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Authors

Solomon, AA
Kammen, Daniel M
Callaway, D

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The role of large-scale energy storage design and dispatch in the power grid: A study of very high grid penetration of variable renewable resources

A.A. Solomon [a,b,*], Daniel M. Kammen [a,b,c], D. Callaway [a]

[a] Energy and Resources Group, University of California Berkeley, Berkeley, CA 94720-3050, United States
[b] Renewable and Appropriate Energy Laboratory, University of California Berkeley, Berkeley, CA 94720-3050, United States
[c] Goldman School of Public Policy, University of California Berkeley, Berkeley, CA 94720-3050, United States

HIGHLIGHTS

- Approximates the maximum threshold of the required storage system size.
- Examines backup capacity requirement corresponding to a given storage size.
- Compare the role of transmission increase to energy storage on high penetration.
- Show how energy dumping reduces backup needs via increased use of storage.
- Describe important factors to design a least cost large storage renewable grid.

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ABSTRACT

We present a result of hourly simulation performed using hourly load data and the corresponding simulated output of wind and solar technologies distributed throughout the state of California. We examined how we could achieve very high-energy penetration from intermittent renewable system into the electricity grid. This study shows that the maximum threshold for the storage need is significantly less than the daily average demand. In the present study, we found that the approximate network energy storage is of the order of 186 GW h/22 GW (approximately 22% of the average daily demands of California). Allowing energy dumping was shown to increase storage use, and by that way, increases grid penetration and reduces the required backup conventional capacity requirements. Using the 186 GW h/22 GW storage and at 20% total energy loss, grid penetration was increased to approximately 85% of the annual demand of the year while also reducing the conventional backup capacity requirement to 35 GW. This capacity was sufficient to supply the year round hourly demand, including 59 GW peak demand, plus a distribution loss of about 5.3%. We conclude that designing an efficient and least cost grid may require the capability to capture diverse physical and operational policy scenarios of the future grid.

1. Introduction

The existing grid is not yet optimized to accommodate very large variable renewable energy systems. Due to its ability to produce low carbon electricity, integrating variable generators to electricity grid has attracted significant worldwide research attention. The dominant question of interest is as regards to the ability of the existing grid to accommodate their variable output as we increase system size [1–17]. In the low to high penetration of energy from these resources, such approach could help us understand the technical and economic value of these technologies [1–10]. However, very high penetration will most likely require the capability to enhance the use of energy from the variable technologies. These have three important aspects. The first is regarding the possibility to achieve an optimal temporal match between the variable generators output to the demand profile. The second one relates to a set of technological requirements that enable these optimal matching capabilities while providing sufficient capacity to meet the demand at any time of the year. The third is the possible operational requirements to optimize the use of these resources in order to achieve carbon reduction.

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* Corresponding author. Present address: Addis Ababa Institute of Technology, P.O. Box 385, Addis Ababa, Ethiopia.

E-mail address: abebe.solomon@gmail.com (A.A. Solomon).

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Multiple studies have shown that reduced carbon emission could be achieved through an increased use of intermittent renewable energy sources [1,2]. For the reported low to high penetration, it was shown that switching from the less flexible coal firing generators to a more flexible gas firing technologies could help the grid to handle the fluctuating output of the variable generators. However, generating very significant electric energy from intermittent renewable resources would require significant use of energy storage technologies [11–17]. Little is known about the nature of storage need in an interconnected grid and factors that can limit/enhance its potential benefit in increasing grid penetration of intermittent renewable energy resources.

Very high grid-penetration of variable generators with large-storage have been a subject of a few studies. Studies by Denholm and Margolis [11] have shown the possibility of about 70% PV penetration to the ERCOT – Texas grid. An independent series of reports by Solomon et al. [12–17] have shown PV penetration of up to 90% of the annual demand to Israeli-grid using energy storage and by allowing 20% total energy loss. In these reports, the energy storage capacities were lower than the daily average demand. Unlike the former, the later study employed a computational algorithm that can calculate a storage design requirement based on the seasonal and diurnal profile of the electricity demand. This was one of the reasons for the reported very high penetration in the later case. These series of reports identified two most important information about grid mainly fed by PV-storage system.

The first one is that designing proper storage is a significant part of achieving very high penetration, and that the design should be based on seasonal and diurnal interaction of PV output and the demand profile to be met by PV [12]. Second an employment of proper grid operation strategy could significantly reduce the existing grid's conventional capacity requirement and grid operation cost [17]. Based on the data from the year 2006 if appropriate PV-storage grid were built, the total conventional generator capacity required would have been at least 3 GW less than the 10.5 GW capacity operated that year. Technology wise, large coal power plants were unnecessary but units that serve for intermediate and peak demand times are generally needed. Moreover, as the consequence of the above findings, the economic performance analysis of storage should incorporate the engineering aspect of storage design and use [12,16,17].

In the present study, we investigate the role of energy storage to increase grid penetration of intermittent renewable systems in an interconnected grid. Furthermore, this paper will discuss the value of storage design and dispatch, the corresponding conventional backup and operational requirements, etcetera. In the following sections, we present brief description of our methodology followed by a detailed presentation of the main results. In the end, we will give the summary of the result and our overall conclusion.

2. Framework of the research

2.1. Database information

This study uses one-year hourly demand data of California's electricity grid together with the hourly-simulated output of various solar and wind technologies distributed throughout the state. The hourly data's for the year 2011, total transmission networks thermal capacity and the corresponding losses between load-areas in the state are taken from the SWITCH database [1]. Following [1], we also divide the state into 12 load areas. Fig. 1 presents the map of these load areas while Table 1 summarizes existing sets of generators in the state of California. There are several studies examining how we incorporate intermittent renewable into the existing grid. In this study, we focus on examining the case of a grid supplied by very large intermittent renewable resources. In order to identify factors that limit grid penetrations, we only include existing intermittent renewable systems in the set of our generators. Even if California receives significant energy from outside the state, we ignore the incoming power in order to capture the role of the existing transmission line dispatch, storage technology requirement and the temporal match between the demand and the variable generator output on maximizing penetration as we increase variable generator size. To overcome the limits of the computational runtimes, we assume that we can represent the backup requirement in each load area as a set of conventional generators with 100% flexibility. Such kind of generator flexibility is important to allow the optimal use of energy from the intermittent renewable systems. The detail of the hourly output of the intermittent renewable systems used for this study can be found in SWITCH-model documentation [1]. The renewable technologies that are included in this study are 1-axes tracking photovoltaic (1-axes PV), Concentrated Solar Power (CSP) without storage, residential and commercial building rooftop photovoltaic, offshore and onshore wind technologies.

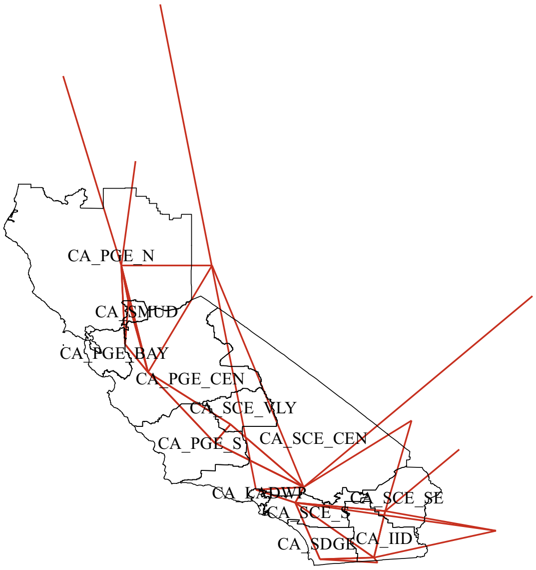

Fig. 1. Schematic map of transmission interconnections between the 12 load areas of California and links with out-of-state stations (lines are not scaled).

Table 1
Generators by load area.

Load areas	Conventional generators (GW)	Pumped hydro (GW)	Wind (GW)
CA_IID	1.0	0.0	0.0
CA_LADWP	2.4	0.0	0.0
CA_PGE_BAY	6.6	0.0	0.6
CA_PGE_CEN	7.9	1.8	0.0
CA_PGE_N	8.9	0.4	0.6
CA_PGE_S	8.2	0.0	0.0
CA_SCE_CEN	5.7	1.4	0.9
CA_SCE_S	11.8	0.0	0.7
CA_SCE_SE	0.7	0.0	0.0
CA_SCE_VLY	0.1	0.0	0.0
CA_SDGE	5.0	0.0	0.1
CA_SMUD	1.1	0.0	0.0
Total	59.5	3.7	2.8

2.2. Model framework

Optimizing the existing grid for high penetration of intermittent renewable energy system requires prioritizing the use of these resources as available. To study the nature of the possible grid, we developed a linear optimization model based on the AMPL-CPLEX set. This mathematical framework starts by calculating the so-called no-dump system [14], a set of variable generating systems size required to achieve the maximum possible penetration without any energy dumping throughout the year. This is a logical place to begin assessing the impact of different approaches – such as energy dumping (curtailment), transmission network and energy storage – on grid penetration of intermittent renewable. In order to study the nature of the possible highly optimized grid to absorb energy from variable generators, we assume that the grid is composed of a set of conventional power plants that can give 100% operational flexibility. Economic considerations are not the subject of this study for a reason that would be clear later on. Future versions will address those caveats.

