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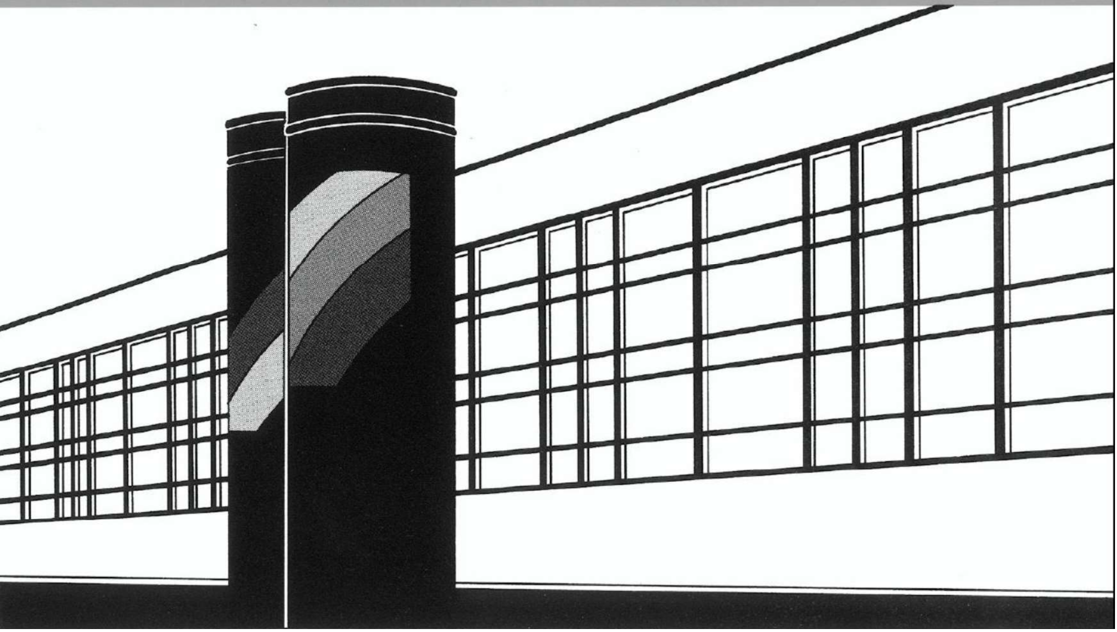

Heft 266 Jannik Haas

Optimal planning of hydropower and energy storage technologies for fully renewable power systems

Optimal planning of hydropower and energy storage technologies for fully renewable power systems

von der Fakultät Bau- und Umweltingenieurwissenschaften der Universität Stuttgart zur Erlangung der Würde eines Doktor-Ingenieurs (Dr.-Ing.) genehmigte Abhandlung

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Dedication

To our Earth, which is not flat, in the hope that we won't kill it and that climate change won't kill us.

To my wife Camila, the best life-partner I could wish for, for joining me in this adventure. In return, she will now have to call me Dr. Husband.

To my doctor-dad Wolfgang, for his permanent, tremendous, and sincere support and his famous brain-storming/bombing moments.

To my co-supervisor Rodrigo for his always-sharp ideas and our long-term honest and fruitful cooperation.

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To my colleagues for the nice working atmosphere, and all the celebration cakes and schnapps. Maybe that's why I'm not in shape; then again, round is a shape.

To my Stuggies, Cristobal T, Simon M, and Marce C —and the Mexican Stuggies, Christian K, Marcela K, Mauricio S, Jan L— who are always there. For the fun, and for the trouble, and for the beer. And to Bruno M who is also there, for the beer.

To my besties Wybe, Leo, and Gerrit, who are like brothers to me. With the exception of Gerrit, who actually is my brother. And to Felipe M, my math bestie.

To my parents for loving me and making me more than just a pretty face.

To my cats Lilo and Milan (no, I don't use them as passwords).

To a solar world.

Contents

List of figures

List of tables

List of acronyms

(a)CAES	(adiabatic) Compressed air energy systems
AC	Alternating current
BESS	Battery energy storage systems
BEV	Battery electric vehicles
CAP	Capacitors
CHP	Combined heat and power
CSP	Concentrated solar power plants
DC	Direct current
DSM	Demand-side management
DW	Drinking water installations
EL	Electrolyzers
ESS	Energy storage system
EV	Electric vehicles
FC	Fuel cells
FW	Flywheels
G	Generic storage
GEP	Generation expansion planning
GT	Gas turbine
GT	Gas turbines
H_2	Hydrogen
HT	Heat technologies
LP	Linear Programming
MILP	Mixed Integer Linear Programming
MINLP	Mixed Integer Nonlinear Programming
NLP	Nonlinear Programming
P2G	Power to gas
PHS	Pumped-hydro storage
PV	Photovoltaic
SEP	Storage expansion planning
VRE	Variable renewable energy systems
WR	Water reservoirs

Abstract

Greenhouse gas emissions need to stop shortly after mid-century to meet the Paris Agreement of keeping global warming well below 2°C. Fully renewable energy systems arise as a clear solution. To cope with their highly fluctuating power output (wind and solar photovoltaic), power systems need to become more flexible than they are today. Energy storage is one source of flexibility and is widely esteemed as a key-enabler for the energy transition. Hydropower often has storage, and can also help in this task.

To assess how much energy storage is needed, expansion planning tools are commonly used. In general terms, they aim to minimize system-wide investment and operational costs, while meeting a set of techno-economic constraints. In the task of quantifying the need for energy storage, the present thesis makes *four contributions*, related to the overarching research question: *how to plan the optimal energy storage mix for fully renewable power systems with important shares of hydropower?* These contributions aim to assist the energy transition and to be relevant for energy system modelers, energy policy makers, and decision makers from ecohydrology, storage companies, and the renewable industry.

- First contribution: The last couple of years have seen a particularly strong enrichment of such expansion tools. In response, the first contribution of this thesis is to provide a comprehensive review of the existing models, including a clear classification of the approaches and derivation of the current modeling trends.

  This review culminates by identifying the following open challenges for storage planning. First, the many available storage devices are quite diverse in their technical and economic parameters (including efficiency and lifetime), and this must be considered in the models. The tools also need to count with a high resolution of space and time to adequately capture the challenges of integrating renewable generation. Second, the many services that storage technologies can provide (beyond energy balancing, such as power reserves) need to be acknowledged. And third, the different energy sectors (electricity, heat, transport) all have sources of flexibility; thus, planning has to become multi-sectoral.
- Second contribution: Many storage expansion studies have been produced within the last 5 years, but these resulted in a very broad range of storage requirements. To shed light on their recommendations, the *second contribution* systemizes over 400 scenarios of these studies for the U.S., Europe, and Germany.

