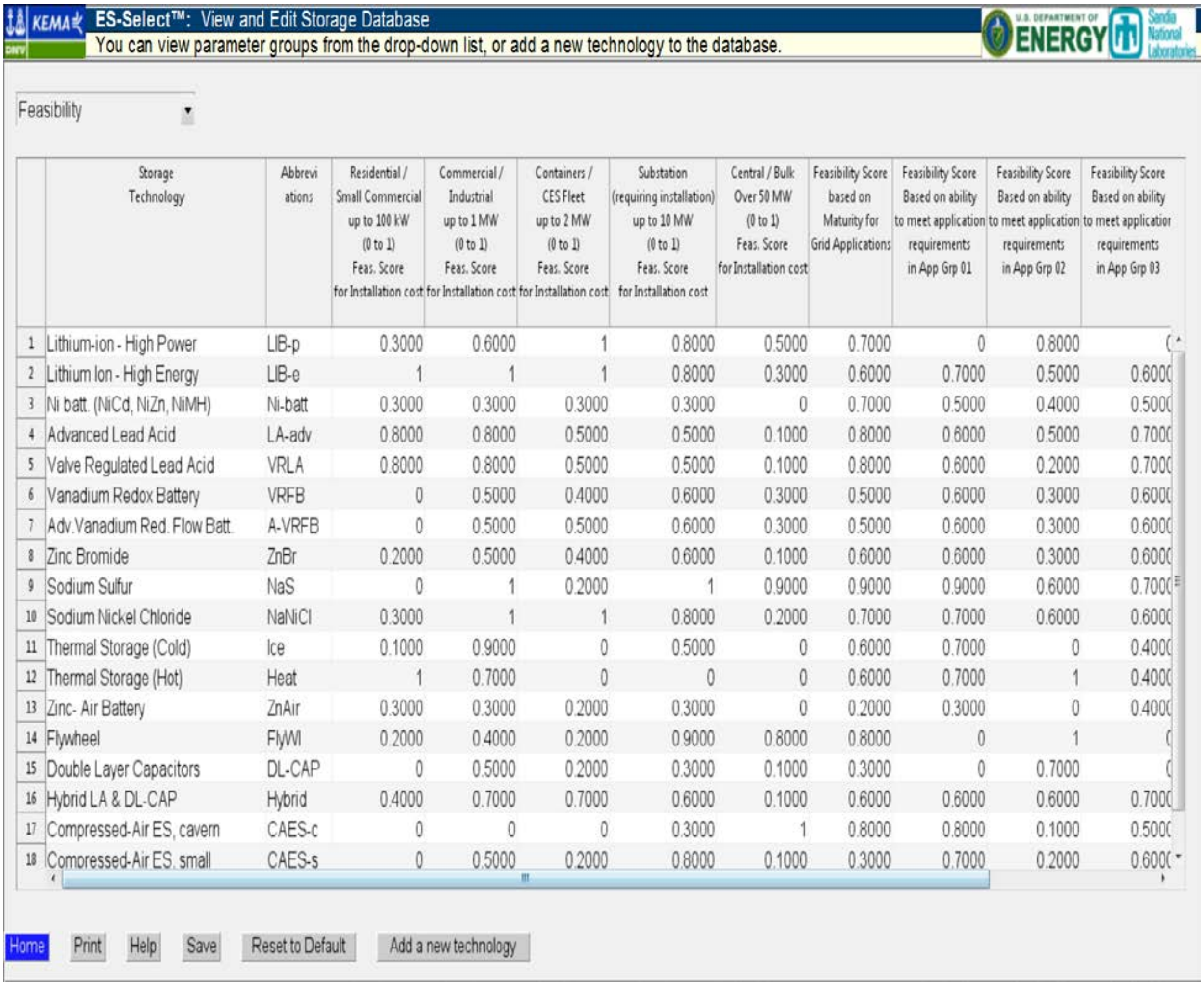
Figure A.2: ES Select database inputs [Sandia National Laboratories, 2012]



	Storage Technology	Abbreviations	Installation Cost at Residential / Small Commercial up to 100 kW ($/kW) LO	Installation Cost at Residential / Small Commercial up to 100 kW ($/kW) HI	Installation Cost at Commercial / Industrial up to 1 MW ($/kW) LO	Installation Cost at Commercial / Industrial up to 1 MW ($/kW) HI	Installation Cost at Containers / CES Fleet up to 2 MW ($/kW) LO	Installation Cost at Containers / CES Fleet up to 2 MW ($/kW) HI	Installation Cost at Substation (requiring installation) up to 10 MW ($/kW) LO	Installation Cost at Substation (requiring installation) up to 10 MW ($/kW) HI	Installation Cost at Central / Bulk Over 50 MW ($/kW) LO	Installation at Central / Over 50 N ($/kW HI
1	Lithium-ion - High Power	LIB-p	300	450	300	500	250	600	400	800	250	
2	Lithium Ion - High Energy	LIB-e	400	600	500	650	300	600	500	900	250	
3	Ni batt. (NiCd, NiZn, NiMH)	Ni-batt	300	450	300	700	300	700	500	900	NaN	N
4	Advanced Lead Acid	LA-adv	500	700	400	700	600	1200	600	1100	300	
5	Valve Regulated Lead Acid	VRLA	450	650	400	650	550	1100	550	1000	300	
6	Vanadium Redox Battery	VRFB	NaN	NaN	600	1200	600	800	600	1000	NaN	N
7	Adv.Vanadium Red. Flow Batt.	A-VRFB	NaN	NaN	100	200	90	140	100	150	NaN	N
8	Zinc Bromide	ZnBr	800	1000	300	900	500	600	400	700	NaN	N
9	Sodium Sulfur	NaS	NaN	NaN	600	800	1000	1100	800	1000	700	
10	Sodium Nickel Chloride	NaNiCl	300	400	400	600	300	500	300	500	300	
11	Thermal Storage (Cold)	Ice	NaN	NaN	500	1500	NaN	NaN	500	1200	NaN	N
12	Thermal Storage (Hot)	Heat	100	200	100	150	NaN	NaN	NaN	NaN	NaN	N
13	Zinc- Air Battery	ZnAir	300	700	500	1000	300	700	NaN	NaN	NaN	N
14	Flywheel	FlyWl	300	600	400	800	400	800	500	800	400	
15	Double Layer Capacitors	DL-CAP	100	250	400	700	300	450	300	600	200	
16	Hybrid LA & DL-CAP	Hybrid	400	600	300	650	500	1000	500	1000	250	
17	Compressed-Air ES, cavern	CAES-c	NaN	NaN	NaN	NaN	NaN	NaN	0	0	0	
18	Compressed-Air ES, small	CAES-s	NaN	NaN	400	900	250	750	600	900	NaN	N

Figure A.3: ES Select database inputs [Sandia National Laboratories, 2012]



	Storage Technology	Abbreviations	Residential / Small Commercial up to 100 kW (0 to 1) Feas. Score for Installation cost	Commercial / Industrial up to 1 MW (0 to 1) Feas. Score for Installation cost	Containers / CES Fleet up to 2 MW (0 to 1) Feas. Score for Installation cost	Substation (requiring installation) up to 10 MW (0 to 1) Feas. Score for Installation cost	Central / Bulk Over 50 MW (0 to 1) Feas. Score for Installation cost	Feasibility Score based on Maturity for Grid Applications	Feasibility Score Based on ability to meet application requirements in App Grp 01	Feasibility Score Based on ability to meet application requirements in App Grp 02	Feasibility Score Based on ability to meet applicatior requirements in App Grp 03
1	Lithium-ion - High Power	LIB-p	0.3000	0.6000	1	0.8000	0.5000	0.7000	0	0.8000	(
2	Lithium Ion - High Energy	LIB-e	1	1	1	0.8000	0.3000	0.6000	0.7000	0.5000	0.600(
3	Ni batt. (NiCd, NiZn, NiMH)	Ni-batt	0.3000	0.3000	0.3000	0.3000	0	0.7000	0.5000	0.4000	0.500(
4	Advanced Lead Acid	LA-adv	0.8000	0.8000	0.5000	0.5000	0.1000	0.8000	0.6000	0.5000	0.700(
5	Valve Regulated Lead Acid	VRLA	0.8000	0.8000	0.5000	0.5000	0.1000	0.8000	0.6000	0.2000	0.700(
6	Vanadium Redox Battery	VRFB	0	0.5000	0.4000	0.6000	0.3000	0.5000	0.6000	0.3000	0.600(
7	Adv.Vanadium Red. Flow Batt.	A-VRFB	0	0.5000	0.5000	0.6000	0.3000	0.5000	0.6000	0.3000	0.600(
8	Zinc Bromide	ZnBr	0.2000	0.5000	0.4000	0.6000	0.1000	0.6000	0.6000	0.3000	0.600(
9	Sodium Sulfur	NaS	0	1	0.2000	1	0.9000	0.9000	0.9000	0.6000	0.700(
10	Sodium Nickel Chloride	NaNiCl	0.3000	1	1	0.8000	0.2000	0.7000	0.7000	0.6000	0.600(
11	Thermal Storage (Cold)	Ice	0.1000	0.9000	0	0.5000	0	0.6000	0.7000	0	0.400(
12	Thermal Storage (Hot)	Heat	1	0.7000	0	0	0	0.6000	0.7000	1	0.400(
13	Zinc- Air Battery	ZnAir	0.3000	0.3000	0.2000	0.3000	0	0.2000	0.3000	0	0.400(
14	Flywheel	FlyWl	0.2000	0.4000	0.2000	0.9000	0.8000	0.8000	0	1	(
15	Double Layer Capacitors	DL-CAP	0	0.5000	0.2000	0.3000	0.1000	0.3000	0	0.7000	(
16	Hybrid LA & DL-CAP	Hybrid	0.4000	0.7000	0.7000	0.6000	0.1000	0.6000	0.6000	0.6000	0.700(
17	Compressed-Air ES, cavern	CAES-c	0	0	0	0.3000	1	0.8000	0.8000	0.1000	0.500(
18	Compressed-Air ES, small	CAES-s	0	0.5000	0.2000	0.8000	0.1000	0.3000	0.7000	0.2000	0.600(

Figure A.4: ES Select database inputs [Sandia National Laboratories, 2012]

Appendix C: ES-Select Parameters and Equations

Table A.1: ES-Select Parameters and Equations [Sandia National Laboratories, 2012]

	Abb.	Parameters	Display Unit	Calculation	Comments
1	ACM	Annual Cost of Maintenance	$/y/kW	Input from Database	Normalized to the storage rated power
2	ACOL	Annual Cost of Operational Losses	$/y/kW	= AOL x CE/1000	
3	ADD	Required Application Discharge Duration	cycles	Input from Database	
4	AMP	Application Market Potential	GW	=1000 x Ec10 / PV10	

		in 10 years			
5	AnB	Annual Benefit	$/kW	Input from Database	
6	AnE	Annual Expenses	$/y/kW	= ACM + ACOL	Estimated operating expenses in $/y normalized to the storage rated power
7	AOL	Annual Operational Losses (of storage)	kWh/y/kW	Normalized to the storage rated power	
8	CE	Cost of Energy for charge	$/MWh	User input or default value	
9	CL10	Cycle Life at 10% depth of discharge	Cycles	Input from Database	
10	CL80	Cycle Life at 80% depth of discharge	Cycles	Input from Database	
11	CLC10	Storage Equipment cost per cycle at 10% dod.	Cents/kW	= SCw / CL10	See note for CLC80
12	CLC80	Storage Equipment cost per cycle at 80% dod.	cents/kW	= SCw / CL80	This is the capital cost per cycle the storage is used, regardless of the discharge duration
13	dod	Depth of Discharge	%	10% or 80% (from database)	
14	DR	Discount Rate	%/y	User input or default value	
15	EB	Escalation of Benefits	%/y	User input or default value	
16	Ec10	10-year Economy (total benefits)	$ billions	Input from Database	
17	EFF	AC roundtrip Energy efficiency	%	Input from Database	
18	FA	Storage Feasibility Score for meeting Application requirements	%	Input from Database	Different scores based on power, energy and frequency of use.
19	FC	Fixed Charge Rate	%/y	User input or default value	
20	FCh	Storage Feasibility Score for Cost in $/kWh	%	= 500 /(500 + SCh)	Based on the AC equipment

					cost in $/kWh
21	FCw	Storage Feasibility Score for Cost in $/kW	%	= 1500 /(1500+SCw)	Based on the AC equipment cost in $/kW
22	FL	Storage Feasibility Score for selected Location	%	Input from Database	Different scores for different location on the grid
23	FM	Storage Feasibility Score for Maturity	%	Input from Database	Commercial maturity based on whether it is experimental, prototype, pre commercial or fully commercial
24	InCw	Installation Cost	$/kW	Input from Database	Installation cost varies at different locations on the grid
25	InCh	Installation Cost	$/kWh	= InCw / SDD	
26	ISCh	Installed Storage Cost	$/kWh	= ISCw/ SDD	
27	ISCw	Installed Storage Cost	$/kW	= SCw + InCw	
28	LTC10	Storage Equipment cost per lifetime throughput energy at 10% dod.	cents/kWh	= SCw / LTE10	See note for LTC80
29	LTC80	Storage Equipment cost per lifetime throughput energy at 80% dod.	cents/kWh	= SCw / LTE80	This is a levelized cost of storage for total expected output energy to be delivered over its lifetime. This is based on storage ability to cycle energy whether it is actually used or not.
30	LTE80	Lifetime throughput energy	MWh/kW	= CL80 x SDD x 0.8	Unit is MWh normalized to

		at 80% dod			the equipment rated power (kW)
31	LTE10	Lifetime throughput energy at 10% dod	MWh/kW	= CL10 x SDD x 0.1	Unit is MWh normalized to the equipment rated power (kW)
32	PBK	Payback	years	Range of payback is defined as follows: LOW number = the year where probability of cumulative net cash flow is 50%. HIGH number = the year where probability of cumulative net cash flow is 85%.	
33	PE	Electricity Price Escalation	%/y	User input or default value	
34	PV( )	Present Value of …	PV calculation based on the financial parameters		
35	PV10	Present Value of 10-year benefits	$/kW	= PV(AnB)	
36	SCw	AC Storage cost	$/kW	Input from database	
37	SCh	AC Storage cost	$/kWh	= SCw / SDD	
38	SDD	Storage Discharge Duration	cycles	Input from Database	
39	TCO	Total Cost of Ownership	$/kW	= ISCw + PV (AnE) + PV(Replacement Cost	

Appendix D: ESCT Applications and benefits

Renewables energy time shift

The Renewables Energy Time-shift application involves storing electricity from renewable sources when the price of electricity is low and selling that stored energy when the price of electricity is higher. Because wind typically produces energy at night when electricity prices are low, the price differential between the electricity used to charge the battery and the electricity sold at peak can be very large. The energy that is discharged from the storage could be sold via the wholesale market, sold under terms of an energy purchase contract, or used by an integrated utility to reduce the overall cost of providing generation during peak times.