The model is composed of four major independent problems. One of these problems are aimed at examining the highest possible penetration without storage and the role of transmission lines capacity to achieve very high penetration of energy from intermittent renewable resources while two of them are intended to study storage design issues. The fourth is intended to employ predefined storage properties in order to assess the role of that storage and the corresponding grid penetration under slightly different operations. Full detail of the mathematical algorithm is given in Appendix A. However, the next subsections will provide a brief summary of the model and some of the underlying assumptions.

2.2.1. Non-storage

We began by optimizing the total energy generated by variable renewable generators while setting the hourly power output of these systems to be at most the local load in every load area. This helps to calculate the statewide ND-system. We have then expanded the model so that we could investigate the potential penetration increase when variable generating system is oversized beyond the state wide ND system size by allowing some energy dumping. In this extension we explored scenarios in which transmission potential between load areas were set to some multiples of the existing capacity, the scaling factors being 0, 1, 1.1, 1.2, 1.3, etcetera. The zero scaling factors are selected in order to compare suitability of distributed grid over the existing transmission network (scaling factor = 1). Considering scales between 0 and 1 proves nothing because under any circumstance the existing transmission network will serve the purpose of power transfer between load areas. Therefore, we focused on scaling factors larger than 1 in order to examine the role of an increased transmission capacity along the existing paths. For every transmission scenarios, the total variable generation capacity was subsequently increased by 10% of the ND-system to allow the assessment of the penetration as a function of the allowed energy dumping. This approach is employed to explore the impact of energy dumping and transmission line capacity on grid penetration of intermittent renewable energy systems. Full detail of the mathematical algorithm is given in Sections A.1 and A.2 of Appendix A.

2.2.2. Study of storage design requirement

Decision variables and symbols:

VG – variable generator capacity
RPC – hourly vector of consumed renewable power
T – hourly vector representing power transfer between load area
SP – hourly vector of storable power
RP – hourly vector of storage released power
HB – hourly vector of power coming from backup conventional generators
HE – hourly excess power
Load – hourly load
EinS – hourly vector tracking time dynamics of energy in the storage
EC – energy capacity of storage
PC – power capacity of storage
NEC – network energy capacity
NPC – Network Power capacity
GC – conventional backup generator capacity
TGC – total conventional generator capacity
dl – distribution loss

*Subscripts a, y, h, i and t represents load-area, year, hour of the year, project id and technology type, respectively.

Storage design is indicated to play significant role in enhancing demand matching capability of variable generators output [12,15,16]. These sections are exploring the minimum network storage requirement as we increase the variable generator capacity as discussed in Section 2.2.1. By network storage, we mean the total storage system requirement of the grid. The model is constructed in a way that allows it to minimize the network energy storage's required power capacity and energy capacity while maximizing the energy penetration from renewable. But it increases the storage capacity in order to avoid/reduce energy spill every time the variable generation capacity is increased. To ensure hourly balance of demand and supply throughout the year, the model also builds the minimum conventional backup capacity required to meet the demand according to the circumstance. For simplicity, we assume that the backup represent a set of quick start and fast ramping generators in each load area.

The energy dynamics in storage generally evolves as a function of stored and released energy, which can be represented as:

$$\frac{\partial EinS(t)}{\partial t} = \eta_c * SP(t) - \frac{1}{\eta_d} * RP(t) \tag{1}$$

where η_c and η_d stands for charging and discharging efficiency of storage, respectively. In the present hourly simulation, we use a discrete representation of the storage time dynamics as detailed in Appendix A. Moreover, we model the storage technology using an assumed round trip efficiency of 75%, and an hourly self-discharge rate "$1 - p$" of 0.01% (equivalent to a monthly self-discharge rate of about 6%). The hourly storage energy balance is then calculated as:

$$EinS_{a,y,h} = p * EinS_{a,y,h-1} + \eta * SP_{a,y,h} - RP_{a,y,h} \tag{2}$$

In non-economic model, such as this one, putting renewable penetration as an objective does not tell the entire story because of such model's capability to build an arbitrary storage system size and optimize the energy penetration. To construct a model that would maximize penetration while minimizing the storage need, we will need to write a non-linear problems that are not allowed in the present AMPL-CPLEX set.[1] However, we can write the objective function in a way that would enable us to achieve multiple goals simultaneously, i.e. optimize penetration, and minimize storage system properties and the conventional backup capacity.

First, let us present formulas corresponding to some of the variables that appear in the objective. Network energy capacity "*NEC*" is:

$$NEC = \sum_a EC_a \tag{3}$$

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[1] Note that multi-objective modeling could provide an alternative approach that would avoid loosing semantic meanings. However, such approach emphasizes the primary objectives and, as a result, requires relaxing our definition of minimum storage and conventional backup systems at every renewable system size. In the contrary, the present formalism provides us the best capability to measure the required minimum storage and backup capacity related to a certain level of renewable penetration.

Network Power capacity is:

$$NPC = \sum_a PC_a \tag{4}$$

Total conventional generator capacity required for backup:

$$TGC = \sum_a GC_a \tag{5}$$

Objective

Maximize_Renewable_penetration_while_minimizing_storage_and_conventional_Backup_requirements:

$$\left.\underbrace{\sum_{a,y,h}(Load_{a,y,h} * (1 - dl) - HB_{a,y,h})}_{\text{first term}} + \underbrace{\sum_{a,y,h}(\eta * SP_{a,y,h} - RP_{a,y,h} - p * EinS_{a,y,h})}_{\text{second term}} - \underbrace{(\mathrm{NEC} + \mathrm{NPC} + \mathrm{TGC})}_{\text{Third term}}\right\} \tag{6}$$

The top term represents annual energy supplied by variable generators while the middle term, which from Eq. (2) above is internal storage loss.[2] The bottom term in the objective function contains *NEC*, *NPC* and *TGC*. The middle term allows increasing internal loss, as an incentive, in order to avoid simultaneous charging and discharging that occurs during the simulation. But the first and the last term carry significant physical meaning. While the first one optimizes annual energy supplied by variable generators, the third one helps achieving that goal by simultaneously minimizing the required storage and the conventional backup capacity. Consequently, post optimization calculation was used to define the real grid penetration of energy from variable generators.

Due to the obvious formalism of the objective function based on the technical goal, we obtain no semantic meaning. In addition, the component of the objective function contains terms that have units of GW h or GW. On the other hand, as energy storage system capital cost "*CC*" can be calculated using [18]:

$$CC = C_E * EC + C_P * PC \tag{7}$$

where C_E and C_P are cost of units of storage energy capacity (in units of \$/kW h) and cost of units of its power capacity (in units of \$/kW), respectively. Anyone can assume that these coefficients could define the energy storage design. This assumption is correct but in the present condition the storage design depends on the nature of excess energy being generated. Because energy storage serves as a means of increasing the matching capability of the energy generated by variable renewable systems to the demand profile by saving excess variable renewable systems output for later times. The central piece of maximizing grid penetration of intermittent renewable using storage consists the ability to design one of the smallest appropriate hybrid storage systems that is capable of doing power quality control, energy services, etc. Mastery of the complexities involved in proper storage design, the corresponding grid penetration and operational challenges could enhance our capability to design a grid that accommodates very large energy from intermittent renewable sources. As a result, we focus on studying the impact of storage system design on grid penetration. To be able to calculate storage design requirement at various level of grid penetration, the total variable generation capacity was subsequently increased by 10% of the ND-system. Consequently, the model should calculate the lowest storage properties related to the achieved highest penetration at that total system size. The constraint that enforce to build particular system size is:

$$VG_{i,a,t} = sm * ND_{system} \tag{8}$$

where "*sm*" and ND_{system} are system multipliers (starting at 1 and increasing by 0.1 on every incremental step) and ND-system size, respectively.

In this section, we have two parallel models constructed for the purpose of comparison and better approximation of the maximum threshold of the required energy storage. Brief descriptions of both models are given as follows. The detail on storage design is in Section A.3 of Appendix A.

2.2.2.1. Stored Energy to be Transmitted (SET model).

In this model, the energy balance equation allows the power exchange between load areas under all circumstances only constrained by the total thermal capacity of the transmission lines connecting the load areas. The model can transmit excess energy and store in a neighboring load area if necessary while releasing power to the entire network, as needed, constrained by the power capacity of the storage.

2.2.2.2. Stored Energy Used only Locally (SEUL model).

In the foregoing storage version, the storage design could be affected by many factors other than the seasonal and diurnal matching between demand profiles and intermittent renewable energy systems. The SEUL version could help us identify other factors that may affect the storage design requirement. It limits the stored energy use only to the load area where the storage is built, even though it allows direct transmission of the generated renewable energy between load areas. We also assume that the conventional backup is also built to meet the local energy need.

2.2.3. Storage use

The above algorithms are tailored toward investigating the nature of the storage requirement as we increase the variable generator system size. Under such circumstances, storage use is mostly low because the model builds more and more storage capacity in order to increase penetration even if it has the option to curtail energy. But curtails energy only when renewable energy system size is extremely large.

A study by Solomon et al. [16] shows that an increase in storage does not always lead to its increased use. This matter was demonstrated through the use of "Usefulness Index", an identifier created by taking the ratio of energy delivered by storage in a year to the corresponding energy capacity of storage. They reported that "*UI*" initially increases with energy capacity until it reaches some peak where it starts to decrease. They have shown that approximately storage size that corresponds to the peak UI was sufficient to reach PV penetration as high as 87% of the annual demand using other measures such as energy dumping. In the present study we will investigate if we can use this method to approximate our energy storage. We will also compare the above two models in the event the approximations of the proper storage in one of them are not straightforward. Up on selecting the storage, we begin exploring the impact of its increased use. We set the storage characteristics, in the SET model, to the selected values and increase variable

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[2] This internal loss is equivalent to $\sum_{a,y,h}(EinS_{a,y,h} - p * EinS_{a,y,h-1})$.

generator system size; consequently allowing more energy dumping to increase grid penetration.