  This exercise revealed that, as the share of renewable generation grows, the power capacity (e.g. GW, in pumped hydro, related to the number of turbines) and energy capacity (e.g. GWh, in pumped hydro, related to the water held by its reservoir) of storage systems increase linearly and exponentially, respectively. As grids become highly renewable, especially when based on solar photovoltaic, the need for storage peaks. The power capacity is around 40-75% of the peak demand, and the energy capacity 10% of the annual demand. A final finding of this analysis is that assumptions on electrical grid

modeling, grid expansion, and energy curtailment have strong impacts on the found storage sizes.

- Third contribution: Developing a new optimization tool for storage expansion planning in the power sector is the third contribution: LEELO (Long-term Energy Expansion Linear Optimization). LEELO extends the available models by including further services in the planning approach: power reserves and energy autonomy. A further novelty of LEELO is a detailed representation of hydropower cascades, which is a convenient source of flexibility in many regions of the world.

  A case study about Chile for the year 2050 assesses the impact of including these multiple services in the planning stage on the final storage recommendations. Indeed, the found deviations in total power capacities and energy capacities of storage are large; up to 60% and 220%, respectively. Moreover, the resulting storage mix (i.e. the sizes of the individual storage technologies) is also strongly affected. Lastly, planning with such services revealed a 20% cost increase that would otherwise remain hidden to the planners.

  Overall, modeling multiple services in expansion planning is relevant when designing fully renewable systems, as controllable (*dispatchable*) generators disappear.

- Fourth contribution: In the final contribution, two optimization-objectives are added to LEELO. The first one relates to reducing hydropeaking, a highly fluctuating operational scheme of hydropower reservoirs that threatens the downstream river ecology. The second objective minimizes new transmission lines, as they have numerous externalities that result in delays and social opposition. Multi-objective LEELO is able to find the Pareto Front of these three dimensions (costs, hydropeaking, new transmission).

  In a case study, again about Chile, the found trade-offs are assessed from the perspective of the involved stakeholders. It found that the minimum cost solution requires doubling the existing transmission infrastructure while operating at severe hydropeaking. Avoiding all transmission projects will cost between 3 and 11% (depending on the allowed level of hydropeaking). In other words, the upside of new transmission is rather limited. As transmission is avoided, the generation turns significantly more solar while investments in wind decrease. At the same time, and to support a solar grid, the requirements for storage technologies grow. Demand for storage also grows when hydropeaking is constrained, as a direct response to the missing flexibility from hydropower. Severe hydropeaking can be mitigated for as little as 1% of additional costs (if new transmission is installed), which is good news to environmental organizations. Completely avoiding both hydropeaking and new transmission lines is the most extreme scenario, costing an additional 11% and requiring about 20% more storage power capacity.

  In short, cheap storage and solar technologies emerge as key-enablers for reaching such attractive solutions that can avoid both externalities (transmission and hydropeaking). A clear investment strategy for these technologies is needed and, if done right, can make the generation more

sustainable and socially acceptable.

When comparing the storage requirements for Chile to those for Europe and the U.S., it becomes clear that the storage *power capacities* needed for Chile are on the higher end (>70% of peak demand). This is related to the fact that Chile's power system is about 20 times smaller and has highly correlated energy resources. The needed *energy capacities* are also on the higher end (9-13% of annual demand). Here, however, the existing hydropower park already provides a buffer of 6%, making the *remaining* demand much lower (3-7%). If new transmission projects are to be avoided, the need for storage increases very strongly in terms of power capacity (adding 5 to 30 percentage points) and only slightly in terms of energy capacity (adding 1 percentage point). Mitigating hydropeaking also increases the need for power capacity but without exceeding the range above. The strongest storage requirements arise from the multi-service simulations; in particular for meeting high levels of energy autonomy, the (storage) energy capacity needs to be doubled.

Relating back to the main question on how to plan the mix of energy storage systems, it became evident that multi-service, multi-sector, and multi-objective approaches are needed. This thesis took a first step in that direction. Two detailed extensions (multi-service, multi-objective) for storage planning determined a higher need for these technologies in a case study on Chile, where the future for storage looks promising. In general, the performed case study provides the first 100% renewable scenarios for Chile. Altogether, the gained insights showed to be relevant for stakeholders from the energy and environmental sectors on the path to a zero-carbon energy supply.

Kurzfassung

Die Treibhausgasemissionen müssen kurz nach Mitte des 21. Jahrhunderts vollkommen gestoppt werden, um das Übereinkommen von Paris, „die Erderwärmung auf deutlich unter 2°C zu begrenzen“, einzuhalten. Einer der wichtigsten Bausteine hierfür stellt die Stromversorgung vollständig aus erneuerbaren Energien dar. Vor allem Wind und Solar-Photovoltaik sind aber nur begrenzt regelbar, weswegen die Stromnetze flexibler als heute werden müssen. Stromspeicher sind eine Flexibilitätsquelle und werden als Schlüsseltechnologien für die Energiewende angesehen. Auch Wasserkraft hat häufig Speicherkapazität und kann somit bei dieser Aufgabe helfen.

Um den Stromspeicherbedarf zu ermitteln, werden häufig Modelle zur Ausbauplanung eingesetzt. Unter Berücksichtigung von technisch-ökonomischen Restriktionen bezwecken diese im Allgemeinen die Minimierung systemweiter Investitions- und Operationskosten. Die vorliegende Dissertation leistet vier Beiträge zur Quantifizierung des Stromspeicherbedarfs, mit der zentralen Fragestellung: *Wie plant man den optimalen Energiespeichermix für eine erneuerbare Stromversorgung, die einen erheblichen Anteil an Wasserkraft hat?*

Diese Beiträge sollen die Energiewende unterstützen und sind relevant für Energiesystemmodellierer, Energiepolitiker und Entscheidungsträger aus der Ökohydrologie, Speicherunternehmen und der erneuerbaren Energieindustrie.

- Erster Beitrag: Besonders in den letzten Jahren wurden zahlreiche Tools zur Speicherausbauplanung entwickelt. Der erste Beitrag dieser Dissertation bietet daher eine umfangreiche Literaturrecherche über die existierenden Modelle, inklusive einer Klassifizierung der Ansätze, und einer Identifizierung der Trends.
  Folgende offene Herausforderungen der Speicherplanung werden identifiziert. Erstens unterscheiden sich die vielen verfügbaren Speichertechnologien stark in ihren technischen und ökonomischen Eigenschaften (inklusive Lebensdauer und Effizienzkurven), was in den Tools berücksichtigt werden muss. Die Tools müssen außerdem mit einer hohen räumlichen und zeitlichen Auflösung rechnen, um die Herausforderungen der Systemintegration von erneuerbaren Energieträgen adäquat zu erfassen. Zweitens müssen die verschiedenen Systemdienstleistungen (jenseits von Energieausgleich, so wie Leistungsreserven), die Speichertechnologien anbieten können, in den Modellen erfasst werden. Und drittens kann die Sektorenkopplung die Netzintegration von erneuerbaren Energien fördern, so dass auch die Planung multisektoral werden muss.
- Zweiter Beitrag: In den letzten fünf Jahre wurden viele Speicherausbaustudien veröffentlicht, die in ein sehr breites Spektrum an Speicheranforderungen aufzeigen. Deswegen systematisiert der zweite Beitrag über 400 Szenarien dieser Studien für die USA, Europa, und Deutschland, um deren Speicherempfehlungen darzulegen.
  Dies machte deutlich, dass mit steigenden Anteilen erneuerbarer Energien der Speicherbedarf an Leistungskapazität (z.B. GW, in Pumpspeichern bezogen auf die Anzahl der Turbinen) linear und an Energiekapazität (z.B. GWh, in