Primary Benefit: Reduced Electricity Costs (Utility/Ratepayer)

A utility that charges ES with renewable energy when demand is low, and discharges the devices when demand is high, may decrease their energy costs by offsetting the need to operate conventional peaking units that have higher variable operation costs compared to renewables. This will have the effect of reducing a utilities overall cost to provide energy to its customers.

Calculation: Total Energy Discharged for Renewable Energy Time-Shift (MWh) x [Avg. Variable Peak Generation Cost ($/MWh) – Variable Renewable Generation Cost ($/MWh)/ES Efficiency (%)]

Secondary Benefit: Reduced Emissions (Society)

Electricity storage can reduce electricity peak demand and thereby reduce feeder losses. This translates into a reduction in emissions if peak generation is produced by fossil-based electricity generators. However, since electricity storage has an inherent inefficiency associated with it, electricity storage could increase overall emissions if fossil fuel generators are used for charging. Alternatively, by providing certain ancillary services, storage can enable conventional generation resources to be operated at more optimal conditions resulting in an emissions benefit. Finally, storage can yield a reduced emissions benefit by enabling greater utilization of renewable resources.

Calculation: Total Energy Discharged for Renewable Energy Time-Shift (MWh) x [Emissions Factor for Generation on the Margin (tons/MWh) x Value of Emissions ($/ton)

Additional Benefit: Optimized Generator Operation (Utility)

Additional Benefit: Deferred Generation Capacity Investment (Utility)

Additional Benefit: Deferred Distribution Capacity Investment (Utility)

Additional Benefit: Reduced Electricity Losses (Utility)

Additional Benefit: Deferred Transmission Capacity Investment (Utility)

Wind generation grid integration-long duration

As wind generation penetration increases, the electricity grid effects that are unique to wind generation will also increase. Storage could assist with orderly integration of wind generation by managing or mitigating the more challenging and less desirable effects from high wind generation penetration. The Wind Generation Grid Integration (Long Duration) application involves using storage to mitigate long-duration effects such as output volatility, transmission congestion, backup for generation shortfalls, and minimum load violations.

Primary Benefit: Reduced Electricity Costs (Utility/Ratepayer)

A utility that charges ES with renewable energy when demand is low, and discharges the devices when demand is high, may decrease their energy costs by offsetting the need to operate conventional peaking units that have higher variable operation costs compared to renewables. Furthermore, this application may enable the utility to operate the generation units at more optimal levels thereby further reducing variable operation costs. Taken together these 2 mechanisms can reduce a utilities overall cost of providing energy to its customers.

Calculation: Total Energy Discharged for Renewable Energy Time-Shift (MWh) x [Avg.Variable Peak Generation Cost ($/MWh) – Variable Renewable Generation Cost ($/MWh)/ES Efficiency (%)]

Secondary Benefit: Reduced Emissions (Society)

Electricity storage can reduce electricity peak demand and thereby reduce feeder losses. This translates into a reduction in emissions if peak generation is produced by fossil-based electricity generators. However, since electricity storage

has an inherent inefficiency associated with it, electricity storage could increase overall emissions if fossil fuel generators are used for charging. Alternatively, by providing certain ancillary services, storage can enable conventional generation resources to be operated at more optimal conditions resulting in an emissions benefit. Finally, storage can yield a reduced emissions benefit by enabling greater utilization of renewable resources.
Calculation: Total Energy Discharged for Renewable Energy Time-Shift (MWh) x [Emissions Factor for Generation on the Margin (tons/MWh) x Value of Emissions ($/ton)
Additional Benefit: Optimized Generator Operation (Utility)
Additional Benefit: Deferred Generation Capacity Investment (Utility)
Additional Benefit: Deferred Distribution Capacity Investment (Utility)
Additional Benefit: Reduced Electricity Losses (Utility)

Electric Service Reliability

The Electric Service Reliability application involves using ES to ensure highly reliable electric service. In the event of an extended system disruption, ES can be used to ride through the outage, complete an orderly shutdown, or transition to on-site generation.
Primary Benefit: Reduced Outages (Utility/Ratepayer)

Electricity storage can be used during a power outage as a backup power supply for one or more customers until normal electric service can be restored. The backup would only be available for a limited time (a few hours) depending on the amount of energy stored. However, even a temporary backup power supply can reduce the number of outages experienced by customers and/or greatly mitigate the impact of a disturbance event. Alternatively, storage can be used to provide grid support that will inherently increase the reliability of the system.

A utility may install ES near a customer site, or on a feeder, to bolster poor reliability or ensure highly reliable electric service. From the utility's perspective, this issue can either be addressed with either an ES solution or conventional solution. Since both solutions will provide the same reliability benefit the maximum monetary value that can be attributed to improving reliability with ES is equal to the minimum capital investment that would have been made to address the problem with a conventional solution. Because it is likely that an ES deployment used for this application would also be used for one or more applications, it may make sense to use ES to provide this service even if the ES solution is more expensive than the conventional solution.
Calculation: Capital Cost of Conventional Electric Service Reliability Solution ($/kW) x Total ES Capacity Installed (kW) x Fixed Charge Rate]
Note: This yearly deferral amount only accrues between the initial and final year of transmission deferral.

Renewables capacity firming

The Renewables Capacity Firming application involves using energy storage to enable the power output from intermittent renewable energy resources to be more consistent by providing energy when the power output from these sources drops temporarily. In a regulated market, firming renewable resources may enable a utility may defer the need to invest in additional conventional generation. In a deregulated market, where the electric supply capacity market is evolving, firming a renewable generation resource could enable a non-utility merchant to sell additional renewable energy capacity into the market resulting in a larger capacity credit revenue stream. However, this market is evolving and in some markets, generation capacity cost is included in wholesale energy prices.

Primary Benefit: Deferred Generation Capacity Investment (Utility/Ratepayer)

By shifting peak demand or providing ancillary services that are typically provided by conventional generation assets, ES can result in deferred generation capacity investment benefits. By shifting peak demand, less generation capacity will be required to meet the system needs and by providing ancillary services more generation capacity will be freed up to meet system energy needs.

Calculation: [Effective Load Carrying Capacity (ELCC) of Renewable Post-Firming(%) – ELCC of Renewable Pre-Firming (%)] x Nameplate Capacity of Renewable Resource (MW) x Price of Conventional Capacity ($/MW)

Price of Conventional Capacity – This represents a proxy for avoided new central generation as a result of firming renewable resources. Assuming the marginal generation would be a conventional natural gas combined cycle plant with a base overnight cost of $978 per kW and a fixed O&M cost of $14/kW with an annual fixed charge rate of 11% for a utility or 15% for a non-utility, results in an Annual Cost of Generation Capacity of $121.000 per MW and $161.000 per MW respectively.

Secondary Benefits: Reduced Emissions (Society)

The capacity provided by the ES is coming from renewable sources and therefore offsets otherwise polluting conventional capacity.

Calculation: [Effective Load Carrying Capacity (ELCC) of Renewable Post-Firming (%) – ELCC of Renewable Pre-Firming (%)] x Nameplate Capacity of Renewable Resource (MW) x Capacity Factor of Renewable Resource (%) x 8.760 h x Emissions Factor for Base Generation(tons/MWh) x Value of Emissions ($/ton).

Wind generation grid integration – short duration

As wind generation penetration increases, the electricity grid effects that are unique to wind generation will also increase. Storage could assist with orderly integration of wind generation by managing or mitigating the more challenging and less desirable effects from high wind generation penetration. The Wind Generation Grid Integration (Short Duration) application involves using storage to mitigate short-duration effects such as output volatility and poor power quality.

Primary Benefit: Deferred Generation Capacity Investment (Utility/Ratepayer)

By shifting peak demand or providing ancillary services that are typically provided by conventional generation assets, ES can result in deferred generation capacity investment benefits. By shifting peak demand, less generation capacity will be required to meet the system needs and by providing ancillary services more generation capacity will be freed up to meet system energy needs.

Calculation: [Effective Load Carrying Capacity (ELCC) of Renewable Post-Firming(%) – ELCC of Renewable Pre-Firming (%)] x Nameplate Capacity of Renewable Resource (MW) x Price of Conventional Capacity ($/MW)

Price of Conventional Capacity – This represents a proxy for avoided new central generation as a result of firming renewable resources. Assuming the marginal generation would be a conventional natural gas combined cycle plant with a base overnight cost of $978 per kW and a fixed O&M cost of $14/kW with an annual fixed

charge rate of 11% for a utility or 15% for a non-utility, results in an Annual Cost of Generation Capacity of $121.000 per MW and $161.000 per MW respectively.
Calculation: [Effective Load Carrying Capacity (ELCC) of Renewable Post-Firming(%) – ELCC of Renewable Pre-Firming (%)] x Nameplate Capacity of Renewable Resource (MW) x Price of Conventional Capacity ($/MW)
Price of Conventional Capacity – This represents a proxy for avoided new central generation as a result of firming renewable resources. Assuming the marginal generation would be a conventional natural gas combined cycle plant with a base overnight cost of $978 per kW and a fixed O&M cost of $14/kW with an annual fixed charge rate of 11% for a utility or 15% for a non-utility, results in an Annual Cost of Generation Capacity of $121.000 per MW and $161.000 per MW respectively.
Secondary Benefits: Reduced Emissions (Society)

The capacity provided by the ES is coming from renewable sources and therefore offsets otherwise polluting conventional capacity.
Calculation: [Effective Load Carrying Capacity (ELCC) of Renewable Post-Firming (%) – ELCC of Renewable Pre-Firming (%)] x Nameplate Capacity of Renewable Resource (MW) x Capacity Factor of Renewable Resource (%) x 8.760 h x Emissions Factor for Base Generation(tons/MWh) x Value of Emissions ($/ton)

Appendix E: ES Select-results

Case 1.2

Step 1: Bulk storage / Up to 50 MW

Step 2

Application
1. renewables capacity firming
2. wind generation grid integration-short duration
3. renewables energy time shift

Step 3

The Total bundle value that comes from this set of applications is 154 to 214 $/kW/y

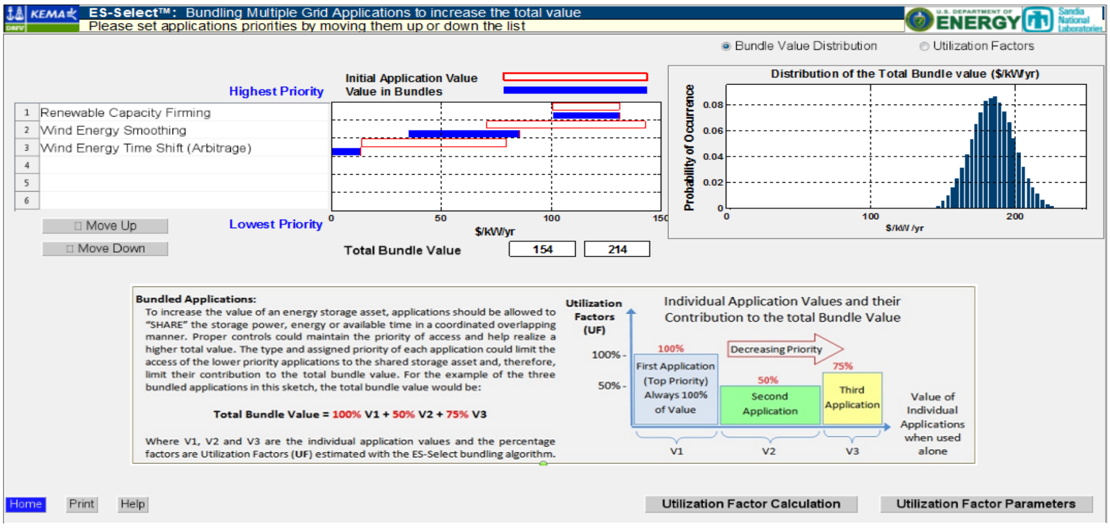


Figure A.5: Total bundle value calculation for case 1.2

Step 4

The best-fit energy storage technologies located next to bulk storage (up to 50MW), are Pumped Hydro with a total feasibility score of 78% and NaS with 74%. Figure A.6 illustrates the individual scores of meeting application and location requirements, commercial maturity and total cost, which form the total feasibility score.

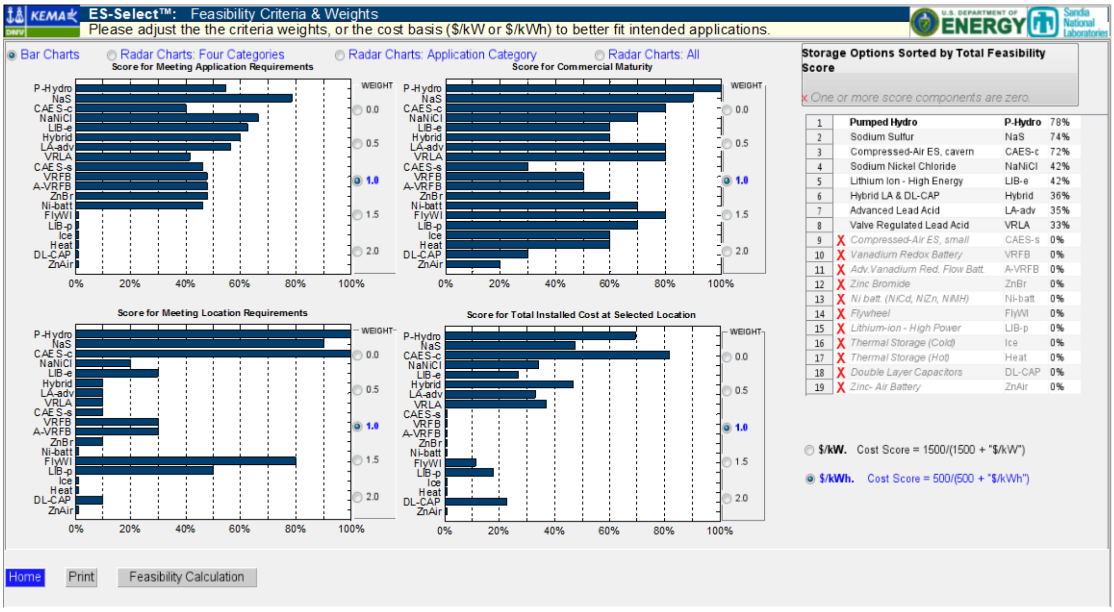


Figure A.6: Feasibility criteria analysis of various ESTs' for case 1.2

All storage options sorted by total feasibility score shown in Figure A.7.