3. Results

3.1. Grid penetration without storage

Before delving into the matter of storage design and dispatch, it is important to briefly see the maximum grid penetration that we could achieve without the use of storage. It is, therefore, instructive to start this section by discussing the maximum penetration achieved under the condition that no-energy spill is allowed. Renewable penetration when we impose our strict no dump rule at each load areas is approximately 29% of the annual need. The corresponding system size is 41 GW. Now let us see Fig. 2, which presents grid penetration as the function of energy spill and transmission system-size.

Fig. 2 shows how allowing energy dumping increases grid penetration of energy from variable renewable generators at different transmission condition. In all cases, modest energy dumping is shown to increase grid penetration significantly but its benefit appears to slow down as we allow further energy dumping.

The figure also shows that grid penetration was consistently higher when transmission lines are used to increase power exchange between load areas. The substantial gain is due to the capability to build technologies with better output profile, supported by the possibility to transmit the surplus power at one load-area to the other. For instance, a system with capacity of 41 GW was shown to achieve a penetration level of about 31.5% without transmission but if the existing transmission is effectively used penetration could reach 38.2% of the annual demand.

The impact of building resources with a poor performance or matching capability can be seen even when transmission line is used. Fig. 3 compares the three options, i.e., Distributed solar, non-distributed solar and the most efficient centralized systems (termed by the scenario name “No generator preference”). The distributed generations (DGs) are composed of the residential and commercial PV. The centralized plants include static PV, 1-axis tracking PV, solar thermal without storage, offshore and onshore wind technologies. Existing wind turbines are close to 10% of the 41 GW reference systems. For the purpose of uniformity, we set the share of the distributed and the non-distributed solar to about 90% of the total capacity in two scenarios. The third scenario does not limit the type of generators that the model builds. Consequently, the model builds the best resources composed of wind and non-distributed solar technologies. As shown in the figure, grid penetration under the 90% DGs scenario achieves about 10% and 15% less penetration below that of the corresponding 90% solar and No generator preference scenarios. The later systems do not build any DGs even if it could have. The main reason is because the energy generated by DG resources is significantly lower than the centralized counterparts even if we limit the centralized systems to PV technologies alone. All the three scenarios increase penetration by dumping more and more energy as system size increases. The foregoing discussion shows that even if we ignore DG’s impact on power quality and the additional need for controlling devices, it displaces lower polluting emissions as compared to the equivalent centralized plants. These results signify the risk of emphasizing DGs and, by that way, the importance of finding proper DG and centralized grid combination.

Fig. 2 also reveals that little increase in grid penetration occurs as we increase transmission capacity above the existing. This underscores that temporal match between demand and the generators output profile present a significant limit on our ability to reach very high penetration than transmission capacity. Since both the load profile and intermittent renewable system output profile

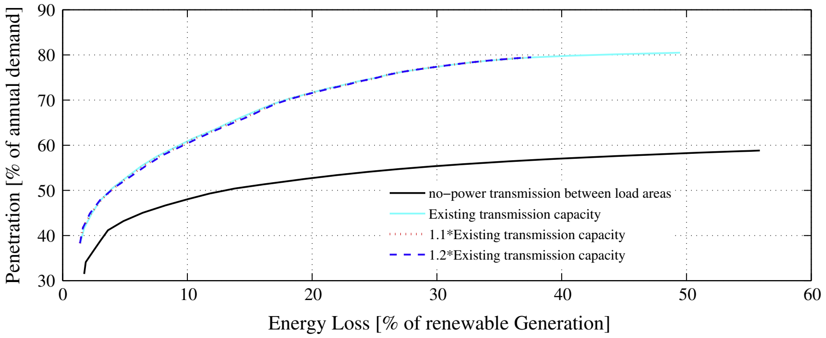

Fig. 2. Grid penetration of energy from variable renewable system as a function of energy loss at different transmission lines transfer capacity.

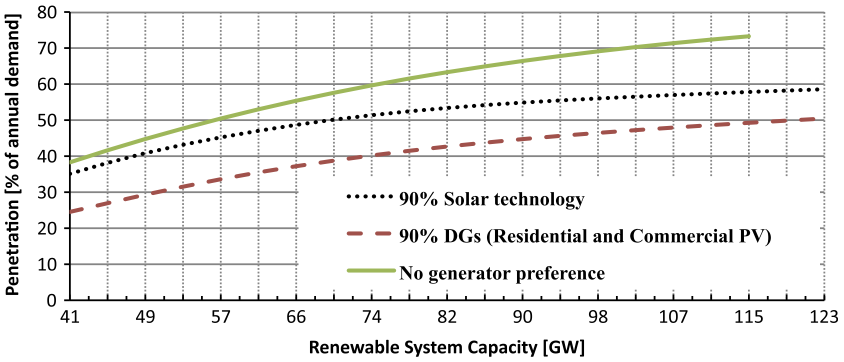

Fig. 3. Penetration as a function of system size for three scenarios. The model increases system size starting from the reference 41 GW and dumps more energy as system size increases to reach to the indicated penetration.

changes from year to year, it is not easy to draw a simple lesson for long term planning. However it can be inferred that, at least for the present study, the long distance transmission increase between various load areas should not substantially exceed the transmission capacity needed to reliably supply the regular load increase.

Overall, it can be seen that theoretically existing transmission line would have sufficed to increase grid penetration of variable renewable systems to about 52% of the annual demand by allowing only 5% energy dumping. Further increase will come at the expense of curtailing significant amount of energy from variable renewable sources, which will reduce economic value of these resources. However, it is worth reminding the reader that achieving such a high penetration requires, at least, the ability to dispatch transmission lines as needed by these technologies', and the conventional generators capability to tolerate the required quicker on/of cycle and frequent ramping. Consequently, it should be clear by now that the best alternative for a very high penetration of these technologies involve significant use of energy storage technology.

By comparison, the observed penetration to Israeli-grid at the 5% energy dumping was close to 46% for the CPV-wind hybrid system [15]. The higher penetration in the present study can be attributed to the diversity of the variable renewable resources, which give higher possibility for complementarities, and the ability to share their power over the robust transmission network as opposed to an island IEC grid.

Finally, we summarize that due to the limited capability of conventional generators to change its output as quickly as possible, and the matching capability of the variable generators output to the demand profile, achieving very high penetration will require the use of storage. In the following sections, we present our study regarding the role of storage for a very high penetration scenario and an estimation of the potential large network storage that efficiently maximize their grid penetration.

3.2. Storage design and the choice of appropriately sized system

The foregoing discussion indicates that increased grid penetration of very-large intermittent renewable resources necessitate the use of storage. Therefore, it is instructive to explore the role of energy storage design and dispatch on grid penetration. In the following we will present how the required storage system size and design changes as we increase system size in order to increase grid penetration of energy from variable generators.

3.2.1. Storage design

We begin this section by describing how grid penetration and the corresponding storage system requirement change as we increase the total variable generator system size. Fig. 4 shows how grid penetrations of energy from variable generators are related to the corresponding storage system network energy capacity. The figure presents two curves, one for each storage design models, i.e., SET and SEUL model. While both curves show similar typical trends of the dependence of grid penetration on NEC, it also demonstrates slight differences on the rate of the interdependence between penetration and NEC. First we will discuss the cause of the difference of the rate of interdependence of penetration and NEC, which will be followed by the study of implication of their trends.

Fig. 4 shows that, for smaller storage, penetration increases at a faster rate when stored energy is used to meet the local demand than when the stored energy is transmitted. This phenomenon occurs because when system size increases the later model builds storage with larger network energy capacity to achieve almost the same level of grid penetration as the former. This can be seen from Fig. 5.

Fig. 5 (right *y*-axis) show that grid penetration increases almost linearly with generator system size for both model. For almost all system sizes, the differences on the achieved penetration between the two models were negligible. However, the figure shows that

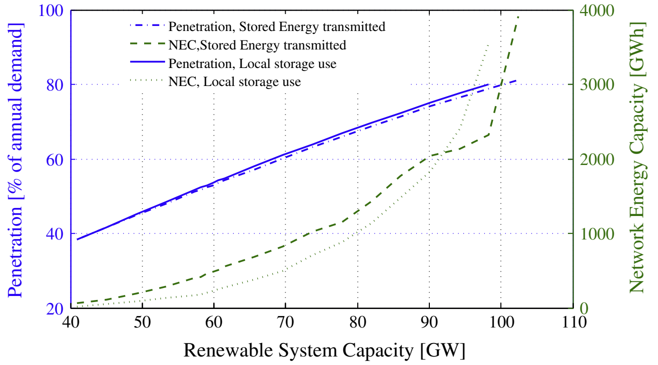

Fig. 5. The trend of grid penetration (right *y*-axis) and NEC (left *y*-axis) as system size increases.