Pumpspeichern bezogen auf Wasserspeicherkapazität) exponentiell zunimmt. Für Stromsysteme mit sehr hohen Anteilen an erneuerbaren Energien, insbesondere an Solar-Photovoltaik, erreicht der Speicherbedarf seinen Höchststand; die Leistungskapazität nähert sich 40-75% der Spitzenlast und die Energiekapazität 10% des Jahresbedarfs. Eine abschließende Erkenntnis dieser Analyse zeigt, dass die Annahmen zur Modellierung des Übertragungssystems —und dessen Ausbau— und die Abregelung (Einschränkung) von erneuerbarer Energieerzeugung starke Auswirkungen auf die zuvor dargelegten Speicherempfehlungen haben.

- <u>Dritter Beitrag:</u> Die Entwicklung eines Optimierungstools zur Ausbauplanung von Energiespeichern im Stromsektor ist der dritte Beitrag: LEELO (Long-term Energy Expansion Linear Optimization). LEELO erweitert die verfügbaren Planungsansätze, indem es weitere Dienstleistungen miteinbezieht: Leistungsreserve und Energieautonomie. Eine weitere Neuheit ist die detaillierte Abbildung von Wasserkraftkaskaden, die in vielen Regionen der Welt eine wichtige Flexibilitätsquelle darstellt.
  Anhand einer Fallstudie über Chile für das Jahr 2050 wird bemessen, welche Auswirkungen die Berücksichtigung mehrerer Speicherdienstleistungen (in der Ausbauplanung) auf den Speicherbedarf hat. In der Tat sind die aufgefundenen Abweichungen im Speicherbedarf von signifikanter Größe; bis zu 60 % beziehungsweise 220 % für jeweils die Leistungs- und Energiekapazitäten. Zudem ist der resultierende Speichermix (d. h. die Kapazitäten der einzelnen Speichertechnologien) stark betroffen. Abschließend offenbarte die Planung mit mehreren Dienstleistungen eine Kostensteigerung von 20%, die den Planern ansonsten verborgen bliebe.
  Insgesamt wird das Modellieren mehrerer Dienstleistungen für die Planung von vollkommen erneuerbaren Stromsystemen immer wichtiger, da regelbare Generatoren verschwinden.
- <u>Vierter Beitrag:</u> Im *letzten Beitrag* werden zwei Optimierungsziele zu LEELO hinzugefügt. Das erste bezieht sich auf die Verringerung vom Schwall- und Sunkbetrieb (Hydropeaking), ein Betriebsschema von Wasserkraftanlagen (mit Stauseen), das stark fluktuierende Wasserflüsse hervorruft, die die Flussökologie stromabwärts gefährden. Das zweite Ziel minimiert neue Hochspannungsleitungen, da diese zahlreiche Externalitäten haben, die zu Verzögerungen und sozialem Widerstand führen. Das multi-objektive LEELO ist in der Lage, die Pareto-Kurve dieser drei Dimensionen (Kosten, Hydropeaking, neue Hochspannungsleitungen) zu finden.
  In einer Fallstudie, ebenfalls zu Chile, werden die gefundenen Trade-offs aus Sicht der involvierten Stakeholder bewertet. Es stellte sich heraus, dass die Lösung mit minimalen Kosten eine Verdopplung der bestehenden Übertragungsleitungen erfordert, während die Wasserkraftanlagen in extremem Hydropeaking betrieben werden. Die Vermeidung aller neuen Übertragungsleitungen kostet zwischen 3 und 11 % mehr (abhängig vom zugelassenen Hydropeaking-level). Mit anderen Worten, die Wirtschaftlichkeit neuer Übertragungsleitungen ist ziemlich begrenzt. Wenn diese vermieden werden, steigen die Investitionen in Solarprojekte, während

die Windinvestitionen sinken. Zur gleichen Zeit, und zur Unterstützung des Solarstroms, wächst der Speicherbedarf. Der Speicherbedarf wächst auch, wenn Hydropeaking verringert wird, als direkte Reaktion auf die eingeschränkte Flexibilität der Wasserkraft. Extremes Hydropeaking kann für einen Kostenanstieg von nur 1 % vermieden werden (mithilfe von neuen Übertragungslinien), was aus gewässerökologischer Sicht eine gute Nachricht ist. Das extremste Szenario ist Hydropeaking und neue Übertragungsleitungen gleichzeitig und vollständig zu vermeiden. Dies kostet zusätzliche 11% und erfordert etwa 20% mehr Speicherkapazität.
Kurz gesagt, günstige Speicher- und Solartechnologien erweisen sich als Schlüsselfaktoren, die die effiziente Vermeidung beider Externalitäten (Übertragungsleitungen und Hydropeaking) ermöglichen. Hierfür ist eine klare Investitionsstrategie erforderlich, die, wenn sie richtig umgesetzt wird, die Stromerzeugung nachhaltiger und sozial verträglicher machen kann.

Der Vergleich Chiles mit Europa und den USA verdeutlicht, dass Chiles Bedarf an Speicherleistungskapazität am oberen Ende liegt (> 70% der Spitzenlast). Dies hängt damit zusammen, dass Chile ein (20 mal) kleineres Stromsystem und hoch korrelierte Energieressourcen hat.

Chiles benötigte Energiekapazitäten liegen ebenfalls am oberen Ende (9-13% der jährlichen Nachfrage). Hier bietet der bestehende Wasserkraftpark jedoch bereits einen Puffer von 6%, so dass die Restnachfrage deutlich geringer ist (3-7%) als für Europa und die USA. Wenn neue Übertragungsprojekte vermieden werden, steigt der Bedarf an (Speicher-) Leistungskapazität stark (5 bis 30 Prozentpunkte) und an Energiekapazität nur geringfügig (Hinzufügen von 1 Prozentpunkt) an. Auch die Linderung von Hydropeaking erhöht den Bedarf an Speicherleistung, ohne jedoch den gerade genannten Bereich zu überschreiten. Der höchste Speicherbedarf ergibt sich aus den Multi-Service-Simulationen, bei denen insbesondere die Energieautonomieanforderungen eine Verdopplung der Speicherenergiekapazität bedeuten.