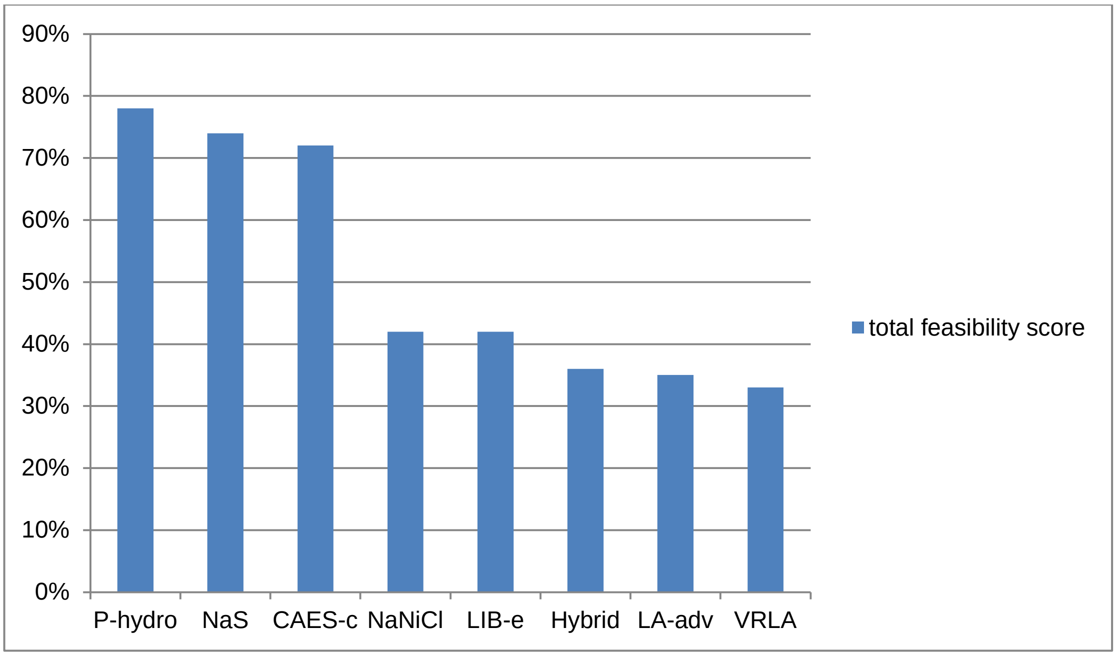


Figure A.7: Storage options sorted by total feasibility score for case 1.2

There is no ES technology that is likely to have a payback in the next 15 years when located on bulk storage grid location. ES Select estimates the probability of having a payback for this case as illustrated in the following figure.

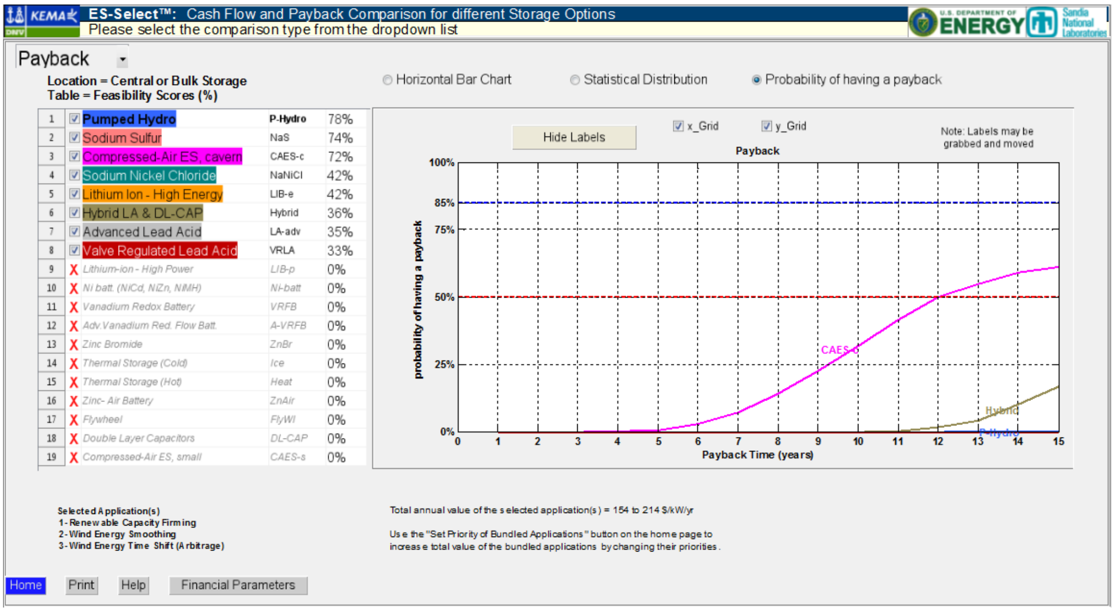


Figure A.8: The probability of having a payback in any given year within the storage lifetime time for case 1.2

Considering the above figures for energy storage options up to 50MW, we conclude that there is no ES technology that fits for case 1.2.

Case 2.1

Step 1: Transmission & distribution / Up to 10 MW (substation)

Step 2

Application
1. electric service reliability
2. wind generation grid integration-long duration
3. renewables energy time shift

Step 3

The Total bundle value that comes from this set of applications is 181 to 441 $/MWh.

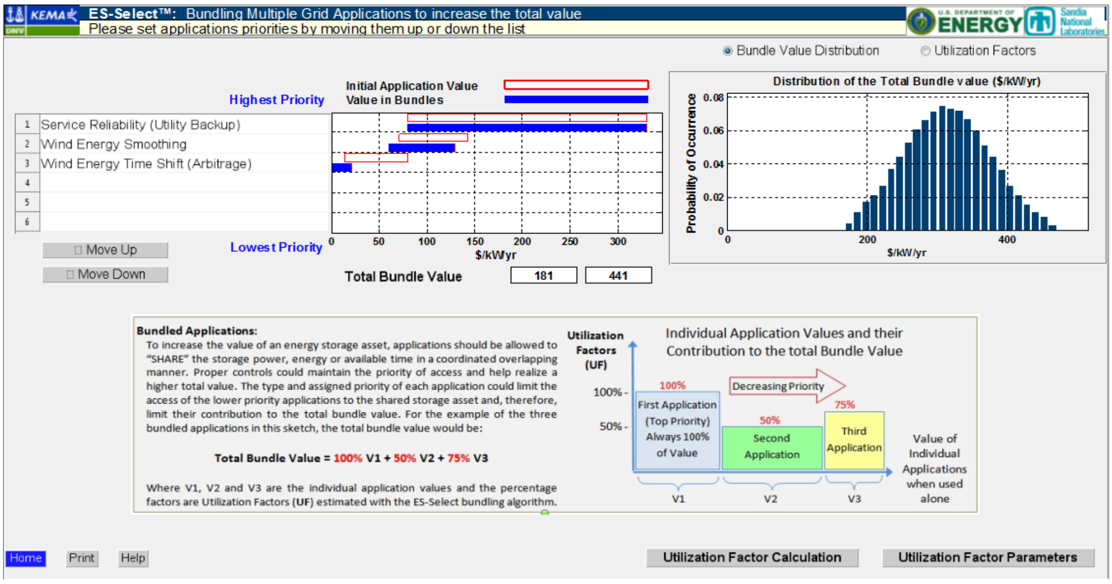


Figure A.9: Total bundle value calculation for case 2.1

Step 4

The best-fit energy storage technologies located next to transmission & distribution (up to 10MW), are NaS with a total feasibility score of 73%, NaNiCl with 58% and Hybrid with 56%. Figure A.10 illustrates the individual scores of meeting application and location requirements, commercial maturity and total cost, which form the total feasibility score.

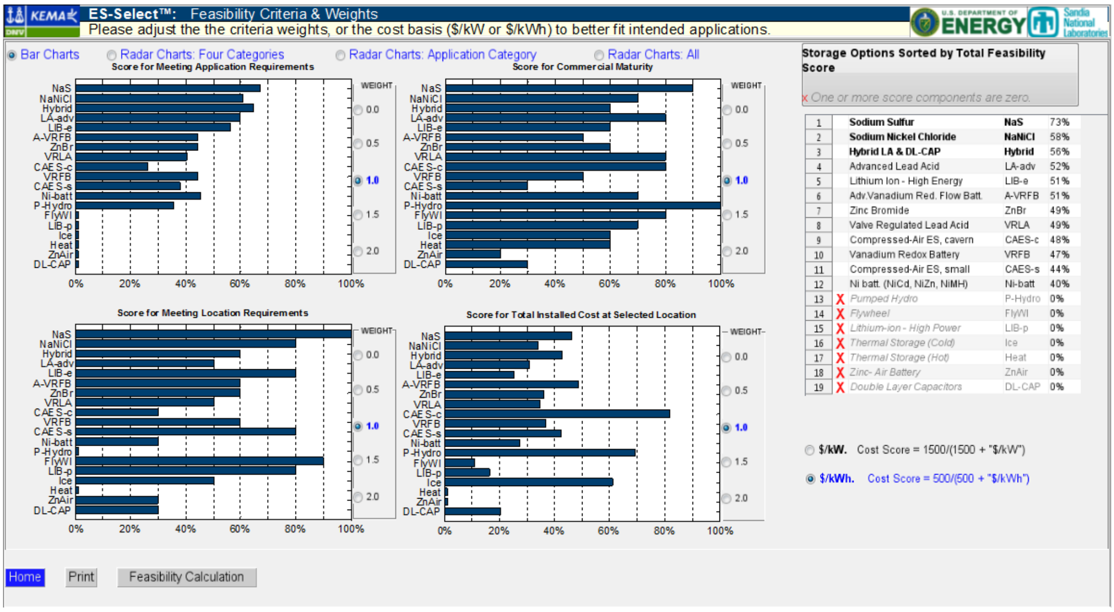


Figure A.10: Feasibility criteria analysis of various ESTs' for case 2.1

All storage options sorted by total feasibility score shown in Figure A.11.

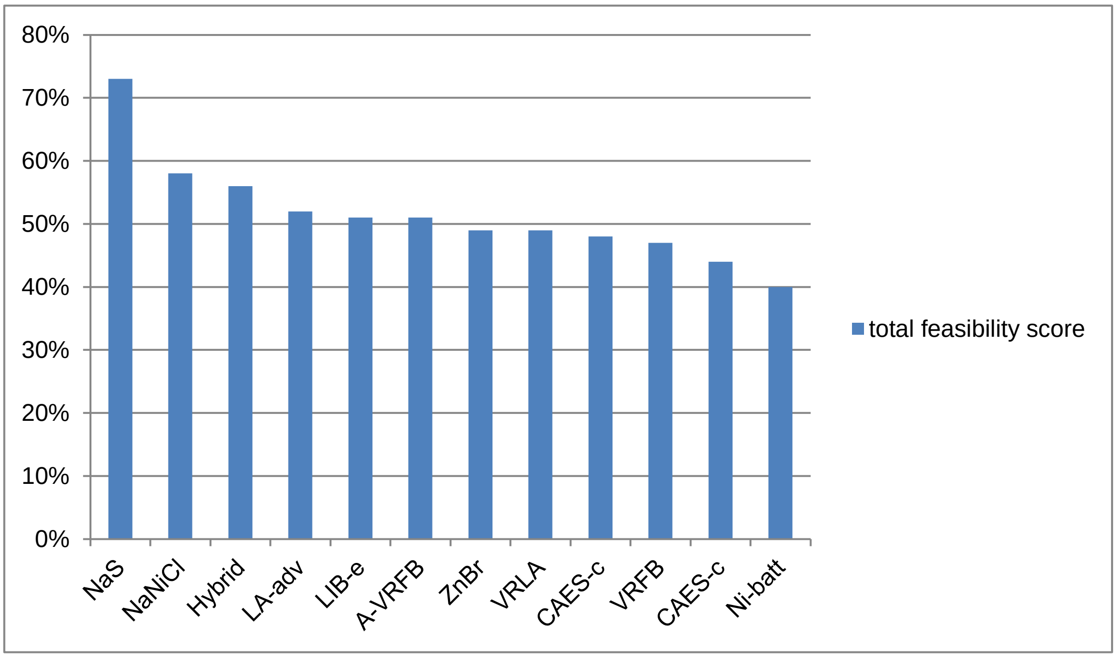


Figure A.11: Storage options sorted by total feasibility score for case 2.1

CAES-c is likely to have a payback in the next 15 years when located on transmission & distribution grid location. ES Select estimates the probability of having a payback for this technology over 85% as illustrated in the following figure.

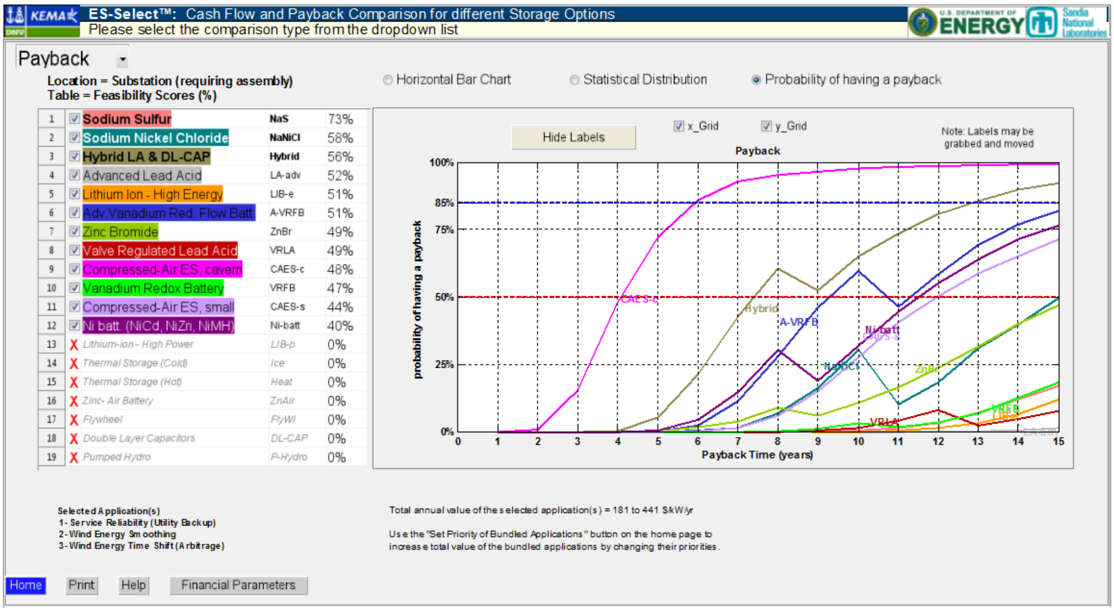


Figure A.12: The probability of having a payback in any given year within the storage lifetime time for case 2.1

There is a high probability of payback time occurrence of CAES-c already between years 5-6 as illustrated in figure A.13.