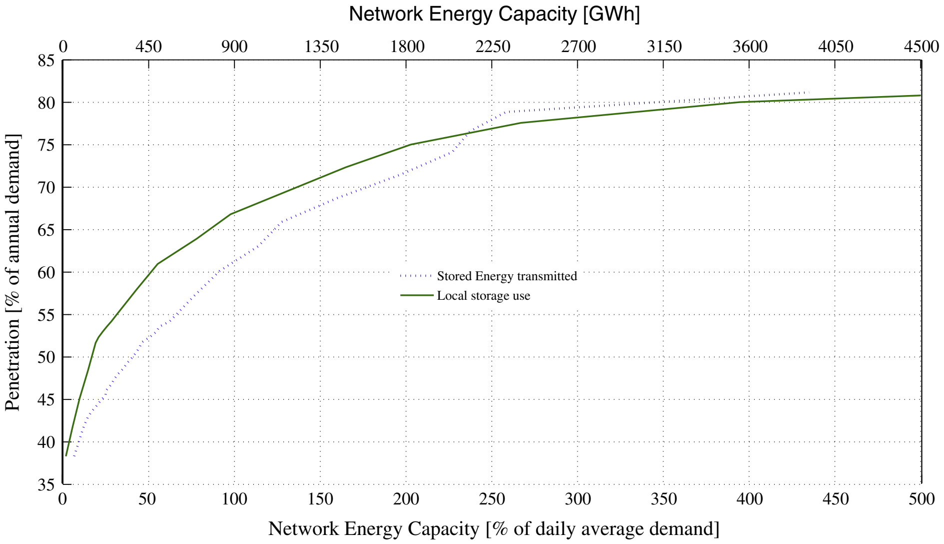

Fig. 4. Dependence of grid penetration on network storage energy capacity.

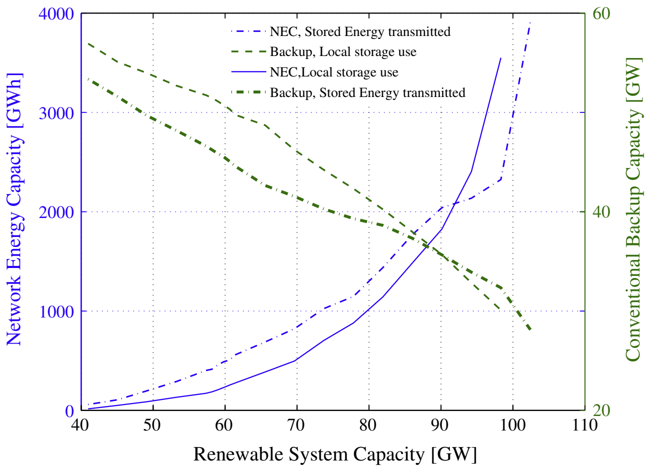

Fig. 6. Network energy capacity (left) and Conventional backup capacity (right) requirement as a function of renewable system size.

these models needed different network energy storage capacity in order to achieve that same penetration. The required network storage capacity for the SET model was larger than SEUL version for most system size less than 90 GW (Fig. 5 left *y*-axis). The main reason for such a difference is that in the former case storage serves the network by more than transferring excess renewable energy to later time. This can be seen from Fig. 6.

Fig. 6 presents the manner in which the required backup capacity and the corresponding energy capacity of the storage varies as we increase the variable generator system size. The figure shows that for both models as generator system size increases the conventional capacity requirement (left-axis) decreases in exchange for the corresponding increase in storage energy capacity. As discussed earlier, this figure shows that the SET model builds larger energy capacity to enforce more decrease in conventional backup capacity as compared to the SEUL model. Nothing could explain this effects than a close correspondence between the lower conventional backup capacities observed for most of the renewable system sizes to the relatively higher required energy capacity of storage under the SET model. Even though the storage system size increases, in both case, leads to a reduction in conventional system size and increased penetration, as we will be seeing later increasing storage without a limit is not the appropriate direction.

Before leaving this subject, it is worth discussing the nature of the power capacity and energy capacity interlink. Fig. 7 shows the Network Power capacity and the corresponding network capacity ratio (defined as the ratio of the network energy capacity to the Network Power capacity) versus the network energy capacity.

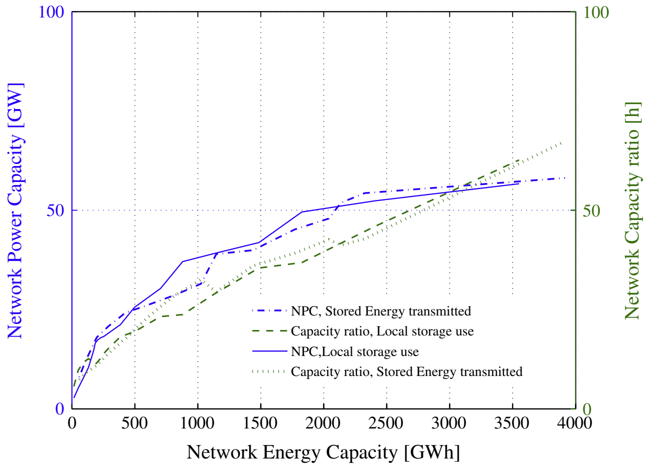

Fig. 7. Network storage power capacity and energy capacity relationship.

The figure indicates that for both models the required Network Power capacity increases with the corresponding energy capacity until it levels off. Alternatively, NEC (*x*-axis) shows an initial linear dependence on NPC followed by a sharp rise for little further increase in NPC. As a consequence, capacity ratio significantly increases with further increase in NEC.

The trend showing the relationship between the network storage energy and power capacity has an interesting similarity to the trends reported for Israeli grid by Solomon et al. [12,16]. This similarity suggests that seasonal and diurnal interaction of variable renewable system output and the demand profile determines the corresponding storage system design requirement in the present study too. The importance of this observation is that the decrease in the initial strong link of NPC and NEC suggests, for a very large storage system, choosing a convenient value for power capacity and then increase the energy capacity to any desired value if necessary.

A closer study of the data further reveals that, as in the case of the Israeli grid study [12,14], the Network Power capacity shows a strong linear dependence on the variable generation system capacity (data not shown) while the energy capacity depends on the seasonal and diurnal interaction of the local demand profile and the corresponding intermittent renewable system output profile. To clarify the latter, we will return to the study of the implication of the trend that we observed in Fig. 4.

Fig. 4 shows that for smaller network energy capacity grid penetration of variable generator shows a sharp increase. Penetration then gradually slows down as we increase the storage system size, leading to a large increase in storage system size in exchange for very small increase in grid penetration. This indicates that for the purpose of very high grid penetration, increasing storage system size beyond some capacity provides little help. Similar observation was also reported by Solomon et al. [12,16]. Fig. 4 clearly shows that a significant rise in penetration occurs when storage is significantly lower than the daily average demand of California. Penetration also starts slowing down well below the daily average demand (Fig. 4). In the following, we will explore the possibility of higher grid penetration using predefined energy storage system capacity and energy dumping.

3.2.2. Selection of appropriately sized storage

The slowing of the increase in penetration, after the turning point, discussed in the previous section indicates that an increase in storage system size does not always lead to an increased storage service under similar condition. Now it is of significant importance to find a way to define the capacity at which the storage service starts to diminish. A study by Solomon et al. [16] have attempted to quantify the storage energy capacity at which the storage use starts to decline for their PV-grid penetration analysis to Israeli grid. According to that study, the usefulness index starts to rise as the storage system size increases until it reaches some peak – which corresponds to storage system size that they termed as "peak EC" – where it begun decreasing. The present study despite significant differences, have produced almost similar dependence of grid penetration on storage system size. This indicates that usefulness index in the present study could show the same trends. In this section, we will examine if the same approach can help us identify the capacity at which storage use starts to decline. Fig. 8 presents storage UI versus the corresponding network energy capacity.

Fig. 8 shows that, initially, the storage UI sharply increases with storage system energy capacity but started decreasing after reaching the peak UI. The trend is similar to what is reported for the

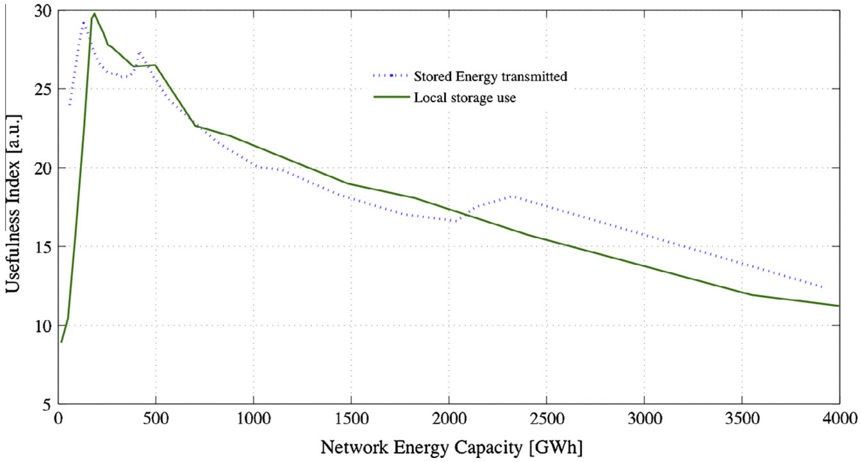

Fig. 8. The trend of storage usefulness index.

Israeli grid by Solomon et al. [16]. However the UI trend in the present study is not as smooth as the Israeli case, especially for the SET model that demonstrated another smaller peaks. This should be expected because in the present study, the model builds systems from large geographic domain as well as various wind and solar resources as compared to the single site PV resource in the Israeli study. For any condition, it is understood that the use of UI curve is not the best way for approximating the maximum threshold for the required storage but in such kind of study it is the only alternative that will help narrow the size selection. However, as we can see it below, the UI curve remains the only powerful tool that will explain many intricacies related to the role of storage. Here we would like to note that the difference in the UI curves for the two models -, shown in the present study, - may be a result of the SET models tendency to reduce the conventional backup more than its counterpart.