Auf die zentrale Fragestellung zurückkommend, wie der optimale Stromspeichermixbedarf zu planen ist, wurde ersichtlich, dass Ansätze benötigt werden, die die verschiedenen Speicherdienstleistungen und Sektorenkopplung abbilden, und Dimensionen jenseits von Kosten berücksichtigen. Diese Dissertation ist ein erster Schritt in diese Richtung. Zwei detaillierte Erweiterungen (Multi-Dienstleistungen, Multi-Objektiv) für die Speicherplanung ermittelten einen höheren Speicherbedarf in einer Fallstudie zu Chile. Dort sieht die Zukunft der Speicherindustrie vielversprechend aus. Im Allgemeinen liefert die durchgeführte Fallstudie die ersten Szenarien mit 100% erneuerbaren Energien für Chile. Insgesamt sind die gewonnenen Erkenntnisse relevant für Stakeholder aus den Bereichen Energie und Umwelt, auf dem Weg zu einer kohlenstofffreien Energieversorgung.

Chapter 1. Introduction

This chapter contains text fragments of my previous publications "Challenges and trends of energy storage expansion planning for flexibility provision in low-carbon power systems – a review", "How much Electrical Energy Storage do we need? A synthesis for the U.S., Europe, and Germany", "A multi-service approach for planning the optimal mix of energy storage technologies in a fully-renewable power supply", and "Multi-objective planning of energy storage technologies for a fully renewable system: implications for the main stakeholders in Chile".

1.1. Motivation and relevance

To sustain the earth, greenhouse gas emissions need to stop. More precisely, to meet the Paris Agreement directive of keeping global warming well below 2°C, this needs to happen shortly after mid-century [1]. However, the more we delay becoming carbon neutral, the more we have to make up for it by becoming carbon negative, which is more difficult to achieve. Switching our energy production to renewable technologies is a clear solution to avoid carbon emissions. However, there are certain challenges involved in the transition to a world fully based on renewable energy generation.

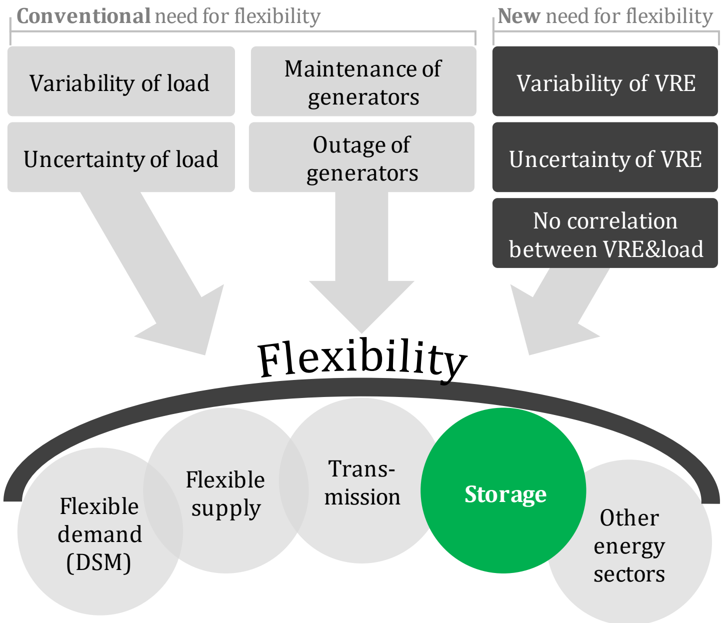

Fig. 1 Need for flexible power systems and sources of flexibility.
Adapted and reprinted with permission from [2].

In particular, wind and solar resources (variable renewable energy systems, VRE) deliver a highly fluctuating power output [3] and are (still) hard to predict in time horizons greater than a couple of days, thus adding variability and uncertainty to the planning and operation of power systems (see Fig. 1). Moreover, locations with good renewable resources can be distant from the demand centers, and their generation profiles rarely correlate in time with the electricity demand[1]. Although these issues are not new —in fact, power systems have always needed to cope with the variability and uncertainty of load and generation, and to transmit the energy to

[1] An exception is the cooling demand for air conditioning in arid regions

the consumers— increasing shares of VRE does exacerbate them. As a response, energy systems need to become much more flexible[2] than they are today [4].

The required flexibility can be provided through several ways (see Fig. 1). In the power sector, flexibility can be provided by the demand side (smart consumers, demand-side management) [5], the supply side (flexible generation technologies, curtailment of renewable generation, more frequent dispatches) [6,7], and infrastructure of transmission and storage systems [8]. Interconnecting the different energy sectors (power, transport, heat, water, gas) is another alternative for upgrading the flexibility levels [9,10].

To design future energy systems, expansion planning approaches are commonly used (in general, expansion planning means elaborating strategies for growth and is used in the most diverse industries). For example, *generation* expansion planning is frequently employed by policy and decision makers to decide *when, where, how much,* and in *which* generation technology to invest. Its goal commonly is to be cost-optimal [11–13] while satisfying a set of economic and technical constraints, such as supplying the demand. More recently, societal constraints, such as opposition to large-scale infrastructure have become more important. In the power sector, depending on the design parameters (decision variables), expansion planning approaches can traditionally be classified into generation expansion planning [14] and transmission expansion planning [15,16]. When the focus is put on investment decisions of storage systems, this thesis will refer to it as *storage expansion planning*. In practice, generation, transmission, and storage can also be planned jointly [17,18].

Particularly, energy storage systems are widely esteemed as potential solutions for high shares of VRE [19–21]. Beyond the use of traditional pumped-hydro storage (currently about 170 GW / 1600 GWh of power / energy capacity[3] worldwide [22]), the deployment of battery energy systems is rapidly growing [22]. Li-ion batteries show an especially promising future due to their fast cost decrease in recent years [23–25]. Currently, there are about 2 GW / 6 GWh of installed power/energy worldwide, with many more on the way [22]. To buffer very short-term power fluctuations, flywheels have been widely used to improve system stability (comprising about 1 GW of power capacity with a couple of minutes of energy capacity) [22]. For seasonal storage, hydrogen systems are an option that is receiving substantial research efforts [26–30]. After the production of hydrogen, it can be stored as such and then be used in fuel cells (for converting it back to power). Alternatively, it can be transformed into methane to be stored in the existing gas infrastructure. From there it can follow the conventional uses of natural gas, such as being burnt in gas turbines. This sector coupling capability is what makes hydrogen so promising, although its currently installed capacity[4] is rather small [22]. Compressed air energy

[2] Ability of the system to match supply with demand.

[3] In contrast to generation technologies, storage systems have two main design parameters: power capacity (e.g. in MW) and energy capacity (e.g. in MWh or hours). In pumped hydro storage, for example, these relate to how many turbines are installed and how much water the reservoir can hold, respectively.