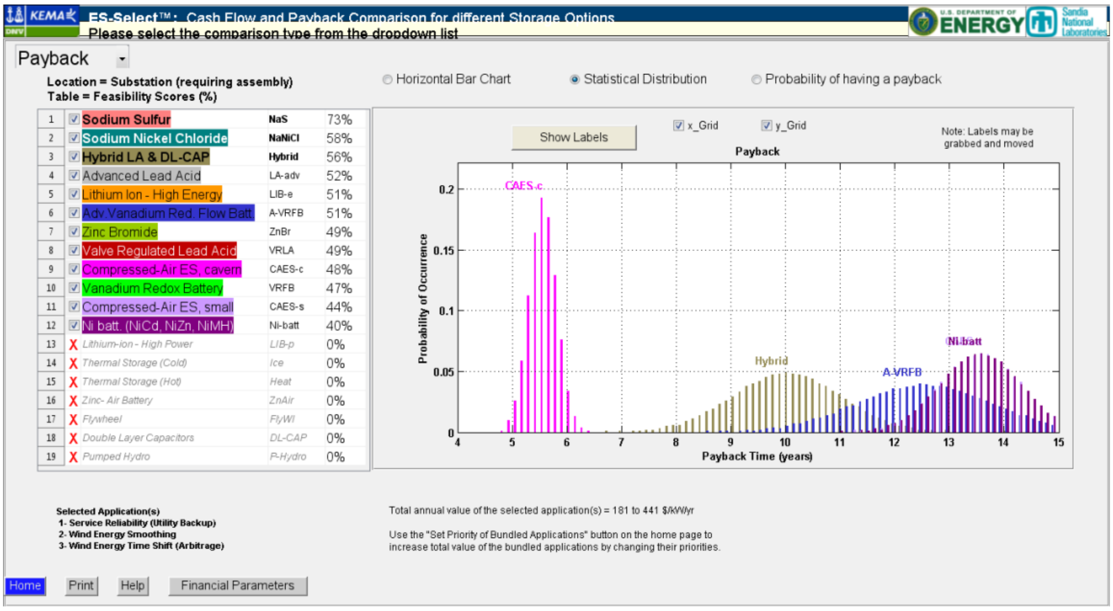


Figure A.13: Statistical distribution of payback years of storage options for case 2.1

Considering the above figures for energy storage options up to 10MW, CAES-c seems to be the storage option that has above 85% probability of having a payback in the next 15 years. On the other hand, it has a low total feasibility score (48%), so we can assume that there is no ES technology that fits for case 2.1.

Case 2.2

Step 1: Transmission & distribution /Up to 10 MW (substation)

Step 2

Application
1. renewables capacity firming
2. wind generation grid integration-short duration
3. renewables energy time shift

Step 3

The Total bundle value that comes from this set of applications is 154 to 214 $/kW/y.

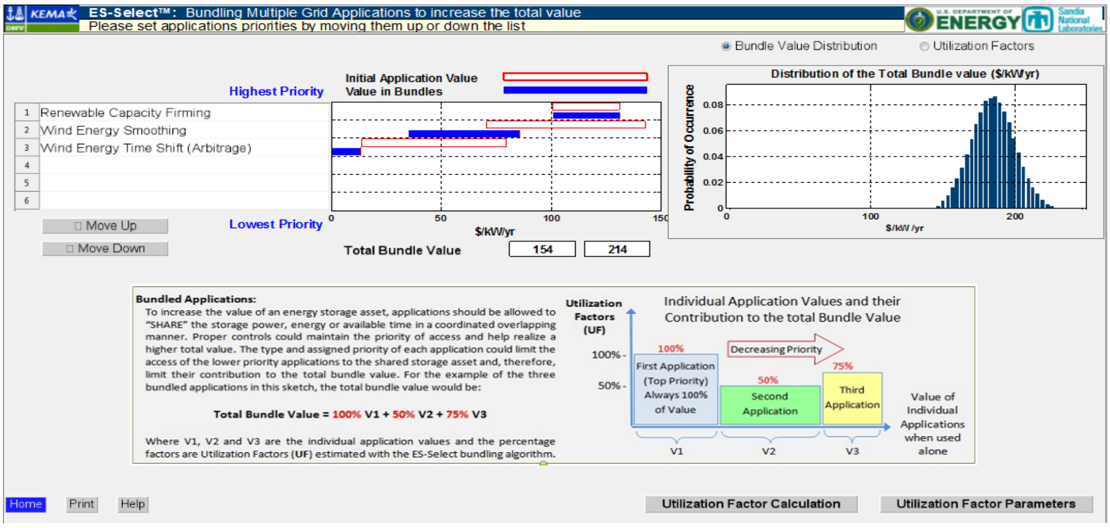


Figure A.14: Total bundle value calculation for case 2.2

Step 4

The best-fit energy storage technologies located next to transmission & distribution (up to 10MW), are NaS with a total feasibility score of 76%, NaNiCl with 60% and Hybrid with 55%. Figure A.15 illustrates the individual scores of meeting application and location requirements, commercial maturity and total cost, which form the total feasibility score.

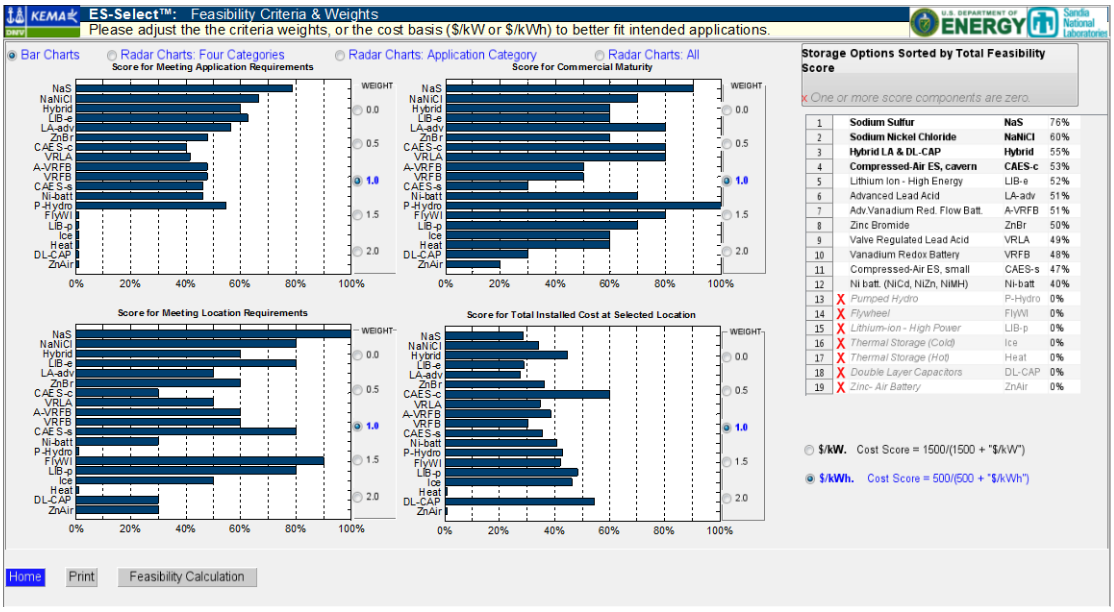


Figure A.15: Feasibility criteria analysis of various ESTs' for case 2.2

All storage options sorted by total feasibility score shown in Figure A.16.

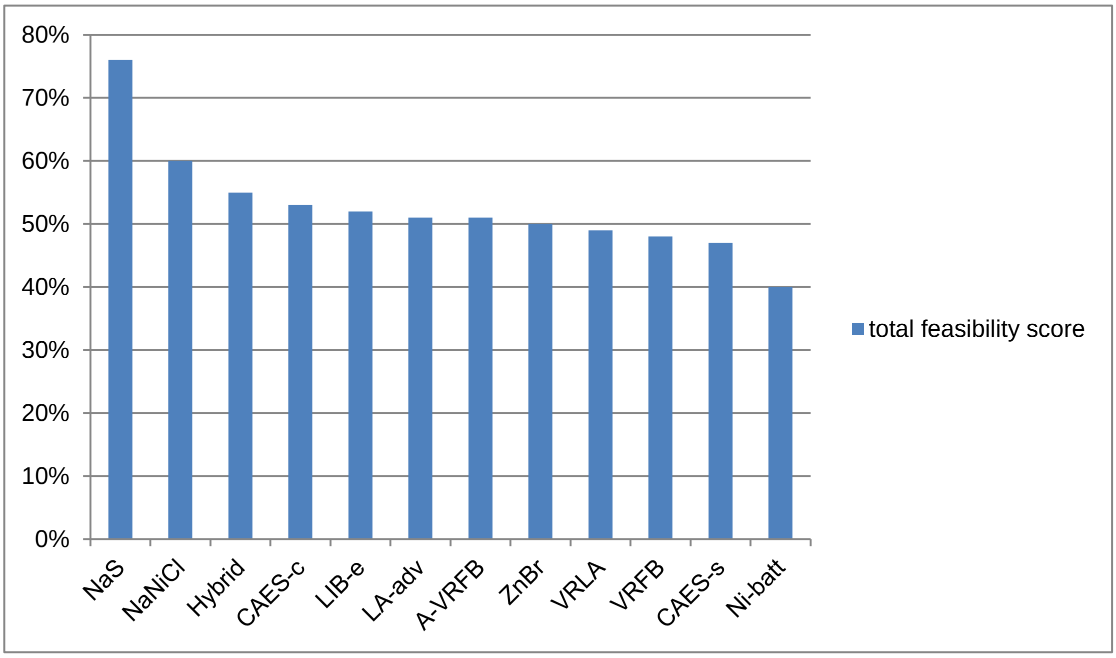


Figure A.16: Storage options sorted by total feasibility score for case 2.2

There is no ES technology that is likely to have a payback in the next 15 years when located on transmission & distribution grid location. ES Select estimates the probability of having a payback for this case as illustrated in the following figure.

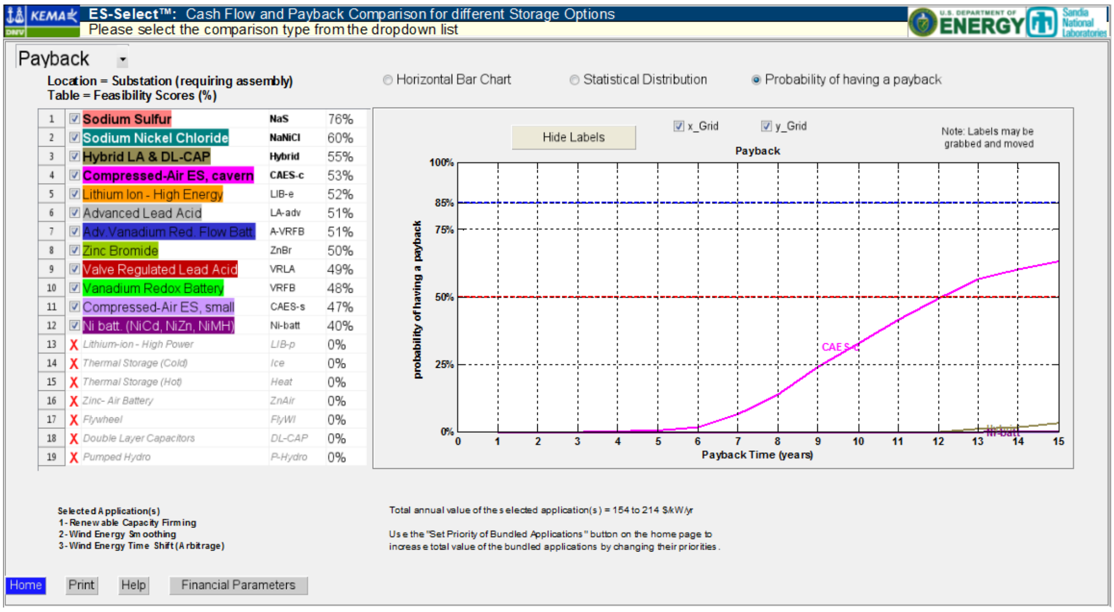


Figure A.17: The probability of having a payback in any given year within the storage lifetime time for case 2.2

Considering the above figures for energy storage options up to 10MW, we conclude that there is no ES technology that fits for case 2.2.

Case 3.1

Step 1: Distribution / Up to 2 MW (container/CES fleet)

Step 2

Application
1. electric service reliability
2. wind generation grid integration-long duration
3. renewables energy time shift

Step 3

The Total bundle value that comes from this set of applications is 181 to 441 $/kW/y

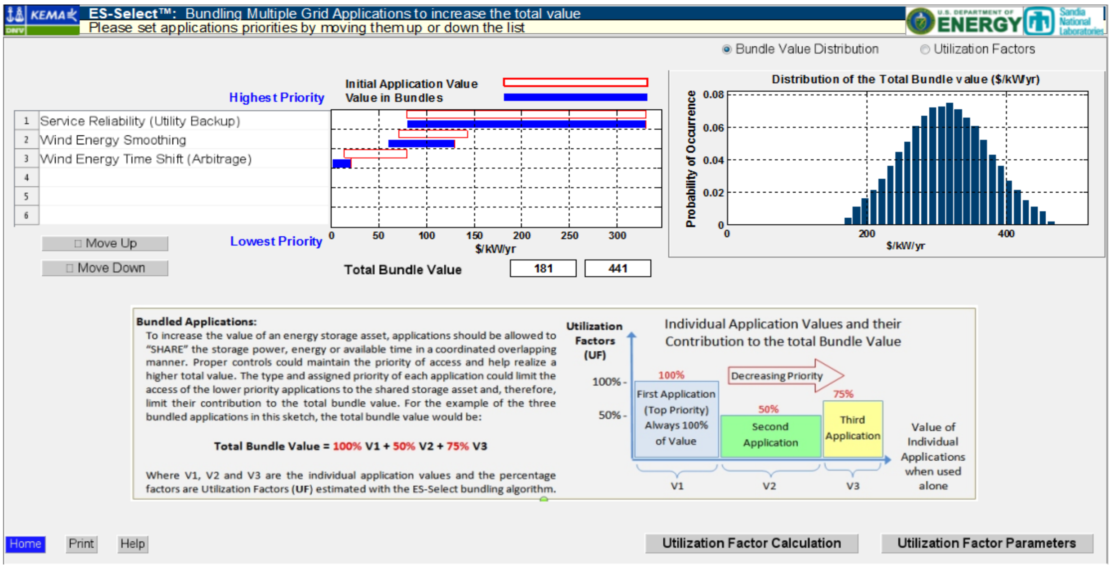


Figure A.18: Total bundle value calculation for case 3.1

Step 4

The best-fit energy storage technologies located next to distribution (up to 2MW) are NaNiCl with 62% and Hybrid with 58%. Figure A.19 illustrates the individual scores of meeting application and location requirements, commercial maturity and total cost, which form the total feasibility score.