The most important lesson we draw from the overall trend observed for both model is that an increase in storage system size does not always lead to an increased storage service. Or alternatively, an increase in storage system size beyond some threshold value to increase grid penetration of intermittent renewable system is a poor strategy. This finding is in good agreement with what is reported in [16]. Especially most of the typical characteristics reported for SEUL model closely follows the trends reported in [12,16] despite significant differences between the models, their input data and the grid types. These results strongly confirm the need of optimizing the existing grid for the use of the variable resources based on the matching capability of these resources output to the demand profile. The major reason for this conclusion is that these results direct to the presence of the same fundamental intricacies that could help us design and operate a grid that relies on a very high energy from intermittent renewable resources. That fundamental detail is the ability to match the seasonal and diurnal profile of the variable generators output to the local demand.

Fig. 8 also shows that the UI remained very low even at its peak value (UI for IEC grid was 150 at 100% grid flexibility[3]). This indicates that: (1) the storage that corresponds to peak UI, peak NEC, could increase grid penetration by a substantial margin if we allow different form of dispatch, as discussed in [12,16]; (2) resource diversity also increased grid matching through their increased complementarities that also reduced storage need/use. Further clarification on the second suggestions will be given elsewhere. However, we will examine the first hypothesis in the following sections.

Now let us take a closer look at Fig. 8. The two prominent peaks for the SET model occurs when storage NEC is close to 130 GW h and 414 GW h, but that of SEUL model occurs at 186 GW h. Our thorough analysis shows that 414 GW h for the SET model and 186 GW h for the SEUL model corresponds to the same renewable system sizes. We, therefore, chose the two storage systems properties for our study. Unlike Solomon et al. [16] we did not use any curve fit, instead we selected the storage with peak UI by studying the data. The main reason is because the observed network wide trend is not expected to smoothly extend to load-areas since the storage design characteristics in such case can have the flexibility to vary by load area. But to make a good approximation of the storage size, we made a run by increasing the system size around these peaks only by 2% per each step.

3.2.3. Details of the selected network storage

Tables 2 and 3 below present the detail of both Network Energy storage systems. The network capacity for the SET model was 414 GW h, more than double the corresponding NEC for its counterpart (which is 186 GW h). Another difference that can be seen from these tables is that SEUL model built storage in 6 load areas as compared to 5 load areas in the SET model. This phenomenon is not surprising since the storage use was more localized in the former model. At the same time, it indicates various possibilities for energy storage deployment depending on resource distribution and other constraints. In this study the optimization models choose the specific load areas where storage is required without any exogenous restrictions on storage buildup.

The other important information to look in Tables 1 and 2 is the hours of storage needed for the aspired increase in grid penetration of intermittent renewable. The hours of storages shown in the tables are all less than 20 h. Most importantly, we can see that the SEUL model finds storage with less than 15 h depending on load areas. As can be seen later, the SEUL model seems to better approximate the peak NEC because of its ability to measure the seasonal and diurnal interaction of intermittent renewable resources. The observed hours of storage are almost within the range of many of the existing storage technologies. For instance, sodium sulfur and vanadium redox batteries are claimed to reach as high as 10 h of storing capacity based on the present technologies. While compressed air and pumped hydro storage can have the potential for longer storing hours.

In the next sections, we will explore the impact of increased storage service on penetration level and conventional backup capacity. Before we begin that we would like to inform the reader that the reported storage energy and power capacity are larger

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[3] Assuming that the storage fully charges and discharges on a daily bases, the maximum UI value will be about 274.

Table 2
Components of peak NEC storage by load area as approximated based on the SEUL model result.

Load_area	Energy capacity (GW h)	Power capacity (GW)	Capacity ratio (h)
CA_SCE_CEN	98.5	9.0	10.9
CA_SCE_S	19.1	4.6	4.2
CA_PGE_N	0	0	0
CA_PGE_BAY	0	0	0
CA_SDGE	0	0	0
CA_PGE_CEN	1.2	0.4	3.0
CA_SMUD	0	0	0
CA_PGE_S	12.6	3.0	4.2
CA_SCE_VLY	0.1	0.0	3.3
CA_LADWP	54.9	5.0	11.0
CA_IID	0	0	0
CA_SCE_SE	0.02	0.01	3.14
Total	186.5	22.1	0.0

Table 3
Components of peak NEC storage by load area as approximated using the SET model result.

Load_area	Energy capacity (GW h)	Power capacity (GW)	Capacity ratio (h)
CA_SCE_CEN	375.6	19.3	19.4
CA_SCE_S	0	0	0
CA_PGE_N	0	0	0
CA_PGE_BAY	0	0	0
CA_SDGE	0	0	0
CA_PGE_CEN	0	0	0
CA_SMUD	0	0	0
CA_PGE_S	1.3	0.3	5.0
CA_SCE_VLY	0	0	0
CA_LADWP	29.5	2.8	10.6
CA_IID	2.9	0.9	3.4
CA_SCE_SE	5.5	0.7	7.4
Total	414.8	24.0	17.3

than the capacity that we see in the model. The model sees 75% of the reported energy and power capacity due to the application of the roundtrip efficiency. However if we have had utilized the charging and discharging efficiencies in our model, we could have obtained a value between the two. We, therefore, divided the calculated energy and power capacity by the roundtrip efficiency to avoid under approximation of storage system capacity.[4,5]

3.3. Benefits of increased storage use

3.3.1. Very high penetration

Now we will explore how we can achieve higher penetration by altering storage dispatch strategy. We modified SET model by constraining the power capacity and energy capacity of the storage technologies not to exceed the value given in Tables 2 and 3. Consequently, when we push for very high penetration the model applies more energy dumping. Fig. 9 presents grid penetration versus the corresponding total energy loss.

Grid penetration of intermittent renewable energy increases significantly as we allow more energy losses, reaching a penetration of about 85% of the annual demand at 20% total energy loss. The 414 GW h/24 GW energy storage achieves slightly higher penetration over its counterpart even though its capacity is more than double. This suggests that, by comparison, this particular storage design is less appropriate for the desired purpose. Conversely, we see that the selection of peak NEC with the SEUL model would suffice to reach about the same level of penetration. In general, this discussion indicate that in achieving massive grid penetration of energy from variable generators, the ability to design a proper storage based on the seasonal and diurnal interaction of demand and renewable energy system output plays significant role. This conforms to similar findings by Solomon et al. [12,16].

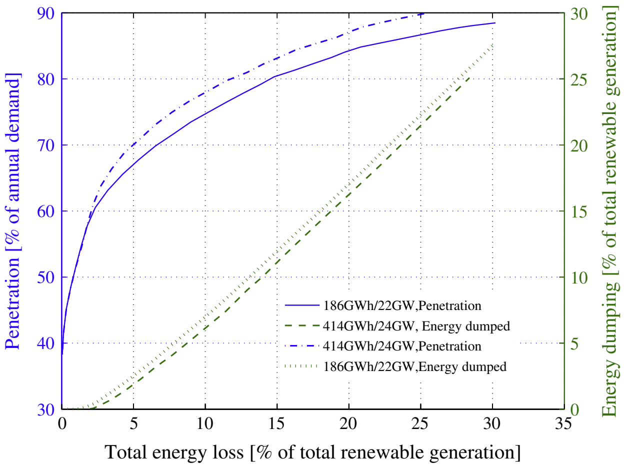

Fig. 9. Penetration (right) versus total energy loss, and the corresponding energy dumping (left).

Fig. 9 also presents the share of energy dumping in the total energy loss (i.e. total energy loss representing the loss due to storage efficiency plus energy dumping). The figure shows that the energy dumping was the major driving force behind the increase in total energy loss. By comparison, the loss due to storage efficiency has been less than 3% of the total renewable generation under all circumstances. But it is worth reminding the reader that storage use increased as shown in Fig. 10.

Fig. 10 shows that the storage usefulness index has increased as we increase the total energy loss. The increase for the 186 GW h storage shows that it was giving better service as compared to the larger 414 GW h storage. According to an estimation by Solomon et al. [16], if energy storage was fully charged and discharged on a daily bases, the maximum UI would have been 274 for the assumed roundtrip efficiency of 75%. This indicates that the larger storage was underutilized.

The UI trend in Fig. 10 shows that for both storage (i.e. the 186 GW h and 414 GW h) a small increase in total energy loss lead

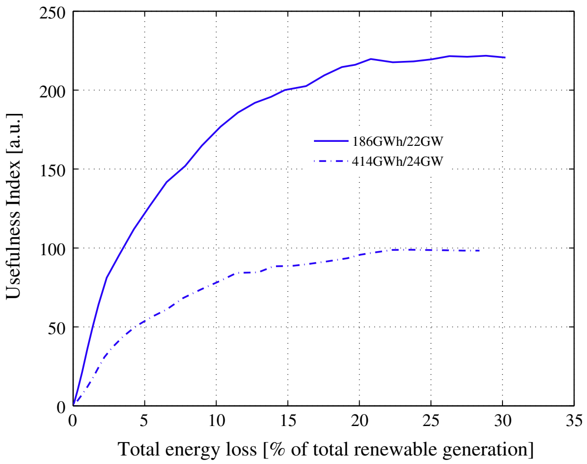

Fig. 10. Fraction of renewable energy delivered by storage.

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[4] If we assume storage with equivalent charging and discharging efficiency, 75% round trip efficiency would mean charging and discharging efficiency of about 0.86. This implies that the reported storage capacity could be a battery storage operated at 86% DOD.