[4] For hydrogen systems, the currently installed power and energy capacity as reported by reference [22] are very incipient (below 0.1 GW / 0.1 GWh). The energy capacity from the existing natural gas grid, however, are much larger.

systems can also serve for long-term storage [31]. However, beyond the two older installations, McIntosh and Huntdorf (from 1978 and 1991), which add up to 0.4 GW / 5 GWh, no further significant installations have been concreted [22].

Several recent studies [32–37] provide comprehensive reviews of these storage technologies. From there it comes clear that the available storage technologies differ vastly in terms of investment costs per power capacity and per energy capacity, lifetime, storage losses, efficiency, and ramping rates (rate of change in power output) [19,38,39]. A widely accepted conclusion is that there is no storage option that outperforms all others [35]. Indeed, the requirements for storage systems depend on the characteristics of the power system under study and on the characteristics of the VRE. Planning with a *combination* of storage options is a direct consequence. And despite intensive research efforts of the last couple of years, finding the optimal storage mix is still not fully understood by the scientific community, but improving its understanding is a necessity to meet the Paris Agreement. The present thesis will be centered around this task.

1.2. Goals and research questions

The overarching goal of this thesis is to assist to energy transition by improving the quantification of energy storage requirements. Or in other words, the thesis it aims to answer: *how to plan the optimal energy storage mix for fully renewable power systems with important shares of hydropower*? More specifically, it aims to (1) shed light on current storage expansion approaches, (2) systemize existing recommendations of energy storage demand, (3) enhance current models by adding multi-services (beyond the conventional energy balance), and (4) develop a multi-objective framework for planning with other dimensions beyond costs. Four specific research questions will be answered:

- Numerous models for storage planning have been published in the lasts decades, with many diverse modeling approaches, planning goals, modeling details of the systems, consideration of uncertainty, energy sectors, and so on. *What are the trends and open challenges in expansion planning of storage technologies?*
- During the last five years, numerous studies have put effort into dimensioning storage requirements for highly renewable power systems around the world. However, these resulted in a very broad range of storage requirements, making it difficult for decision-makers to identify clear recommendations. *How can these unexplained differences of storage recommendations be resolved?*
- Current storage expansion models tend to focus on balancing the energy fluctuations from renewable technologies but are usually blind to the need for dealing with forecast errors. As power systems rely more strongly on renewable generation, acknowledging the corresponding services (here: power reserves and energy autonomy), already in the planning stage, becomes more critical. *How does the need for these services impact the optimal combination of storage technologies in a fully-renewable system?*

- Besides energy storage systems, hydropower reservoirs can provide flexibility but often cause massive fluctuations in flow releases (hydropeaking), deteriorating the ecology of the downstream rivers. Expanding transmission infrastructure is another flexibility source but is frequently plagued by social opposition and delays. *Can storage systems minimize hydropeaking and the need for transmission, and what are the trade-offs between these sources of flexibility?*

1.3. Approach and outline

After the present introduction, four contribution-chapters follow, one for each of the above research questions. The first two contributions rely on an analysis and synthesis of existing literature, whereas the last two contributions use an own-developed optimization tool. Based on their similarity in methods, the thesis is split into *Part I – Analysis and synthesis of literature* and *Part II – New energy storage expansion model* (each containing two contributions chapters). Furthermore, each chapter details its own methods, which is why a general method chapter is absent. *Part III – Epilogue* wraps up the thesis. More in detail, these are contributions are:

<u>Part I – Analysis and synthesis of literature</u>

- Chapter 2 presents the fundamentals of storage expansion planning, including a comprehensive literature review and a classification of the models. This classification is then used to analyze a database of about 90 publications to identify the trends in storage expansion planning. The chapter climaxes with identifying the open challenges, which will serve as a basis for the model to be developed in *Part II*.
- Chapter 3 systemizes the findings coming from 17 recent storage expansion studies (with over 400 scenarios) pertinent to the U.S., Europe, and Germany. For each region, it derives the storage requirements depending on the share of variable renewable energy and the generation technology, including a discussion on strong modeling assumptions (outliers) and on the relevance of modeling the electrical grid. The gained insights also feed the model of *Part II*.

<u>Part II – New energy storage expansion model</u>

- Chapter 4 develops a storage expansion model, called LEELO (Long-term Energy Expansion Linear Optimization). Its novelty lies in (1) endogenously representing power reserves and energy autonomy, and in (2) having a high-technology resolution on cascading hydropower plants. How these services impact the storage recommendations in a 100% renewable-based power system is the main outcome of this chapter. The numbers are illustrated in a case study about Chile —a system which includes an important hydropower share— for the year 2050.

- Chapter 5 formulates a multi-objective framework for optimizing energy storage expansion decisions, whose core is LEELO. With this framework, the trade-offs between total costs, hydropeaking, and new transmission projects are assessed. Again for Chile 2050, the found implications are described from a multi-stakeholder perspective for the transmission and generation companies, storage companies, and environmental organizations.

The thesis finalizes with *Part III – Epilogue*, including Chapter 6. It summarizes the work done, highlights the learnings from all contributions, and draws overarching conclusions by answering the four research questions posed in Section 1.2. It finalizes by recommending future lines of research for planning renewable energy systems. These insights are useful for decisions makers of the environmental and energy sector that are tackling the design of zero-carbon energy supplies to meet the Paris Agreement.

Part I – Analysis and synthesis of literature

Chapter 2. Approaches and trends of storage planning

This chapter is based on the publication "*Challenges and trends of energy storage expansion planning for flexibility provision in low-carbon power systems – a review*" by J. Haas, F. Cebulla, K. Cao, W. Nowak, R. Palma-Behnke, C. Rahmann, P. Mancarella, published 2017 in the Journal of Renewable and Sustainable Energy Reviews.

This work was funded by the DAAD, the Chilean Council of Scientific and Technological Research (CONICYT/ FONDAP/15110019, CONICYT/ FONDECYT/1151438) and EPSRC through the HubNet project (EP/I013636/1). Helpful remarks from Frank Leañez about the time structure of models and assistance from Jonas Schradi in Fig. 4 are also appreciated.

Executive summary

Expansion planning models are often used to support investment decisions in the power sector. In the task of massively integrating renewable energy sources, expansion planning of energy storage systems (SEP – Storage Expansion Planning) is becoming more popular.

To shed light on the existing approaches, this chapter first presents the fundamentals and then a broad classification of SEP. The latter is then used to analyze a database of about 90 publications to identify trends and challenges in SEP.

The trends we found are that while SEP was introduced more than four decades ago, only in the last five years increasing research efforts were put into the topic. The planning has evolved from adequacy criteria to broader targets, such as direct costs, mitigation of CO_2 emissions, and renewable integration. The modeling of the network, power system, energy storage systems (ESS), and time resolution are becoming more detailed. Uncertainty is often considered and the solution methods are still very diverse.