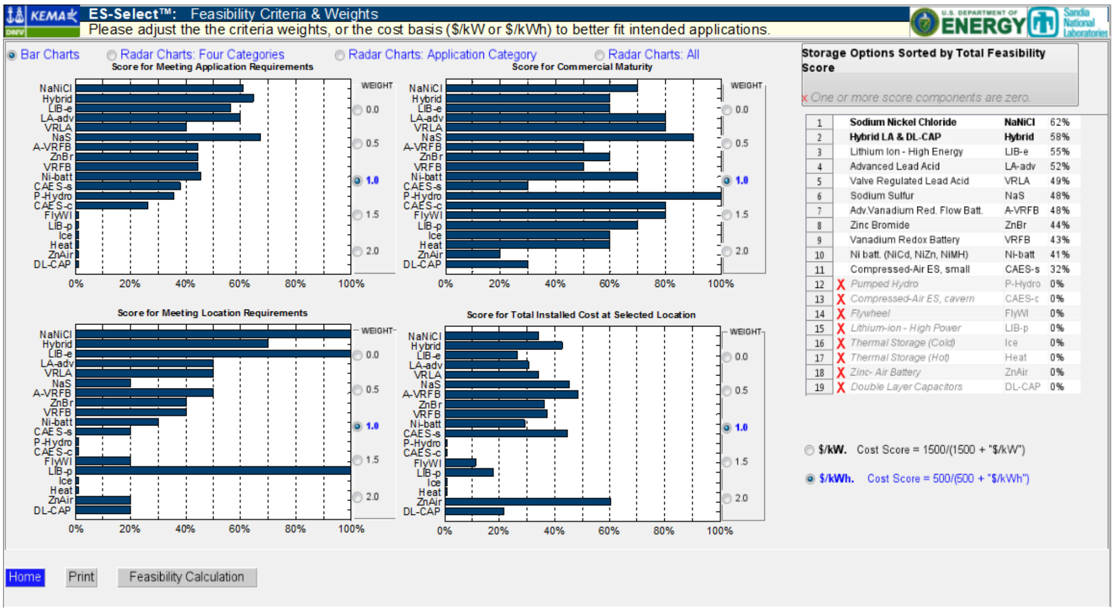


Figure A.19: Feasibility criteria analysis of various ESTs' for case 3.1

All storage options sorted by total feasibility score shown in Figure A.20.

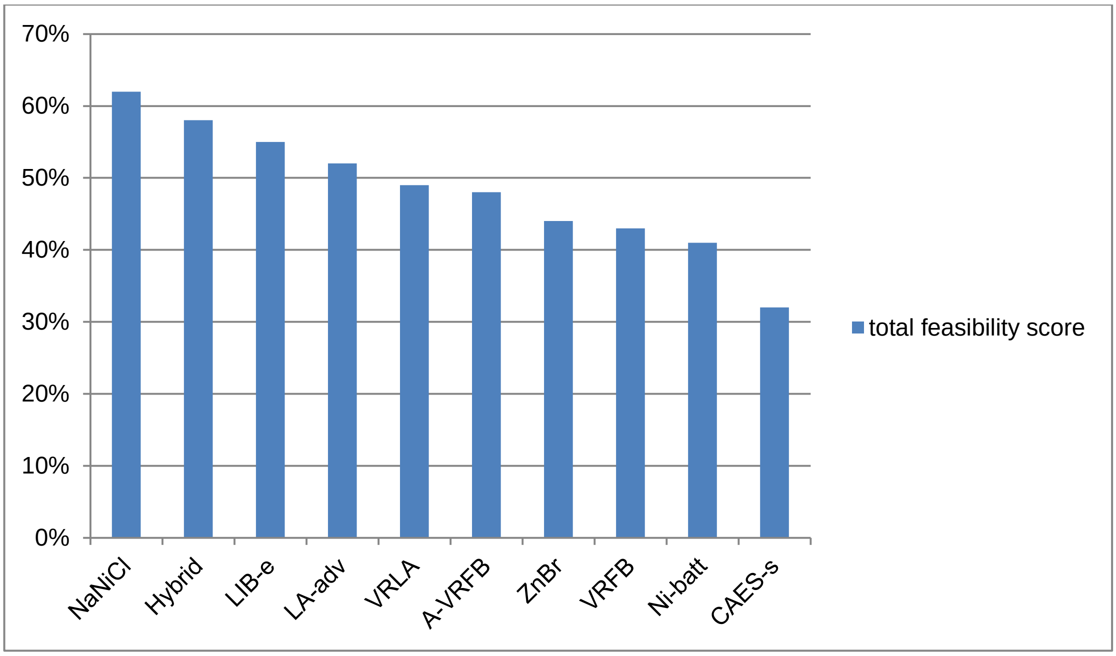


Figure A.20: Storage options sorted by total feasibility score for case 3.1

There is no ES technology that is likely to have a payback in the next 15 years when located on transmission & distribution grid location. ES Select estimates the probability of having a payback for this case as illustrated in the following figure.

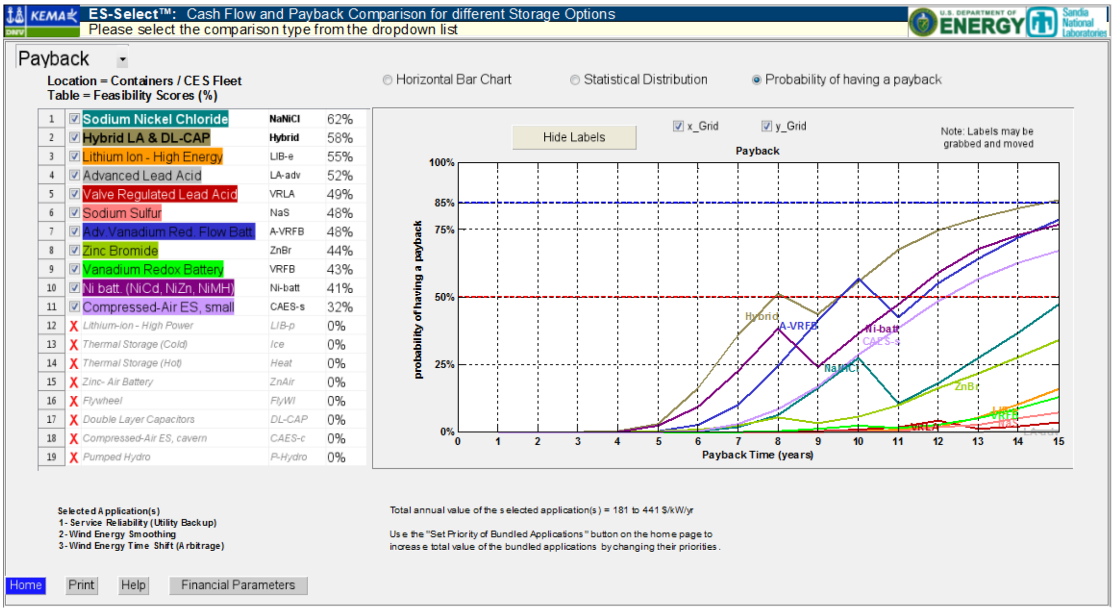


Figure A.21: The probability of having a payback in any given year within the storage lifetime time for case 3.1

Considering the above figures for energy storage options up to 2MW, we conclude that there is no ES technology that fits for case 3.1.

Case 3.2
Step 1: Distribution / Up to 2 MW (container/CES fleet)

Step 2

Application
1. renewables capacity firming
2. wind generation grid integration-short duration
3. renewables energy time shift

Step 3

The Total bundle value that comes from this set of applications is 154 to 214 $/kW/y

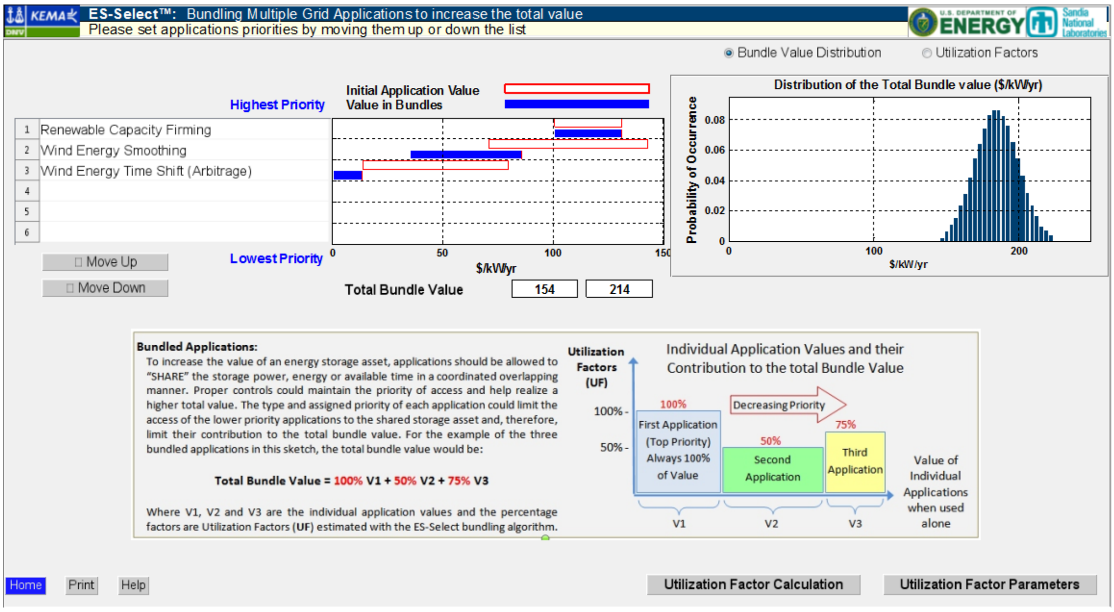


Figure A.22: Total bundle value calculation for case 3.2

Step 4

The best-fit energy storage technologies located next to distribution (up to 2MW) are NaNiCl with 63% and Hybrid with 57%. Figure A.23 illustrates the individual scores of meeting application and location requirements, commercial maturity and total cost, which form the total feasibility score.

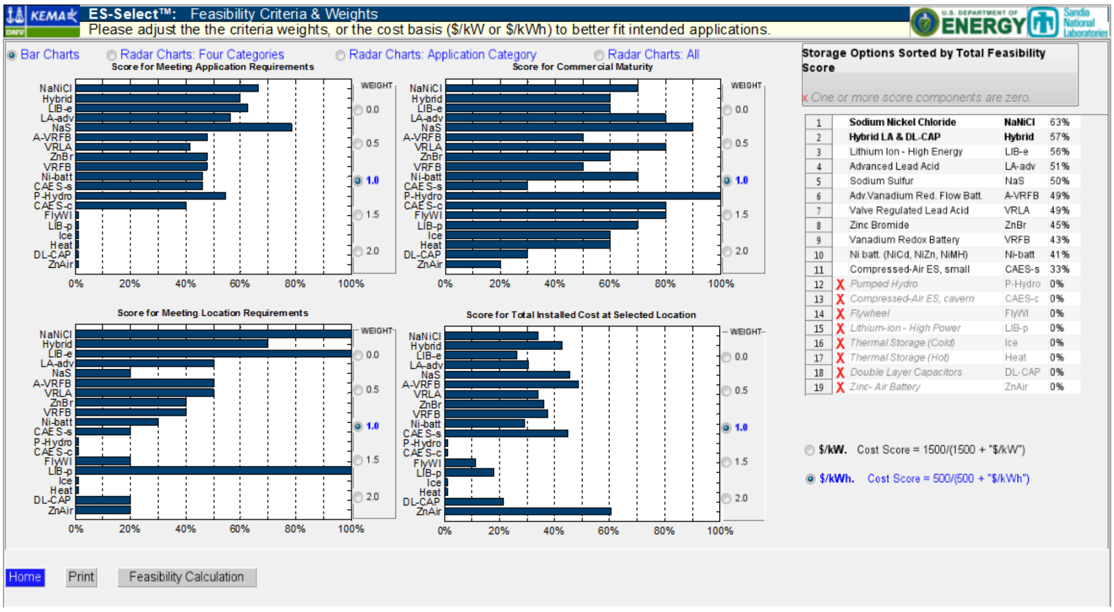


Figure A.23: Feasibility criteria analysis of various ESTs' for case 3.2

All storage options sorted by total feasibility score shown in Figure A.24.