[5] Note that this approximation of storage capacity does not account for important reliability and security criteria.

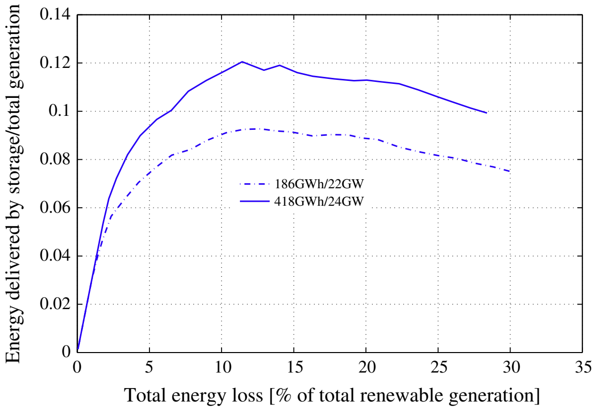

Fig. 11. Fraction of renewable energy delivered using energy storage.

to a sharp increase in storage use, which gradually slows down as we allow more energy dumping. This indicates that an increase in energy dumping does not always lead to increased storage use. We can see the above assertion from Fig. 11. The figure reveals two important findings. The first is that the storage delivered smaller amount of the energy to the grid (approximately 9% and 12% of the renewable energy at the highest condition for 186 GW h and 414 GW h, respectively) but it played a significant role of an enabler for intermittent renewable energy resources. The second is that the energy delivered by storage sharply increases when we start allowing energy dumping, which starts to decline after reaching some peak value. Fig. 11 shows that the trend of energy delivered by storage reaches its peak between 10% and 15% of the total energy loss (but may be considered as a plateau region stretching from 10% to 20% total energy loss since the peak is not that sharp specially for the 186 GW h storage), where it starts to decline. Similar trend was also reported for the Israeli grid [16], in which case, storage delivered significant amount of the energy from intermittent renewable resources. This is because that study, on top of being an island grid (treated as one load area system), considers the case of PV technology only. In the presence of diverse resources and large interconnectivity, the complementarities of the resources and the power exchange potential reduce storage requirement. Our investigation of the potential of resource complementarities will be published elsewhere along with other findings.

3.3.2. Conventional backup system requirement

The above discussion shows that a change in storage dispatch, via the use of energy dumping, increases grid penetration of intermittent renewable energy and storage use. In this section, we will explore how this dispatch strategy impacts the conventional backup requirements. Fig. 12 presents the backup capacity requirement versus total energy loss. The figure shows that the backup capacity requirement significantly decreases as total energy loss increases. When total energy loss reaches 20% of the total renewable generation, the conventional backup capacity requirement has decreased approximately to 33 GW and 35 GW for the 414 GW h and 186 GW h of storage, respectively. This is very significant because the same capacity was sufficient to meet the year round hourly demand, including the 59 GW peak demand hour plus the 5.3% hourly distribution loss. In addition to the decrease in capacity, the backup also provides only 15% of the annual demand because it was called upon only to complement when the variable generator and storage system falls short in meeting the demand. The present finding carries a very significant implication for storage economics and the operation of such a grid.

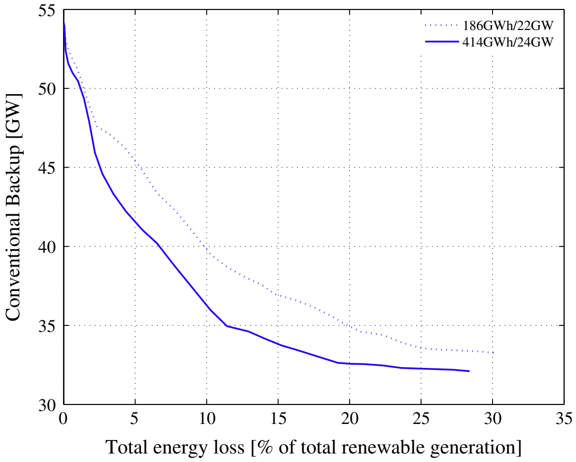

Fig. 12. Conventional backup requirement.

Table 4
Comparing the role of transmission increase versus storage at 80% energy penetration.

Transmission	Storage	Total energy loss (% of annual demand)	Total renewable generator capacity (GW)
Existing	184 GW h/ 22 GW	15	115
Existing	None	40	170
1.2 * existing	None	40	170

Recall that Fig. 9 reveals that the 414 GW h storage shows small advantage over the 186 GW h in increasing grid penetration. At the same time, Fig. 12 implies that the 414 GW h storage has shown significant advantage in reducing the conventional backup capacity need. However, this advantage is counter balanced by its more than double energy capacity as well as its power capacity that is 2 GW larger than the other storage. From this and the foregoing discussion, we conclude that the largest storage need for California under the present study is approximately 184 GW h. This storage is about 22% of California's daily average demand. The corresponding storage capacity reported for Israeli grid was about 72% of its daily demand. This shows that designing storage based on the seasonal and diurnal interaction of the intermittent renewable output and the load profile significantly matters to achieving very high penetration and an efficient system performance. More importantly, designing an efficient grid requires the ability to manage a complex trade-offs involving diverse factors such as environment, economic, efficient use of resources, new and existing operational criteria, new and existing system reliability criteria, etcetera.

In addition to the significant potential of the storage technology to decrease the conventional backup need, Table 4 shows that it also carries a potential to avoid the need to dump/curtail significant energy to achieve the same level of very high penetration without storage. Contrary to the customary wisdom that declares transmission increase as a necessity for an increased penetration, allowing 20% inter-load area transmission capacity increase above the present total capacity does not show any significant gain in terms of increased penetration or reduced energy dumping. Moreover Table 4 shows that, in the absence of storage, we should build significantly large intermittent renewable systems to reach the targeted 80% penetration. This result indicates that at a very large penetration, energy storage could render a significant technical, environmental and social benefits. It also affirms that grid design for renewable penetration should focus, inter-alia, on taking advantage of the resource diversity as well as its year round matching capability to the load profile.

3.4. Economic modeling requirements

The above study indicates that designing an efficient storage grid that relies on large storage may not be a simple economic problem, and several other researchers have addressed similar issues [19–22], though without the level of detail required for designing large storage-grid that we include in this paper. We have left economics out of the present study because future storage costs are highly uncertain and we seek to capture the less ambiguous physical, timing and efficiency issues associated with storage deployment without obscuring those issues with uncertain economic factors (this approach is similar in spirit to preceding analyses, e.g. [23]).

At this point, it is nevertheless instructive to enquire how an economic model could measure the role of storage using the issues discussed above as context. The foregoing discussion suggests that realizing such an efficient grid in a least cost way requires the capability to measure many physical and policy dimensions. In the following, we will briefly discuss some of the most important criteria in the context of the present study. We intend to extend the present work to address these issues in a detail in a future study.

3.4.1. Flexibility of storage design and dispatch

Unlike conventional generators, which converts other form of energy to electrical energy, energy storage stores electrical energy in whatever form (depending on storage technology) and converts that back to electrical energy when needed. This process carries time dynamics because storage cannot deliver energy if it did not store. Nor can it store more than its energy capacity at a given time. More importantly, when it stores excess energy generated by variable generators and delivers it at later hours. The time dynamics become more important because (1) the benefit of storage in performing the task depends on temporal matching between demand and the intermittent renewable system output; and (2) the amount of energy that it can deliver/store depends both on its power capacity and energy capacity. Therefore, the model should have the flexibility to capture the required storage design. Together with that comes the importance of dispatch flexibility. The foregoing storage studies show that the storage energy capacity requirement depends on how they are dispatched from day to day. To find the optimal design one have to capture their optimal dispatch performance under certain operational policy. But as shown above, the present operational policies appear to undermine the potential benefit of storage. Finally, without the capability for storage design and dispatch, and storage time dynamics, it is difficult to measure the value of various operational policies.

3.4.2. Flexible operational policy

The present power market does not allow any kind of energy curtailment. In the future grid where spring excess generation becomes common, we may need to have a policy that separates excess renewable generation time from under generation time. Unlike the present day grid, in which excess energy is very low. The massive excess generation of the future grid may require us to design the market in a way that motivates safe curtailing or storage service or both to maintain grid stability rather than keeping online conventional spinning reserves. The above study also shows that proper implementation of storage and energy curtailment significantly reduces the conventional backup capacity requirement. As a result, developing a model that can test such operational policy scenarios could help in examining the cost of dumped energy plus storage system versus avoided investment in the conventional capacity that would have been built under storage without dumping. Or it could be useful to investigate the cost of energy under a largely storage and renewable energy system that can dump some energy versus an equally decarbonizes grid with present day operational policy.

3.4.3. Complementarities of grid operation

High penetration of intermittent renewable system requires the ability of conventional backup system to substitute for the shortcomings of intermittent renewable system plus storage technologies. This will require that we have adequate number of units that can be online in short notice and have the capability to do many on/off cycles as necessary. This operational complementarities requires that the models have the ability to build and operate power plants that have this capability, constrained by their number of on/off cycle, minimum up/down time, ramp rate and range if any, etc. Even if, we have a base load unit that should continuously be online, variable renewable' ability to supply substantial part of the remaining load depends on our ability to employ proper operational strategy.

In addition to the above criteria, other factors such as renewable resource complementarities and reserve allocation strategies may have their own impacts.