As outstanding challenges, we found that (1) the large diversity of ESS, in contrast to conventional generation technologies, and (2) the complex lifetime and efficiency functions need to be addressed in the models. (3) Only a high temporal and spatial resolution will allow for dimensioning the challenge of integrating renewables and the role of ESS. (4) Although the value of ESS lies beyond shifting energy in time, current SEP is mostly blind to other system services. (5) Today, many flexibility options are available, but they are often assessed separately. In the same line, although cross-sectoral (power, heat, transport, water) SEP is becoming more frequent, there are many open tasks towards an integrated coordination. The planning of future energy systems will be multi-sectoral and multi-objective, consider the multi-services of ESS, and will inherently require interdisciplinary efforts.

2.1. Introduction

Many research and review papers about expansion planning of the energy sector can be found in the literature, including power generation [40,41], power transmission [16,42,43], and gas- and power-transmission [44]. A comprehensive review of the available software is shown in [45] and [46]. However, reviews about SEP remain scarce.

The present chapter aims to fill this gap and makes three contributions to the existing literature:

- First, we provide a clear classification and overview of SEP models. We analyze the modeled ESS, energy sectors and flexibility options, the planning goal, the modeling detail of the systems, the time treatment of the investment and operational decisions, the consideration of uncertainty, and the solution methods.
- Second, we identify trends in how current SEP literature evolves in dealing with these aspects.
- Third, by contrasting newer SEP approaches to conventional GEP, we outline the challenges of planning ESS expansion. In these challenges, we focus on the diversity of ESS, the lifetime and efficiency functions of ESS, the required temporal and spatial resolution for adequate modeling of ESS, the multiple services ESS can provide, and the inter-sectoral coupling through ESS.

The remainder of this chapter is structured as follows. Section 2.2 provides the fundamentals and a classification of models for SEP. Section 2.3 details the methods, Section 2.4 analyses the trends of ESS investment planning, while Section 2.5 identifies the remaining challenges. Finally, Section 2.6 presents the conclusions and recommendations for future work.

2.2. Review and classification of storage expansion planning models

SEP considers the total costs of the system, given by operational and investment decisions over a time horizon of typically 10-30 years. Its most basic version is an energy balance that matches (e.g. yearly) generation with demand assisted by the use of ESS.

The planning models for ESS have evolved over time. However, current approaches still make strong simplifications when compared to real systems. Thus, we classify existing SEP according to their abstraction level: (1) considered ESS, (2) goal and planning perspective of models, (3) considered energy sectors and flexibility options, (4) network modeling, (5) detail of power system and ESS, (6) time treatment of investment decisions and (7) of system operation, (8) treatment of uncertainty, and (9) solution methods for the resulting model. This classification is explained in more detail in Sections 2.2.1 to 2.2.9.

2.2.1. Modeled ESS

SEP can be classified according to the types of ESS and the number of different ESS that are taken into account in the planning process. ESS types can again be classified based on their storage capacity, spatial distribution, and mobility.

First, according to their storage capacity, it is possible to divide ESS into short-term and long-term systems (although to date there is no consensus in the literature about a clear limit). Reference [47] considers short-term storage to have an energy capacity from seconds to days, such as flywheels (FW), capacitors (CAP), battery energy storage systems (BESS), molten salts (in concentrated solar power plants – CSP), and compressed air energy systems (CAES). The same reference considers long-term systems to have an energy capacity from weeks to seasons, such as water reservoirs (WR) and gas or hydrogen (H_2) storage. Pumped hydro storage (PHS) and heat storage, depending on their size, can serve both the short- or the long-term [47]. CAP and FW have particularly low energy capacities and are suited for high-power applications up to 10 seconds. Consequently, CAP and FW are commonly not considered in SEP.

Second, ESS can be grouped in centralized and distributed systems. The former includes large installations, such as PHS, while the latter refers to modular units such as home-batteries in combination with roof-top photovoltaic (PV) systems [47].

The third and last criterion considers their mobility. Systems fixed to one location comprehend most of the centralized and many of the distributed ESS [47]. Mobile storage is given mainly by electric vehicles (EV) or gas trucks, all of which are distributed ESS.

The number of considered ESS types allows classifying SEP into single- or multi-storage approaches. In contrast to the former, multi-storage SEP can detect the synergies between different ESS systems.

2.2.2. Goal and planning perspective of models

In SEP, cost minimization is usually applied by central planners (e.g. vertically integrated power companies) or policymakers (of a government or group of nations) as opposed to the benefit maximization of private investors [48]. Central planners rely on a cost minimization formulation and consider the expansion of a whole region. Private companies decide investments in their areas based on the energy price projections of the remaining system. When every private company tries to maximize its benefit, both planning perspectives (central and private) should lead to the same outcome under perfect market competition and without transmission constraints. However, real markets are rarely perfect, provoking differences, for which agent-based models can be used [49]. Nevertheless, the existence of complex markets and distortions does not mean that central planning has become obsolete. On the contrary: the result of central planning is commonly used as a benchmark for measuring the health of the system and for identifying the required corrective actions to be taken by policy makers [50]. Especially when planning a long-ranging horizon, the market may be of secondary importance as it is highly dynamic and can adapt accordingly.

The target of SEP (i.e. the objective function of the resulting optimization problem) can be economic as a cost minimization or benefit maximization [51–55]. But many more dimensions play a role in the SEP decision-making process [56], such as CO_2 emission reduction in terms of maximum targets or penalties [57,58], robustness of the system [59] and resilience of the system, e.g. to climate change. If not all targets can be translated into economic units, the problem becomes multi-objective [60,61].

2.2.3. Modeled energy sectors and flexibility options

Depending on the sectors considered, the existing SEP approaches can be divided into electricity models and (multi-sectoral) energy models (see Fig. 2). In the latter, different forms of coupling between the heat, transport, gas, and water sectors are taken into account.

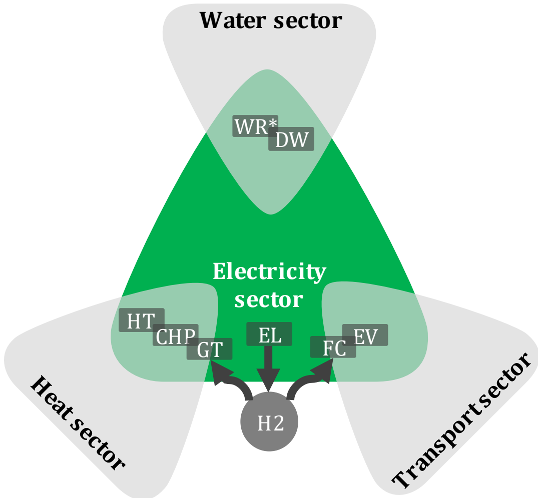

Fig. 2 Sector coupling: heat, transport, water, and electricity.