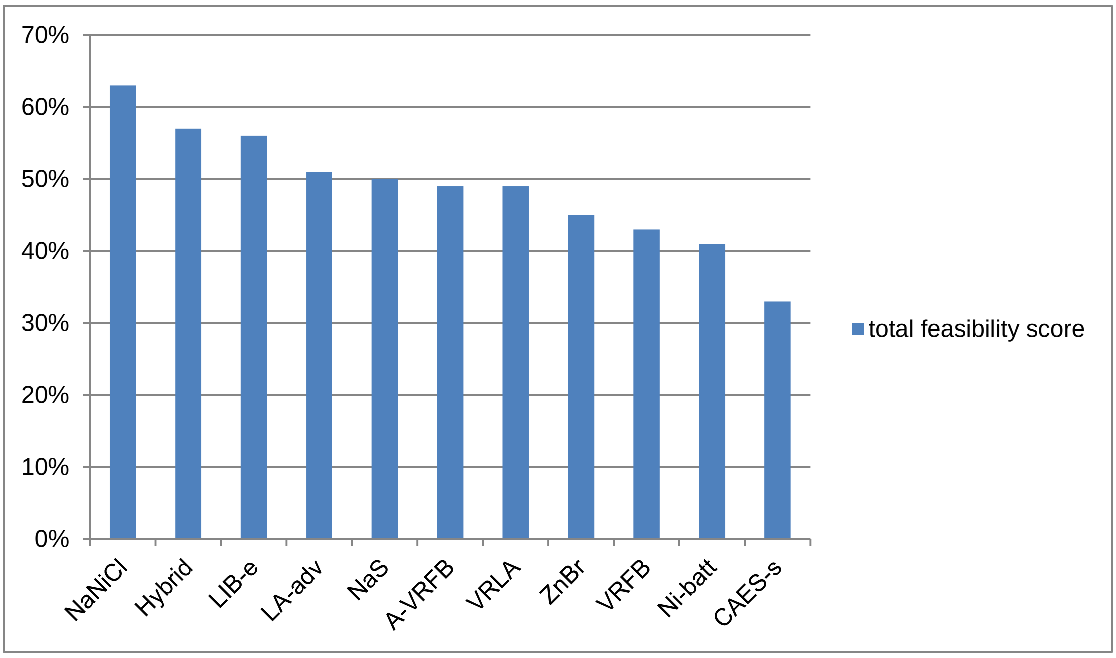


Figure A.24: Storage options sorted by total feasibility score for case 3.2

There is no ES technology that is likely to have a payback in the next 15 years when located on transmission & distribution grid location. ES Select estimates the probability of having a payback for this case as illustrated in the following figure.

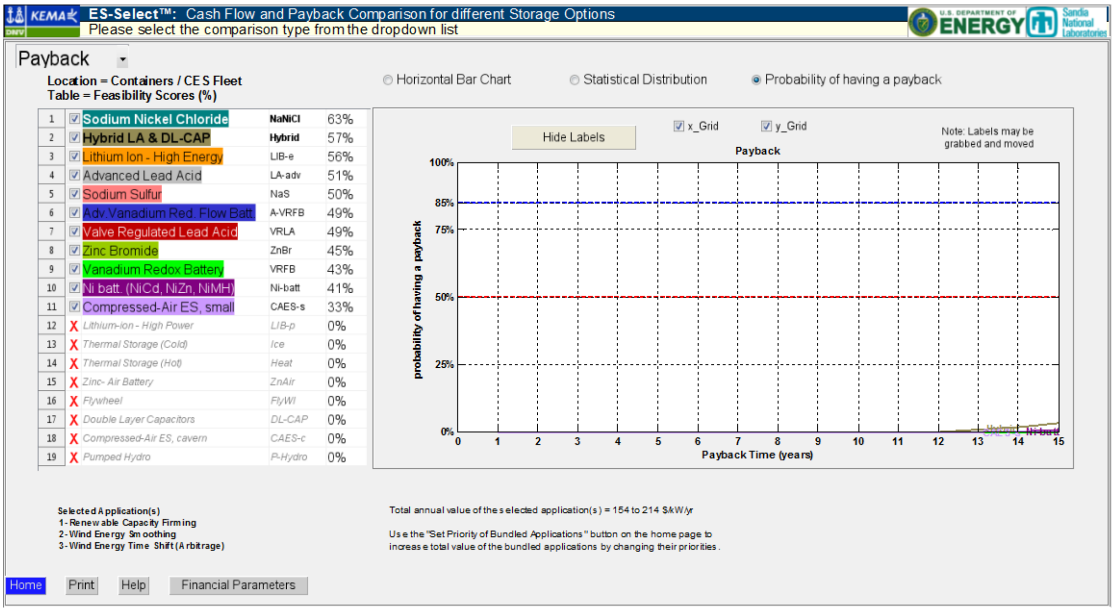


Figure A.25: The probability of having a payback in any given year within the storage lifetime time for case 3.2

Considering the above figures for energy storage options up to 2MW, we conclude that there is no ES technology that fits for case 3.2.

Case 4.1

Step 1: Commercial-industrial / Up to 1 MW

Step 2

Application
1. electric service reliability
2. wind generation grid integration-long duration
3. renewables energy time shift

Step 3

The Total bundle value that comes from this set of applications is 201 to 490 $/kW/y.

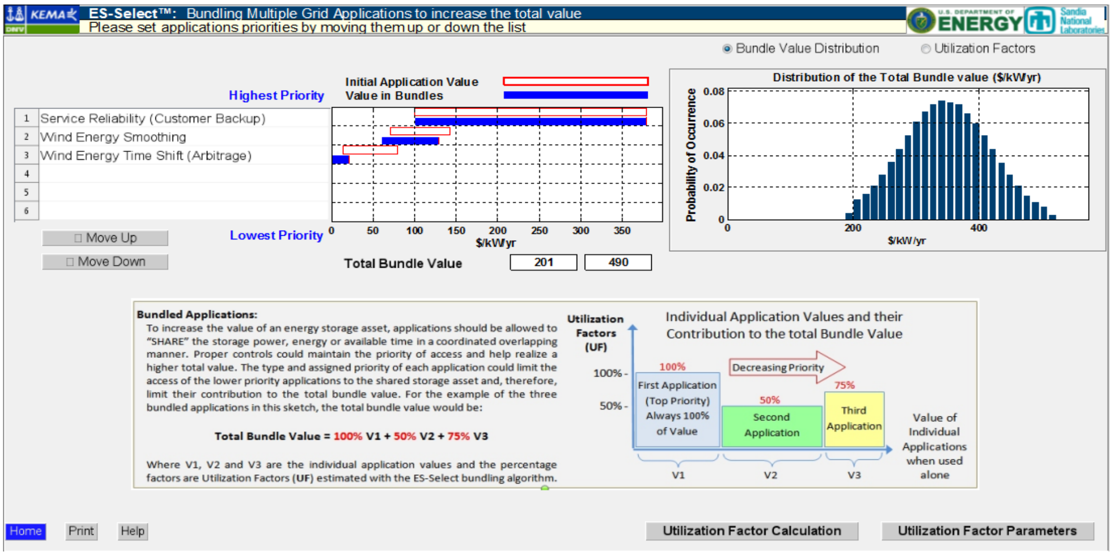


Figure A.26: Total bundle value calculation for case 4.1

Step 4

The best-fit energy storage technologies located next to commercial-industrial (up to 1MW) are NaS with 73% and NaNiCl with 61%. Figure A.27 illustrates the individual scores of meeting application and location requirements, commercial maturity and total cost, which form the total feasibility score.

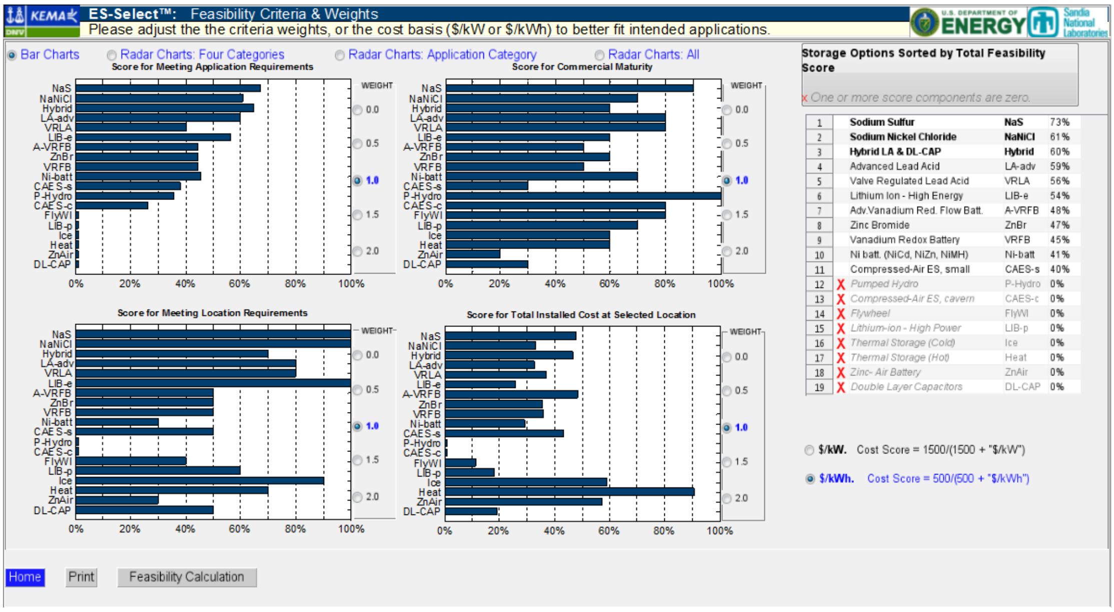


Figure A.27: Feasibility criteria analysis of various ESTs' for case 4.1

All storage options sorted by total feasibility score shown in Figure A.28.

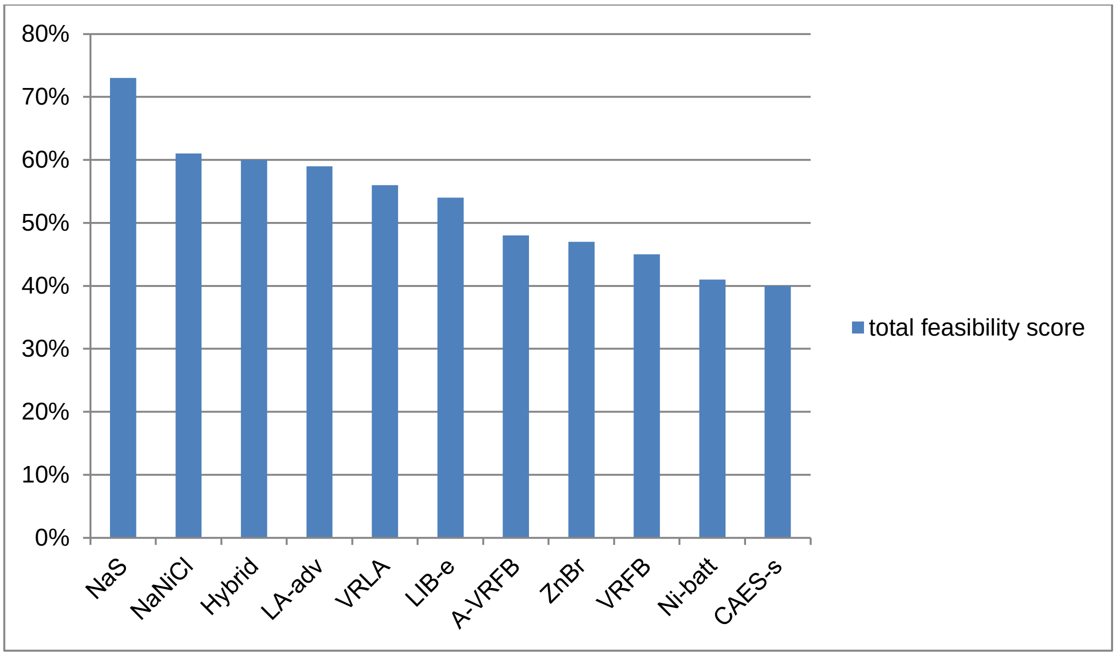


Figure A.28: Storage options sorted by total feasibility score for case 4.1

Hybrid is likely to have a payback in the next 15 years when located on commercial-industrial grid location. ES Select estimates the probability of having a payback for this case as illustrated in the following figure.

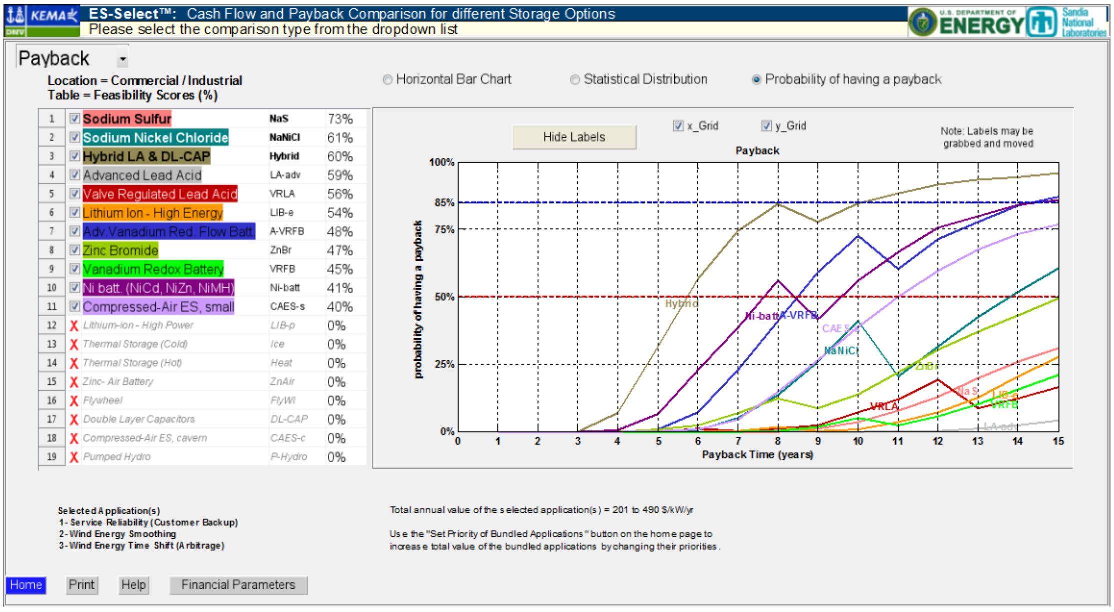


Figure A.29: The probability of having a payback in any given year within the storage lifetime time for case 4.1

There is a high probability of payback time occurrence of Hybrid between years 7-9 as illustrated in Figure A.30.