4. Conclusion and recommendations

We investigated the possibilities for very high grid penetration of intermittent renewable energy output with and without energy storage. The study was performed using hourly load data and simulated intermittent renewable system output for the state of California. The hourly data for the year 2011, transmission networks thermal capacity and the corresponding loss between load areas in the state are taken from the SWITCH database [1]. Following [1], we also divide the state into 12 load areas. Even if the state receives significant energy from outside, we ignore the incoming power in order to capture the role of the existing transmission line dispatch, storage technology requirement and the temporal match between the demand and the variable generator output on maximizing penetration as we increase variable generator size. We assume that conventional generators have 100% flexibility to allow the optimal use of energy from the intermittent renewable systems. The result of this study shows many important findings, some reported and some are not.

First, we found that due to temporal overlap between load profile and the variable generators output, increasing long-distance transmission beyond the existing capacity has little significance to increase grid penetration of intermittent renewable. Since both the load and intermittent renewable system output profile changes from year to year, it is not easy to draw simple lessons for long term planning. However, it can be inferred that, at least for the present study, the inter-load area long distance transmission increase should not substantially exceed the transmission capacity needed to meet the regular load increase. We also found that connecting centralized power plants to the existing network allows the use of the best resources, which leads to higher energy penetration (by at least 10% of the annual demand) as compared to the equivalent distributed systems.

Second, designing and operating a grid based on the seasonal and diurnal match between load profile and the local variable resources output may lead to a more efficient use of resources. At the core of such a question is the capability to find the best grid skeleton (as can be seen in comparing Tables 2 and 3 and the subsequent discussion regarding the conventional backup), the appropriate design properties of the storage system and their proper mix, and managing complex trade-offs involving diverse factors such as environment, economic, efficient use of resources, new and existing operational criteria, new and existing system reliability criteria, etcetera. This study and the one by Solomon et al. [12,16] shows that the maximum threshold for the storage need is significantly less than the daily average demand. In the present study, we have found that the approximate network energy storage is of the order of 186 GW h/22 GW. The maximum threshold value may vary, however, depending on local resources, the nature of the network, the composition of the storage hybrid system, targeted penetration level, etcetera. The 186 GW h/22 GW network storage is about 22% of California's 2011 daily average demand. In the contrary, the Island Israeli grid was shown to require about 72% of the daily average demand in order to increase grid matching of PV generators. It is worth to remind the reader that new reliability criteria and consideration of storage multi-aging factors could also push the storage value a little higher.

Third, allowing energy dumping was shown to increase storage use, and by that way, increase grid penetration of intermittent renewable system and reduce the required backup conventional capacity requirements. In the present study, we found that using the 186 GW h/22 GW storage and allowing 20% energy dumping, grid penetration of intermittent renewable system was increased to approximately 85% of the annual demand of the year 2011 while reducing the conventional backup capacity to 35 GW. This capacity was sufficient to supply the year round hourly demand, including the 59 GW peak demand of the year, plus a distribution loss of about 5.3% of the hourly demand.

Fourth, in addition to reducing conventional backup requirement, energy storage was also shown to enable the achievement of very high penetration with smaller energy dumping and total generation capacity. For example, to achieve 80% penetration with the 186 GW h/22 GW storage, the energy loss and the total renewable capacity would have been approximately 15% and 115 GW, respectively; as compared to the 40% total loss and close to 170 GW renewable capacity without any storage. From this and the foregoing results, we conclude that at a very large penetration, energy storage could render a significant technical, environmental, and social benefits.

Finally, the above findings indicate that the economic and technical performance of different technologies/measures that may help increase the compatibility of the renewable resources to the electricity grid depends on the nature of operational policy that we implement. In transitioning to a future renewable energy grid, it is important that we have the tools that may help us evaluate diverse physical and operational policy scenarios of the future grid. This is important because the performance of some technology may depend on the future operational rules as it also depends on technological advancements and their cost. For example, we saw that depending on the level of the energy curtailment, storage technology could increase grid penetration of variable renewable resources while also reducing the required conventional backup capacity need to meet the year round hourly demand. This indicates that designing an efficient and least cost grid requires the capability to bring together those values and measure how they can be used gainfully in the future power market.

Acknowledgement

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Appendix A.

A.1. No-Dump (ND) system calculation

To make life simple, we begin from calculating the maximum penetration without any energy dumping and storing, and the corresponding generator system size termed as the No-Dump (ND) system. This is a logical place to begin assessing the impact of different approaches, - such as energy dumping/curtailment, transmission network and energy storage, - on grid penetration of intermittent renewable. To calculate the ND system, we create a model that maximize state wide penetration by setting the hourly power generated by a set of intermittent renewable generators in every load area to be equal at most the local load.

A.1.1. The algorithm

First let us define three hourly vectors – non-distributed variable generator "VG_N", distributed generator "VG_D" and total variable generators "VG_T" – for each load area. These vectors will not appear in the linear program model directly.

$$\begin{aligned} VG_{N_{a,y,h}} &= \sum_{i,t} VG_{i,a,t} * CF_{a,y,h,i,t}, \quad \exists t \notin DistributedGenerators \\ VG_{D_{a,y,h}} &= \sum_{i,t} VG_{i,a,t} * CF_{a,y,h,i,t}, \quad \exists t \in DistributedGenerators \\ VG_{T_{a,y,h}} &= \sum_{i,t} VG_{i,a,t} * CF_{a,y,h,i,t}, \end{aligned} \tag{9}$$

where *VG is* variable generator, *CF* is hourly capacity factor of the generator defined based on the hourly metrological data. While indices a, y, h, i and t stands for load area, year, hour of the year, project identification and technology type, respectively.

The constraints built into the model for the ND system case are:

C1. The hourly-consumed renewable power within each load area, "*RPC*", is at most equal to the local hourly load, "*L*", plus distribution loss, "*dl*".

$$RPC_{a,y,h} \leqslant L_{a,y,h}(1+dl)$$

$RPC_{a,y,h}$ is unsigned variable because we want to allow this vector to take negative values if solar thermal is included in the final generator mix, which could have a negative output due to the energy needed to avoid condensation of the heat transfer fluid at low temperature time. Alternatively, we could use the constraint

$$RPC_{a,y,h} + HB_{a,y,h} = L_{a,y,h}(1+dl)$$

and $HB_{a,y,h} = L_{a,y,h}(1+dl)$. But we use the former to for computational simplicity.

C2. The intermittent renewable system to be built should include existing capacity.

$$VG_{i,a,t} = VG_{i,a,t}, VG_{i,a,t} \in Existing\_plants$$

C3. The ND constraint requires that the hourly renewable power consumed be the same as the total local hourly generation plus the distribution loss that is avoided by the distributed solar technologies. Note that power transfer can also be considered if need be.

$$RPC_{a,y,h} = VG_{T_{a,y,h}} + dl * VG_{D_{a,y,h}}$$

C4. The capacity of the installed generator is constrained by the resource availability. For wind technologies and distributed solar technologies the capacity to be installed is limited to the maximum project capacity "*cl*", but for central solar stations the limiting factor is land availability. The latter relates to the maximum project capacity via capacity limit conversion factor "*clc*" and should not exceed the total central solar project capacity "*CSS*" at a specific location "*l*".

$$\begin{aligned} & VG_{i,a,t} \leqslant cl_{i,a,t}, \quad \exists\{i,a,t\} \notin Central\ solar\ plants \\ & \tfrac{VG_{i,a,t}}{clc_{i,a,t}} \leqslant CSS_{l,a}, \quad \exists\{i,a,t\} \in Central\ Solar\ Plants \end{aligned} \tag{10}$$

The objective function is:

$$\text{Maximize TotalRenewableEnergy} = \sum_{a,y,h} RPC_{a,y,h}$$

A.2. Increasing renewable penetration by spilling excess energy

This algorithm extends the previous section in order to examine the potential penetration increase when we oversize variable generating system beyond ND system size and allow energy dumping. We will first present the case in which transmission potential between load areas are ignored, followed by cases involving transmission lines. Even if the concept is changing the objective function will remain the same as the one given above. We also keep constraints C1, C2 and C3 of the above in this section and all that follows.

A.2.1. No transmission between load areas

The additional constraints for this subsection are:

C5. The hourly renewable power consumed within a given load area is at most the total available power from the variable generators.

$$RPC_{a,y,h} \leqslant VG_{T_{a,y,h}} + dl * VG_{D_{a,y,h}}$$

C6. The condition that the total variable generator capacity increases as a multiple of the ND-system size. This allows us to increase system size beyond ND step by step using simple system multiplier, "*sm*". In this study, the default value of "*sm*" is 1 but it was set to increase by 10% for every step increase.

$$\sum_{i,a,t} VG_{i,a,t} = sm * ND_{system}$$

where ND_{system} is total statewide nodump capacity.

A.2.2. Transmission between load areas

Constraint C6 will be part of this section and all that follows. Two additional constraints specific to this problem are:

C7. The hourly renewable power consumed within a given load area is the total available power generated by local variable generators plus the net power exchange with other load areas.

$$RPC_{a,y,h} \leqslant VG_{T_{a,y,h}} + dl * VG_{D_{a,y,h}} + \eta_t * T_{a1,a,y,h} - T_{a,a1,y,h}$$

where $T_{a1,a,y,h}$ and represents power transmitted from load area "*a1*" to load area "*a*" in hour "h" and transmission efficiency, respectively, while $T_{a1,a,y,h}$ being power flowing in the opposite direction.