In the general context of future multi-energy systems [62], the electricity and heat sectors are coupled through combined heat and power (CHP) plants, as well as cooling and heat power plants (when also adding cooling) [10], and in general in distributed multi-generation plants [63,64]. These couplings bring *virtual* electricity storage options through the possibility to operate CHP plants flexibly [65,66], especially in the presence of thermal storage and/or energy vector substitution options [67,68], as well as through building heating and process heat [65,66]. Other heat storage technologies (HT), especially in the presence of buffers for heat pumps and domestic hot water tanks, can offer additional storage options.

Other energy vectors can provide important forms of flexibility to the power system. For example, sectoral interactions between power and transport clearly involve EV, powered by fuel cells (FC) or batteries, which are *per se* a form of mobile storage [69,70].

Further, there are various couplings that emerge when considering a joint operation of the electricity and gas networks [9,71]. In particular, the Power-to-Gas (P2G) technology represents an ESS option that arises from this electricity-gas interaction. Namely, P2G allows production of H_2 via electrolyzers (EL) that can later be used by FC in the power and transport sector or by gas turbines (GT) in the heat and power sector [72]. Also, there may be P2G options to inject hydrogen (as well as synthetic natural gas), produced from otherwise curtailed renewable electricity, into the gas network, which is effectively used as a means of daily [9] or seasonal [73] storage of clean energy.

Focusing on storage interactions, the water and electricity sectors are coupled by water reservoirs, whose multiple purposes (e.g. irrigation, ecological services [74]) usually imply a more constrained operation when using those also as electricity storage resource. However, even in such more constrained cases, technical solutions exist, such as installing after-bays (with/without pumping capacity) that may offer direct/indirect storage options to the electricity sector [75]. Also drinking water installations (DW) couple both sectors, for example emerging desalination plants can use the obtained brines to generate electricity when equipped with an additional turbine [76].

Within the electricity sector, it should be made clear that ESS are not the only source of flexibility for VRE integration. It is important to plan ESS options jointly with other options for maximizing the opportunities of storage and the benefits of the whole system, e.g. ESS and flexible generation [77], ESS and transmission[5] [18], ESS and energy curtailment options [78], and ESS and multi-generation systems [67,79].

2.2.4. Modeling of network

The detail of modeling the power network is relevant to identify transmission constraints and local potentials. Existing approaches range between one-node (also known as *copper-plate models*) and multi-node models of the grid.

When harnessing local potentials of VRE (e.g. wind power from remote offshore areas or solar power from distant deserts) or of ESS (e.g. PHS in the mountains or H_2 in caverns), it becomes relevant capturing their spatial dimension. Although one-node approaches can still model these local potentials (e.g. by modeling them as different technologies, each with a different expansion capacity, energy profile, cost, and yield), these are reasonable only if transmission capacity is not an issue. If transmission congestions (bottlenecks) do exist, multi-node approaches should be applied.

Multi-node models apply different approaches to taking into account power exchange between regions. First, the simplest case is a traditional *transport model*, where each line has a maximum transmission capacity. Other parameters such as voltage and phase angle are not considered. Second, a more detailed approach is offered by direct current (DC) models. These consider current balances (Kirchhoff's

[5] Expansion planning of transmission infrastructure is a flexibility option, which is different to modeling the existing grid as explained in Section 2.2.4.

law) to find the power flows in the network [80]. To keep DC models linear, transmission losses are usually neglected or simplified, for instance, in the form of a fixed proportion of transmitted energy or, alternatively, modeled by piecewise linear functions [81]. Besides, their linearity is in accordance with many of the transmission pricing models [80]. Third and last, alternating current models (AC) additionally include voltage equations, but the computational burden may be prohibitive (nonlinear models, iterative solving schemes, long solving times) for larger systems [82,83].

Given the trade-off between computing time and precision in modeling high voltage networks, transport models are a commonly used approximation for direct current power lines and DC models are often used for alternating current grids [80]. The use of AC models is indispensable when voltage constraints need to be studied explicitly, such as SEP in (low-voltage) distribution grids.

2.2.5. Modeling detail of ESS and power system

ESS can be modeled with different degrees of detail. Basic parameters involve their power capacity (in MW) and energy capacity (in MWh). Those capacities might remain constant in time or decrease due to aging. Some ESS have different capacities for charging and discharging, e.g. PHS, in which the converter (turbine) and charger (pump) may be physically different units. The efficiency can be considered constant or variable as a function of their state of charge, state of health (aging), operating temperature, and dis/charging speed. Self-discharge might also be modeled.

Also, the power system is often simplified in SEP. Models range from a set of simple energy balance equations [52,84] up to complex formulations describing technical constraints of generators and power reserve requirements [85].

Energy balance approaches may involve simple spreadsheet balances that add up the expected energy to be generated during, say, a year, aiming to match demand. The screening curve approach [13] allows through graphical inspection finding the optimal generation mix based on the peak-load-pricing theory [86]. These curves compare the structure of demand (in terms of a load duration curve) with investment and operational costs of the generation and storage technologies. Energy balance models based on optimization can also be found. Here, the load is commonly simplified in the form of discretized time blocks [87], for which the best solution found is a mix of generation and storage technologies that is able to supply energy to all time blocks.

Advancing in the level of detail of SEP models, reliability indices can be considered such as *expected energy not served (EENS)* [88,89] or *loss of load probability or expectation* (LOLP/LOLE) [55,87]). Technical constraints important for scheduling the operation of the generation units (unit commitment - UC) can also be included. These involve minimum online/offline times, startup and shutdown times, up/down ramps, and minimum power outputs, among others [85]. Further constraints may involve system operation in terms of operational reserve (e.g. spinning reserves) [85,90] and proxies for frequency support [91,92] and voltage support [93,94].

In practice, when the focus of research is on macroeconomic balances, simple top-down formulations are used. These are usually energy-based models, available in software packages such as LEAP [95], MARKAL [96], ENPEP [97], or NEMS [98].

Conversely, bottom-up models target a high technical detail, for which complex formulations (e.g. reliability, unit commitment) as in HOMER [99], EnergyPLAN [100] and PLEXOS [101] are chosen.

2.2.6. Time treatment of investment decisions

The time treatment of investment decisions in expansion planning can be classified into static and dynamic approaches (see Fig. 3). Static methods calculate the expansion decisions (answering to "where and how much") at the end of a given time horizon [58,102]. Dynamic methods additionally optimize the entry year of new investments (responding to "when"), also called the expansion path. This is considered to be more useful in practice but comes at the cost of solving times [15,103]. A combination of both approaches is to use milestone-years. Here, a static optimization is performed every five years, for example [104]. Sometimes, the results (generation capacity mix) are used as input for computing the next milestone-year [105]. The rolling horizon approach [106,107] follows that logic by splitting the planning horizon into smaller and overlapping periods which are solved sequentially. For example, a common setting in long-term studies is to choose a set of 10-year planning horizons with 5 years of overlap. In contrast to milestone-years, each period is dynamic. Milestone-year and rolling-over approaches optimize each period individually, which reduces the complexity of the optimization problem at the cost of being short-sighted (myopic).