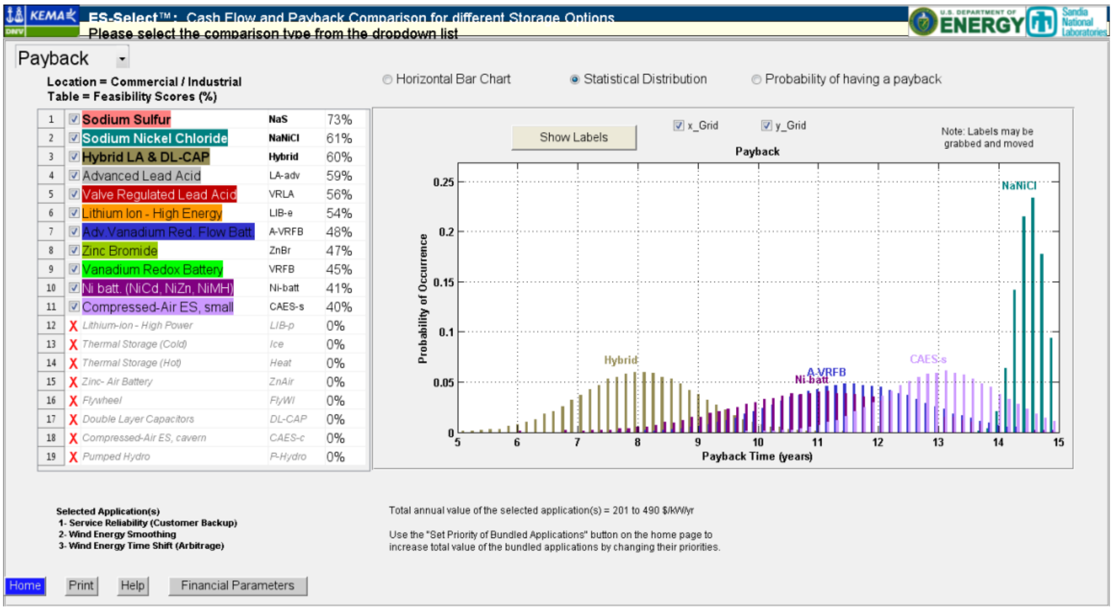


Figure A.30: Statistical distribution of payback years of storage options for case 4.1

Considering the above figures for energy storage options up to 2MW, we conclude that Hybrid might be a solution as it has 60% feasibility score and shows probability of having a payback above 85%.

Case 4.2

Step 1: Commercial- industrial / Up to 1 MW

Step 2

Application
1.renewables capacity firming
2.wind generation grid integration-short duration
3. renewables energy time shift

Step 3

The Total bundle value that comes from this set of applications is 164 to 214 $/kW/y.

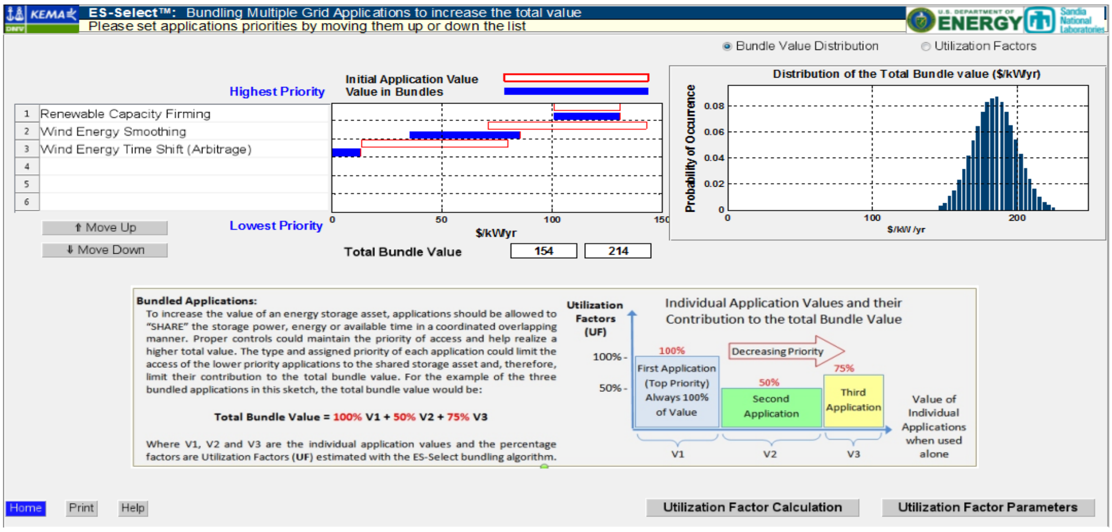


Figure A.31: Total bundle value calculation for case 4.2

Step 4

The best-fit energy storage technologies located next to commercial-industrial (up to 1MW) are NaS with 76% and NaNiCl with 63%. Figure A.32 illustrates the individual scores of meeting application and location requirements, commercial maturity and total cost, which form the total feasibility score.

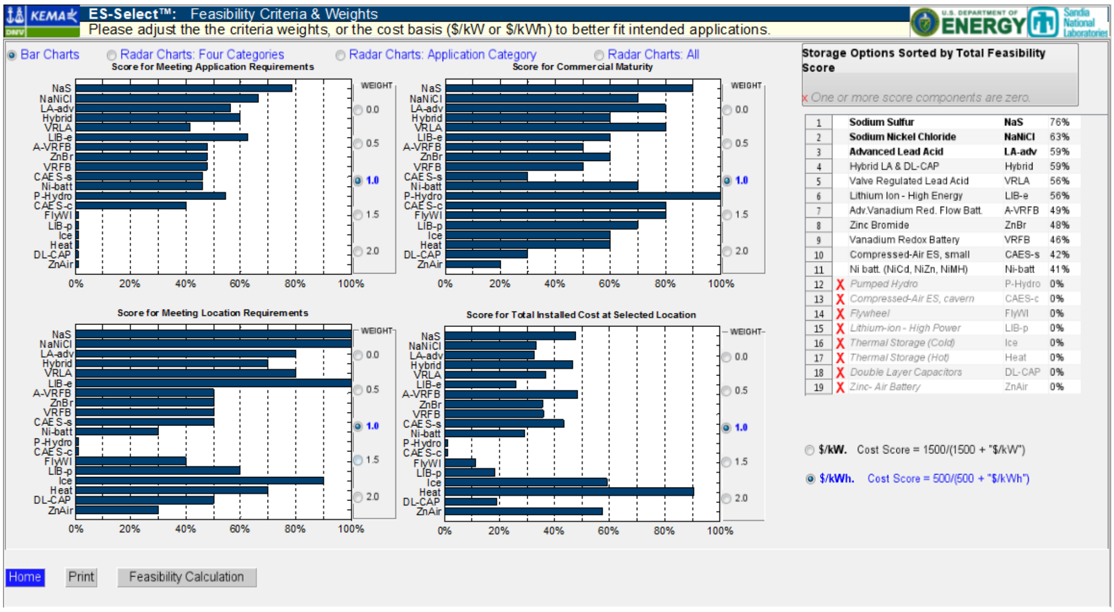


Figure A.32: Feasibility criteria analysis of various ESTs' for case 4.2

All storage options sorted by total feasibility score shown in Figure A.33.

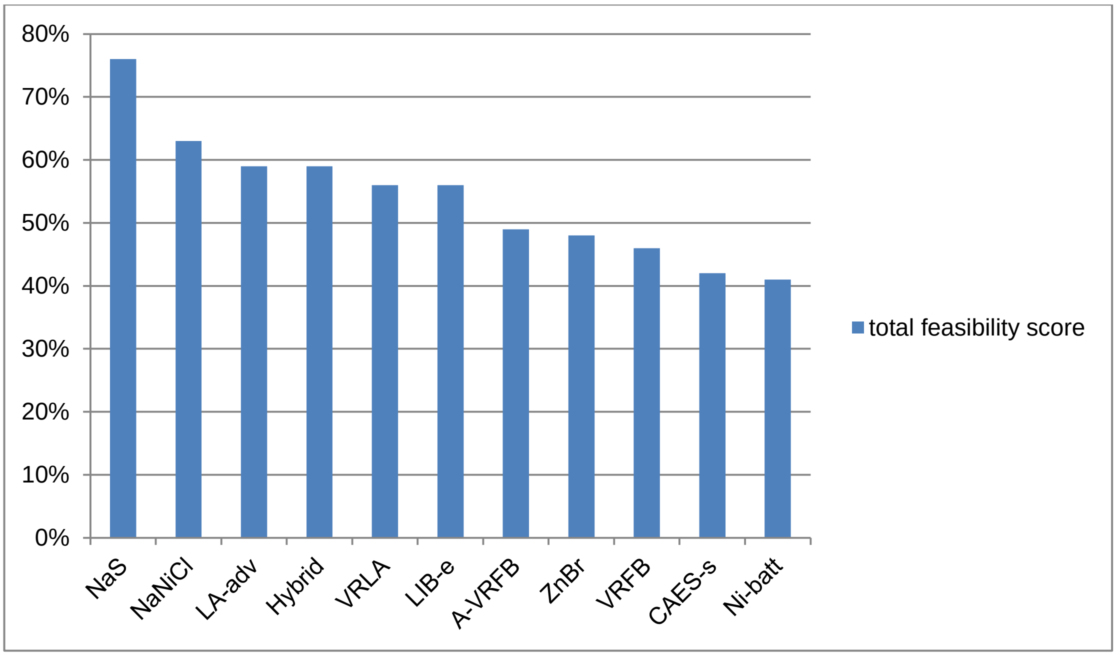


Figure A.33: Storage options sorted by total feasibility score for case 4.2

There is no technology that is likely to have a payback in the next 15 years when located on commercial-industrial grid location. ES Select estimates the probability of having a payback for this case as illustrated in the following figure.

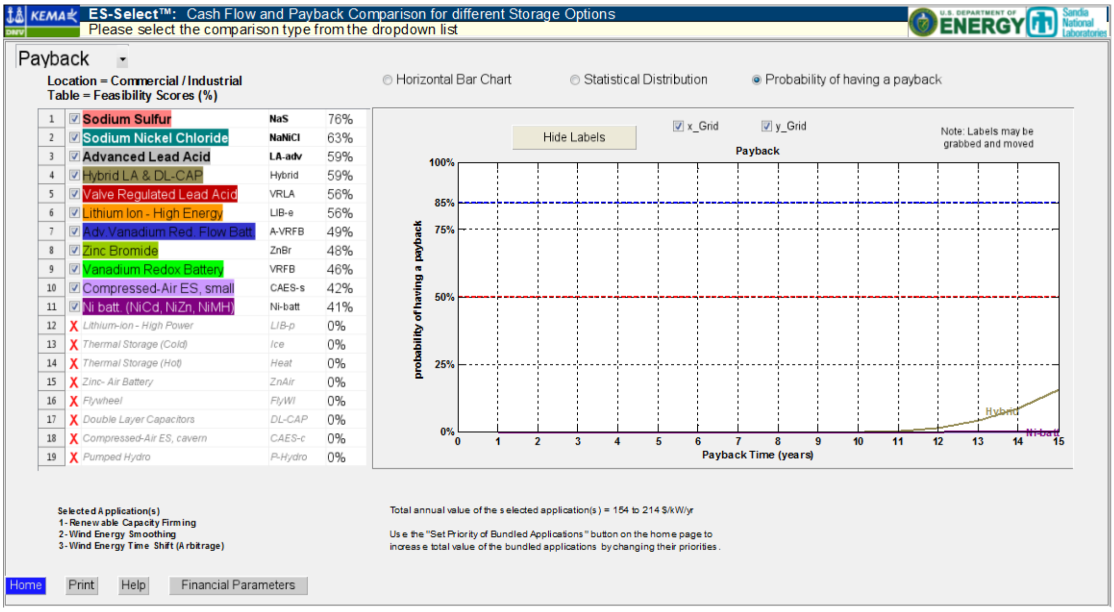


Figure A.34: The probability of having a payback in any given year within the storage lifetime time for case 4.2

Considering the above figures for energy storage options up to 2MW, we conclude that there is no ES technology that fits for case 4.2.

Appendix F: Tables

Table A.2: Summary Matrix of Energy Storage Evaluation Tools by Functionality [Sandia National Laboratories, 2015]

ES Models and Tools							
Modeling Tool	Resource Portfolio Planning	Production Simulation	Load Flow/ Stability	Dynamic Simulation	Electricity Storage Technology Screening	Electricity Storage Cost Effectivness	Grid Operations and Control
Demand Side Management Option Risk Evaluator (DSMore)	•					○	
Electric Generation Expansion Analysis System (EGEAS)	•					○	
Electricity Market Complex Adaptive System (EMCAS)	•	○				○	
Integrated Planning Model (IPM)	○					○	
North American Electricity and Environment Model (NEEM)	•					○	
National Energy Modeling System (NEMS)	•					○	
Portfolio Optimization Model (POM)	•					○	
Regional Energy Deployment System (ReEDS) Model	•					○	
Aurora XMP (Aurora)	○					•	
Day-Ahead Locational Market Clearing Prices Analyzer (DAYZER)	○			•		•	
Flexible Energy Scheduling Tool for Integration of Variable Generation (FESTIV)				•		•	
GE Multi-Area Production Simulation Software (GE MAPS)	○	•				○	
GridView	○	•				○	
HOMER	○	•	•			○	
PLEXOS		•	•			○	
Portfolio Ownership and Bid Evaluation (PROBE)		•	○			○	
PROMOD IV		•	•			○	
REFlex				○	○		
UPLAN Network Power Model (NPM)	•	•	•			○	
ETAP Grid: Transmission Software		•	•				
GE Concordia Power Systems Load Flow Software (PSLF)		•	•	○			
GE Power System Dynamic Simulation (PSDS)				•			
Integrated Dispatchable Resource Optimization Portfolio (IDROP)		•	•	○		○	
Power System Simulator for Engineering (PSS/E)		•	•				
PowerFlow & Short Circuit Assessment Tool (PSAT)		•	○	○			
PowerWorld Simulator (PWS)		•	•				
TRANZER		○	○				
Electricity Distribution Grid Evaluator (EDGE) Model	•	•				•	
ES-Grid	•	○				•	
ETAP Grid: Distribution Software			•	•			
GridLab-D		○	•				
KERMIT			•	•		○	
LoadSEER	○	•				•	
Open Distribution System Simulator (OpenDSS)		•	•	•			
SynerGEE		•					
WindMil			•				
Alstom Distribution Management System - Demand Response Distributed Generation (DMS – DRDG)							•
Decentralized Energy Management System							•
Distribution System Operations Solution							•
GE Distribution Management System							•
Oracle Distribution Management System (DMS)							•
OSI Spectra Distribution Management Systems							•
Advance 2 Control	○					○	•
Battery XT						○	•
BOS4						○	•
Core Operating System						•	•
Cost Performance for Redox Technologies						•	•
DynaTran						•	
Energy Operating System							•
Energy Storage Computational Tool					•	•	
Energy Storage Valuation Tool					•	•	
Energy System Model					○		
ES Simulator					•	•	
ES Select					•	•	
Frequency Regulation Performance Model				•		•	
GridStore	○					•	
Joule.System						•	•
Market Revenue Optimization Model for Behind-the-Meter Storage Projects						•	
Market Revenue Optimization Model for Grid-Connected Storage Projects						•	
Microgrid Optimizer						•	
OnCommand							•
PowerScope						•	•
1E Storage Integrator							•
WindStore						•	

• tool is well suited for the application
○ tool has some functionality for the application

Table A.3: Cost and Performance of Advanced Lead-acid Batteries in Utility T&D [Sandia National Laboratories, 2015]