C8. The power flowing between load areas at a given time cannot exceed the thermal capacity "T_C" of the transmission line connecting them.

$$T_{a1,a,y,h} \leqslant T_{C_{a1,a}}$$

Here we present few formulas that do not appear in the LP but are useful to assess the general information obtained from the model. Grid penetration "*P*" is calculated as:

$$P = \frac{\sum_{a,y,h} RPC_{a,y,h}}{\sum_{a,y,h} L_{a,y,h}(1+dl)} * 100$$

While Energy dumping, "*D*" is calculated as follows (this includes transmission and distribution losses):

$$D = \frac{\sum_{a,y,h}(VG_{T_{a,y,h}} + dl * VG_{D_{a,y,h}} - RPC_{a,y,h})}{\sum_{a,y,h} VG_{T_{a,y,h}}} * 100$$

A.3. Increasing renewable penetration by allowing to store energy

This section is intended to explore the storage design requirement as we increase the variable generator capacity as given in C6. We assume that we have an infinite energy storage capacity, with 75% roundtrip storage efficiency η, that prevents any energy spill. The algorithm will allow us to see the nature of network storage energy capacity and power capacity at each level of grid penetration, and their variations with an increase in grid penetration of energy from variable renewable systems. We also assume that power transfers between load areas are limited by thermal capacity of the existing transmission line as given in C8, which is also part of all the sections that follows. Note that this algorithm is developed based on the assumed round trip efficiency. In case the storage charging and discharging efficiency are available, a minor change to this algorithm will be needed.

A.3.1. Stored energy assumed to be transmitted

This model is created based on the assumption that the stored energy could be transmitted out of load area. The constraints specific to these sections are:

C9. The energy generated by renewable will be either directly consumed locally, or transmitted to other load areas, or stored or dumped if necessary based on the demand supply constraints given below. The backup system serves load when the energy coming from renewable and storages cannot satisfy the corresponding hours demand.

$$\begin{aligned} &RP_{a,y,h} - SP_{a,y,h} + VG_{T_{a,y,h}} + dl * VG_{D_{a,y,h}} + \eta_t * T_{a1,a,y,h} - T_{a,a1,y,h} \\ &\quad + HB_{a,y,h} - HE_{a,y,h} = L_{a,y,h}(1+dl) \end{aligned}$$

The next two constraints will preserve the hour-to-hour dynamics. The energy dynamics in storage generally evolves as a function of stored and released energy, which can be represented as:

$$\frac{\partial EinS(t)}{\partial t} = \eta_c * SP(t) - \frac{1}{\eta_d} * RP(t)$$

where η_c and η_d stands for charging and discharging efficiency of storage, respectively. But in a time discrete case, such as the present study, it becomes:

$$\frac{\Delta EinS}{\Delta t} = \eta_c * SP(t) - \frac{1}{\eta_d} * RP(t)$$

However, since this study uses a uniform time discrete of 1 h, a simplifying approach given below has been implemented. But for time discrete other than 1 h, care should be taken to correctly represent the Δt. Note also that this algorithm is developed based on the assumed round trip efficiency, instead of discharging and charging efficiency.

C10. Energy in storage at the first hour of the year is

$$EinS_{a,y,h=1} = 0 + \eta * SP_{a,y,h=1} - RP_{a,y,h=1}$$

Energy in storage prior to this hour is assumed to be zero. At this point, we can see that the release will automatically be zero because "*EinS*" is a non-negative entry matrix.

C11. For all other hours, the storage energy balance is given as:

$$EinS_{a,y,h} = p * EinS_{a,y,h-1} + \eta| * SP_{a,y,h} - RP_{a,y,h}$$

where "*p*" is stored energy derating factor to reflect energy lost due to storage self-discharge, for this study we took *p* = 0.9999 for each hour. This value is similar to assuming 6%/month self discharge loss.

Constraints C12 through C13 are added to force the upper limit on storing processes using storage characteristics i.e. energy capacity, power capacity and discharge capacity.

C12. Energy stored is always less than the local energy capacity:

$$EinS_{a,y,h} \leqslant E_a$$

C13. Both released power and stored power cannot exceed the power capacity of the storage.

$$\eta * SP_{a,y,h} \leqslant PC_a$$
$$RP_{a,y,h} \leqslant PC_a$$

C14. Power generated by set of conventional systems cannot exceed the conventional capacity.

$$HB_{a,y,h} \leqslant GC_a$$

C15. The constraint that at any hour of the year, except the first hour, the stored power plus the energy already in the storage does not exceed the storage energy capacity.

$$EinS_{a,y,h-1} + \eta * SP_{a,y,h} \leqslant EC_a$$

In non-economic model, such as this one putting renewable penetration as an objective does not tell the entire story. Because the model can build an arbitrary storage system size and optimize the energy penetration. However we can write our objective function in a way that enable us to do multiple things simultaneously i.e. optimize penetration, and minimize storage system properties and the conventional back up capacity.

Below we will present some simplifying representations given in our objectives.Network energy capacity "*NEC*" is:

$$NEC = \sum_a EC_a$$

Network Power capacity:

$$NPC = \sum_a PC_a$$

Total conventional generator capacity required for backup:

$$TGC = \sum_a GC_a$$

Objectivemaximize_Renewable_penetration_while_minimizing_storage_and_conventional_backup_requirements:

$$\left. \underbrace{\sum\nolimits_{a,y,h} (Load_{a,y,h} * (1 - dl) - HB_{a,y,h})}_{\text{first term}} + \underbrace{\sum\nolimits_{a,y,h} (\eta * SP_{a,y,h} - RP_{a,y,h} - p * EinS_{a,y,h})}_{\text{second term}} - \underbrace{(\mathrm{NEC} + \mathrm{NPC} + \mathrm{TGC})}_{\text{Third term}} \right\}$$

The top term represents annual energy supplied by variable generators while the middle term, which from C11 above, is internal storage loss. The bottom term in the objective function contains *NEC*, *NPC* and *TGC*. The middle term allows optimizing internal loss as an incentive in order to avoid simultaneous charging and discharging that occurs during the simulation. But the first and the last term carry significant physical meaning. While the first one optimizes penetration, the third one helps achieving that goal by simultaneously minimizing the required storage and the conventional backup capacity. This objective combines two potentially independent objectives at the expense of the objective functions semantic meaning. Consequently, post optimization calculation was used to define the real grid penetration of energy from variable generators.

A.3.2. Stored energy consumed only locally

In the foregoing storage version, the storage design could be affected by many other factors other than the seasonal and diurnal matching between demand profiles and intermittent renewable energy systems. For the purpose of comparison and identification of better storage design requirements, we constructed a version that limits the stored energy for local use only even if direct power transmission of the generated renewable energy between load areas are permitted. Constraints C12, C13, C14, C15 are also part of this version.

C16. Because of the imposed limitation that the stored energy is used locally,

hourly renewable power consumed in a given load area is a function of hourly storable power "*SP*", hourly excess "*HE*", total available power generated by local variable generators and the net power exchange with other load areas.

$$RPC_{a,y,h} + SP_{a,y,h} + HE_{a,y,h} = VG_{T_{a,y,h}} + dl * VG_{D_{a,y,h}} + \eta_t * T_{a1,a,y,h} - T_{a,a1,y,h}$$

C17. Our power balance equation will then become:

$$RPC_{a,y,h} + RP_{a,y,h} + HB_{a,y,h} = L_{a,y,h}(1 + dl)$$

Even if the power produced by the backup generators are consumed only locally, we consider this treatment to be reasonable for the intended comparison.

C18. The lower limit on the hourly renewable power consumed:

$$RPC_{a,y,h} \geqslant VG_{i,a,t} * CF_{a,y,h,i,t}, \exists t \in Solar\ Thermal\ and\ CF_{a,y,h,i,t} \leqslant 0$$

The objective function remains the same as the previous section.

A.3.3. Increasing storage service

So far the algorithm is tailored toward investigating the nature of the storage requirement as we increase the system size. Under such circumstances, storage use is mostly low because the model builds more and more storage capacity in order to increase penetration even if it has the option to dump energy.

In this section, we will approximate the proper storage technology using storage usefulness index curve as discussed in Solomon et al. [16]. We also compare the above two models in the event the approximation of the proper storage in one of them are not straightforward. Up on selecting the storage, we begin exploring the impact of its increased use. We set the storage characteristics to the selected values and increase system size, consequently the model allows more energy dumping as system size increases to optimize penetration.

This exercise also consists constraints C9, C10 and C11. The additional constraints are:

C19. The energy in storage at any hour cannot exceed the corresponding storage energy capacity, $x_{a,y}$.

$$EinS_{a,t,h} \leqslant x_{a,y}$$

C20. The storable power at any hour of the year cannot exceed the corresponding power capacity of the storage, $p_{a,y}$.

$$\eta * SP_{a,y,h} \leqslant p_{a,y}$$
$$RP_{a,y,h} \leqslant p_{a,y}$$

C21. The constraint that at any hour of the year, except the first hour, the stored power plus the energy already in the storage does not exceed the storage energy capacity.

$$EinS_{a,y,h-1} + \eta * SP_{a,y,h} \leqslant x_{a,y}$$

Objective function maximize_penetration_while_minimizing_conventional backup:

$$\left. \underbrace{\sum\nolimits_{a,y,h}(Load_{a,y,h} * (1 - dl) - HB_{a,y,h})}_{\text{first term}} + \underbrace{\sum\nolimits_{a,y,h}(\eta * SP_{a,y,h} - RP_{a,y,h} - p * EinS_{a,y,h})}_{\text{second term}} - \underbrace{(\mathrm{TGC})}_{\text{Third term}} \right\}$$

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