Application	Utility T&D	Utility T&D	Utility T&D	Utility T&D	Utility T&D	Utility T&D	Utility T&D	Utility T&D	Utility T&D
Technology Type	Adv. Lead Acid	Adv. Lead Acid	Adv. Lead Acid	Adv. Lead Acid	Adv. Lead Acid	Adv. Lead Acid	Adv. Lead Acid	Adv. Lead Acid	Adv. Lead Acid
Supplier	S15	S15	S15	S15	S15	S44	S11	S11	S11
Survey Year	2010	2010	2010	2010	2010	2010	2011	2011	2011
DESIGN BASIS - General									
System Capacity - Net kW	1,000	1,000	1000	1000	20,000	1,000	1,000	12,000	100,000
Hours of Energy storage at rated Capacity - hrs	1	4	8	10	6	3.2	4	4	4
Depth of Discharge (DOD) per cycle - %	33%	33%	50%	80%	33%	75%	60%	60%	60%
Energy Capacity - kWh @ rated DOD	1,000	4,000	8,000	10,000	120,000	3,200	4,000	48,000	400,000
Energy Capacity - kWh @ 100% DOD	3,030	12,121	16,000	12,500	363,636	4,267	6,667	80,000	666,667
Auxiliaries - kW							n/a	n/a	n/a
Unit Size - Net kW		1,000			20,000	1	n/a	n/a	n/a
Number of Units - #	11	26	29	29	685	3	Container	Building Concept	Building Concept
Physical Size - SF/Unit	60X71	60X128	60X141	60X141		1600	160 sf each x 15	Not used	Not used
System Foot Print - SF	4260	7680	8460	8460	101169	1,600	15 x 20ft	13,000	110,000
System Weight - lbs		2220				60000	1 container at	n/a	n/a
Round Trip AC / AC Efficiency - %	90%	90%	90%	90%	90%	87%	90%	90%	90%
Number of cycles / year	365	365	365	365	365	365	365	365	365
GENERAL - Timing									
Commercial Order Date						6 to 9 Months	Q4/2010	Q4/2010	Q4/2010
Plant Life, yrs	15	15	15	15	15	15	15	15	15
TOTAL PLANT COST									
$/kW	$2,477	$4,855	$5,334	$5,023	$5,876	$2,730	$5,166	$4,360	$3,990
$/kWh @ rated DOD	$2,477	$1,214	$667	$502	$979	$853	$1,291	$1,090	$998
$/kWh @ 100% DOD	$817	$401	$333	$402	$323	$640	$775	$654	$599
PLANT CAPITAL COST									
Power - $/kW	$847	$1,004	$1,039	$1,036	$796	$749	$1,344	$527	$546
Storage - $/kWh @ rated DOD	$1,629	$963	$537	$399	$847	$619	$956	$958	$861
SYSTEM COSTS - Equipment & Install	Actual Cost	Actual Cost	Actual Cost	Actual Cost	Actual Cost	Projected Cost	Projected Cost	Projected Cost	Projected Cost
ES System									
ES Equipment	$1,481,040	$3,500,640	$3,904,560	$3,625,000	$92,363,636	$1,792,000	$3,600,000	$39,000,000	$288,000,000
ES Installation	$74,052	$175,032	$195,228	$181,250	$4,618,182	$89,600	$42,000	$5,040,000	$42,000,000
Enclosures	$155,360	$278,480	$306,560	$306,560	$3,644,084	$59,600	$398,400	$470,000	$3,962,000
Owner Interconnection									
Equipment	$367,000	$367,000	$367,000	$367,000	$5,154,500	$367,000	$367,000	$2,288,500	$18,893,500
Installation	$92,000	$92,000	$92,000	$92,000	$644,500	$92,000	$92,000	$572,000	$2,361,500
Enclosures	Included	Included	Included	Included	Included	Included	Included	Included	Included
System Packing	$0	$0	$0	$0	$0	$0	$0	$0	$0
System Shipping to US Port	$0	$0	$0	$0	$0	$10,000	$0	$0	$0
Utility Interconnection									
Equipment	$80,400	$80,400	$80,400	$80,400	$2,012,500	$80,400	$80,400	$695,000	$6,875,000
Installation	$80,400	$80,400	$80,400	$80,400	$2,012,500	$80,400	$80,400	$695,000	$6,875,000
Site BOP Installation (Civil Only)	$8,520	$15,360	$16,920	$16,920	$202,338	$3,200	$217,500	$26,000	$220,000
Total Cost Equipment	$2,083,800	$4,226,520	$4,658,520	$4,378,960	$103,174,720	$2,309,000	$4,445,800	$42,453,500	$317,730,500
Total Cost Installation	$254,972	$362,792	$384,548	$370,570	$7,477,520	$265,200	$431,900	$6,333,000	$51,456,500
General Contractor Facilities at 15% Install	$38,246	$54,419	$57,682	$55,586	$1,121,628	$39,780	$64,785	$949,950	$7,718,475
Engineering Fees @ 5% Install	$12,749	$18,140	$19,227	$18,529	$373,876	$13,260	$21,595	$316,650	$2,572,825
Project Contingency Application @ 0-15% Install	$12,749	$18,140	$19,227	$18,529	$747,752	$13,260	$21,595	$316,650	$5,145,650
Process Contingency Application @ 0-15% of battery	$74,052	$175,032	$195,228	$181,250	$4,618,182	$89,600	$180,000	$1,950,000	$14,400,000
Total Plant Cost (TPC)	$2,476,567	$4,855,042	$5,334,433	$5,023,423	$117,513,678	$2,730,100	$5,165,675	$52,319,750	$399,023,950
OPERATING EXPENSES									
FIXED O&M - $/kW-yr	$9.2	$9.2	$9.2	$9.2	$5.8	$9.2	$9.2	$4.8	$4.3
Replacement Battery Costs - $/kW	$444	$1,050	$1,171	$1,088	$1,385	$538	$1,080	$975	$864
Battery replacement - yrs	8	8	8	8	8	8	8	8	8
Variable O&M - $/kWh (Charging or Discharging)	0.0055	0.0014	0.0007	0.0005	0.0005	0.0017	0.0014	0.0007	0.0007

Table A.4: Cost and performance characteristics of new central station electricity generating technologies [U.S. Energy Information Administration, 2018]

Technology	First available year[1]	Size (MW)	Lead time (years)	Base overnight cost (2017 $/kW)	Project Contingency Factor[2]	Technological Optimism Factor[3]	Total overnight cost[4,10] (2017 $/kW)	Variable O&M[5] (2017 $/MWh)	Fixed O&M (2017$/kW/yr)	Heat rate[6] (Btu/kWh)	nth-of-a-kind heat rate (Btu/kWh)
Coal with 30% carbon sequestration (CCS)	2021	650	4	4,641	1.07	1.03	5,089	7.17	70.70	9,750	9,221
Coal with 90% CCS	2021	650	4	5,132	1.07	1.03	5,628	9.70	82.10	11,650	9,257
Conv Gas/Oil Combined Cycle (CC)	2020	702	3	935	1.05	1.00	982	3.54	11.11	6,600	6,350
Adv Gas/Oil CC	2020	429	3	1,026	1.08	1.00	1,108	2.02	10.10	6,300	6,200
Adv CC with CCS	2020	340	3	1,936	1.08	1.04	2,175	7.20	33.75	7,525	7,493
Conv Combustion Turbine[7]	2019	100	2	1,054	1.05	1.00	1,107	3.54	17.67	9,880	9,600
Adv Combustion Turbine	2019	237	2	648	1.05	1.00	680	10.81	6.87	9,800	8,550
Fuel Cells	2020	10	3	6,192	1.05	1.10	7,132	45.64	0.00	9,500	6,960
Adv Nuclear	2022	2,234	6	5,148	1.10	1.05	5,946	2.32	101.28	10,460	10,460
Distributed Generation - Base	2020	2	3	1,479	1.05	1.00	1,553	8.23	18.52	8,969	8,900
Distributed Generation - Peak	2019	1	2	1,777	1.05	1.00	1,866	8.23	18.52	9,961	9,880
Battery Storage	2018	30	1	2,067	1.05	1.00	2,170	7.12	35.60	N/A	N/A
Biomass	2021	50	4	3,584	1.07	1.00	3,837	5.58	112.15	13,500	13,500
Geothermal[8,9]	2021	50	4	2,615	1.05	1.00	2,746	0.00	119.87	9,271	9,271
MSW - Landfill Gas	2020	50	3	8,170	1.07	1.00	8,742	9.29	417.02	18,000	18,000
Conventional Hydropower[9]	2021	500	4	2,634	1.10	1.00	2,898	1.33	40.05	9,271	9,271
Wind[10]	2020	100	3	1,548	1.07	1.00	1,657	0.00	47.47	9,271	9,271
Wind Offshore[9]	2021	400	4	4,694	1.10	1.25	6,454	0.00	78.56	9,271	9,271
Solar Thermal[9]	2020	100	3	3,952	1.07	1.00	4,228	0.00	71.41	9,271	9,271
Solar PV - tracking[9,11]	2019	150	2	2,004	1.05	1.00	2,105	0.00	22.02	9,271	9,271
Solar PV – fixed tilt[9,11]	2019	150	2	1,763	1.05	1.00	1,851	0.00	22.02	9,271	9,271

Appendix G: Figures

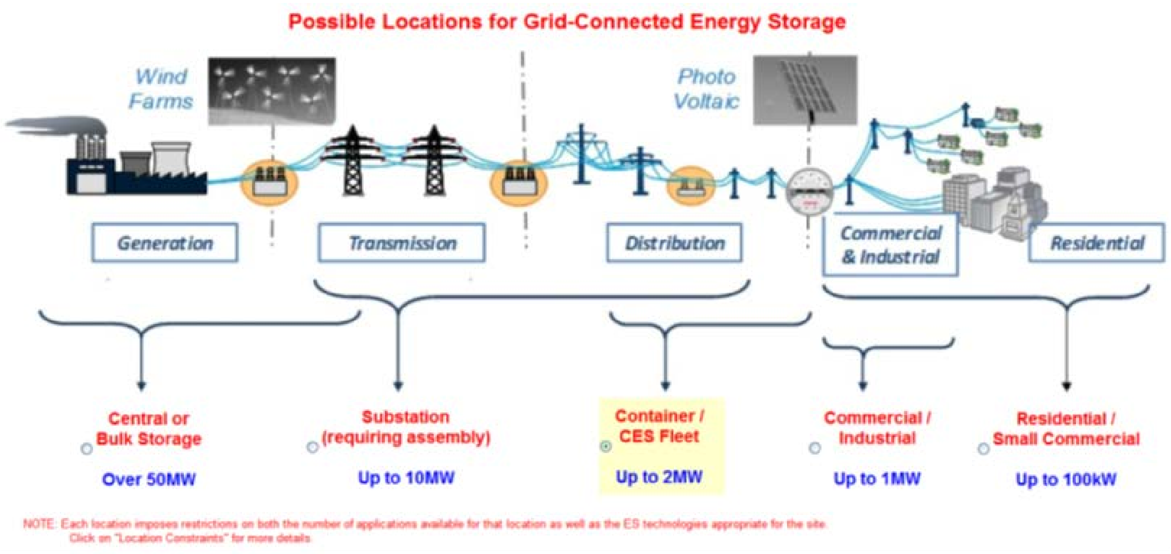


Figure A.35: 5 approximate locations for connecting energy storage to an electric grid [Sandia National Laboratories, 2012]

	Grid Applications	Central or Bulk	Substation (requiring assembly)	Container / CES Fleet	Comm-ercial / Industrial	Res-idential / Small Comm-ercial
1	Energy Time Shift (Arbitrage)	✔	✔	✔	✔	✔
2	Supply Capacity	✔	✔	✔		
3	Load Following	✔	✔	✔	✔	✔
4	Area Regulation	✔	✔	✔	✔	✔
5	Fast Regulation	✔	✔	✔	✔	✔
6	Supply Spinning Reserve	✔	✔	✔		
7	Voltage Support		✔	✔		
8	Transmission Support	✔	✔	✔		
9	Transmission Congestion Relief	✔	✔	✔		
10	Dist. Upgrade Deferral (top 10%)		✔	✔		
11	Trans. Upgrade Deferral (top 10%)	✔	✔	✔		
12	Retail TOU Energy Charges				✔	✔
13	Retail Demand Charges				✔	✔
14	Service Reliability (Utility Backup)	✔	✔	✔		
15	Service Reliability (Customer Backup)				✔	✔
16	Power Quality (Utility)			✔		
17	Power Quality (Customer)				✔	✔
18	Wind Energy Time Shift (Arbitrage)	✔	✔	✔	✔	✔
19	Solar Energy Time Shift (Arbitrage)	✔	✔	✔	✔	✔
20	Renewable Capacity Firming	✔	✔	✔	✔	✔
21	Wind Energy Smoothing	✔	✔	✔	✔	✔
22	Solar Energy Smoothing	✔	✔	✔	✔	✔
23	Black Start	✔	✔			

Figure A.36: Restriction on the grid applications of energy storage based on the storage location [Sandia National Laboratories, 2012]

Storage Technologies	Central or Bulk	Sub-station (requiring assembly)	Container / CES Fleet	Comm-ercial / Industrial	Res-idential / Small Comm-ercial
Lithium-ion - High Power	✔	✔	✔	✔	✔
Lithium Ion - High Energy	✔	✔	✔	✔	✔
Ni batt. (NiCd, NiZn, NiMH)		✔	✔	✔	✔
Advanced Lead Acid	✔	✔	✔	✔	✔
Valve Regulated Lead Acid	✔	✔	✔	✔	✔
Vanadium Redox Battery	✔	✔	✔	✔	
Adv.Vanadium Red. Flow Batt.	✔	✔	✔	✔	
Zinc Bromide	✔	✔	✔	✔	✔
Sodium Sulfur	✔	✔	✔	✔	
Sodium Nickel Chloride	✔	✔	✔	✔	✔
Thermal Storage (Cold)		✔		✔	✔
Thermal Storage (Hot)				✔	✔
Zinc- Air Battery		✔	✔	✔	✔
Flywheel	✔	✔	✔	✔	✔
Double Layer Capacitors	✔	✔	✔	✔	
Hybrid LA & DL-CAP	✔	✔	✔	✔	✔
Compressed-Air ES, cavern	✔	✔			
Compressed-Air ES, small	✔	✔	✔	✔	
Pumped Hydro	✔				

Figure A.37: Restriction on energy storage options based on the storage location [Sandia National Laboratories, 2012]