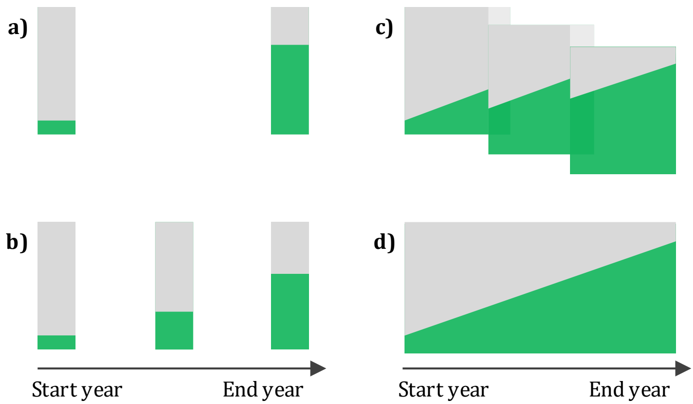

Fig. 3 Time treatment of investment decisions

a) static optimization, b) milestone-years, c) rolling horizon, d) path optimization or dynamic optimization. Grey symbolizes the share of fossil and green of renewable plants.

2.2.7. Time treatment of system operation

SEP can be divided, depending on how they treat the time dimension of the system operation, in sequential (also called chronological) and non-sequential approaches. This distinction is closely related to the modeling detail of ESS and the power system (Section 2.2.5).

Non-sequential approaches include the energy balances approaches (simple balances [84], screening curves [86], and load duration curves [87]). These neglect technical constraints from the system, such as ecological flow limits of hydropower, on/off-line times of conventional generators, and state of charge and state of health for ESS. The neglected effects are, if at all, incorporated in ex-post studies. Hence, in practice, the found solution might be infeasible or more costly (suboptimal).

Instead, chronologic or sequential approaches can model the temporal interdependencies. These are particularly critical in small or isolated power systems with low inertia levels and poor frequency control capabilities [108].

Other approaches of SEP consider *type-days* or *type-weeks* to approximate chronologic formulations by sampling a few representative days or weeks of the year [85,94]. The selection process of type-days or type-weeks might include clustering methods for scenario reduction [85,109,110]. Some of the type-days/weeks are chronologic, while others are based on (non-sequential) load duration curves. However, none of them can capture the operation beyond their horizon (day/week).

All approaches can vary their time resolution. Frequently, hourly up to multi-hourly time steps are observed. Some approaches use heterogeneous time steps aiming to find a good representation of the load curve with a few time steps. Coarse scales allow solving larger systems in a trade-off with the operational model's accuracy.

2.2.8. Treatment of uncertainty

Uncertainties can be classified according to their nature into rational and stochastic [111]. Rational uncertainty arises when trying to anticipate the strategic behavior of agents (suppliers, customers, traders, and regulators) in market competition and is usually addressed with game theory models [49]. Stochastic uncertainties arise from random influences such as weather, load, resource availability, energy and technology prices. Instead of looking for an (deterministic) optimum under allegedly known conditions, stochastic uncertainties can be handled by optimizing an expected value, minimizing the regret, or keeping probabilities of undesired events (e.g. unserved energy) below a given threshold [112]. References [113,114] show an overview of stochastic models applied to general energy planning, while references [115], [109], and [116] show examples of SEP models that include the stochasticity of prices, load, and VRE. Stochastic optimization may also be useful for *flexible* expansion planning when decisions consider the potential resolution of uncertainty in time and the possibility of adjusting decisions based on such resolution [79].

Another valuable option to account for uncertainties is the Monte-Carlo simulation, which runs deterministic models numerous times under randomized conditions to attain probability distributions [61,65,88,93]. When quantification of uncertainty is particularly difficult, scenario analysis (a manually chosen set of possible parameter outcomes) is performed. As a general rule, considering uncertainties multiplies the required solving time by a substantial factor, at least by the number of scenarios or Monte-Carlo repetitions.

2.2.9. Solution methods

SEP is frequently formulated as a mathematical optimization (or mathematical programming) problem. However, many other decision support methods are found in the literature.

Optimization problems can be divided according to their linearity into two groups. First, Linear Programming (LP) is comprised of the problems with a linear objective function and linear constraints [117]. If some variables can only be integers, the problem is called Mixed Integer Linear Programming (MILP) [117]. The second category of problems is Nonlinear Programming (NLP), which has nonlinearities in their objective function and/or constraints [117]. Again, if some variables can only be integers, the problem becomes a Mixed Integer Nonlinear Programming (MINLP) [117]. Although there are many more subtypes of NLP problems, frequent approaches used in the energy sector include Quadratic Programming [118] (with a quadratic term in the objective function) and Quadratically Constrained Programming (with quadratic constraints) [110].

To solve mathematical programming problems, there are many solution methods available. Commonly used exact solution methods include Simplex or Interior Point for LP, Branch and Bound for MILP, QP-simplex for Quadratic Programming, or Barrier for Cone Programming. When a limited computing capacity hinders these algorithms to find the optimal solution in a reasonable time, decomposition techniques can be applied in order to shrink the problem. Examples are Dynamic Programming [119], Benders decomposition [120], and Danzig-Wolfe [112]. They aim to find the same exact optimum, but they can be faster as they split the global problem into smartly chosen coupled subproblems.

When the above methods fail to find the optimum in a prudent time (usually in NLP), heuristics come into play. They trade precision for speed, aiming to find a good solution in a feasible time rather than searching for the global optimum. Examples of heuristics are Artificial Neural Networks [121], Genetic Algorithms or Evolutionary Strategies [122], Tabu Search, Particle Swarm methods [123], Ant Colony approaches, and so forth [124]. Reference [125] studies their performance in traditional GEP, whereas reference [124] analyzed some of them in SEP. Additional advantages of heuristics are that many offer options for parallel computing and are robust against missing and noisy data [126].

Other decision support methods for SEP rely on control rules [94], energy accounting frameworks [84,127,128], or time series analysis [129,130]. As no standard name for this kind of problems could be found in the literature, these models will be called *other solution methods* in the remainder of this review.

Finally, some models are hybrids as they combine several of the approaches mentioned above. These split the problem into one for the investment decisions and another for the operation decisions (although they follow the logic of mathematical decomposition techniques, they are heuristics). For example, reference [122] formulates the investment decisions of ESS as LP (solved with Simplex) and the operational decisions as a set of control strategies (that then feed the operational costs back to the investment problem). It is also frequent to observe hybrid approaches that combine top-down (macroeconomic) with bottom-up (technical) models (see Section 2.2.5) [131,132].

In general, the used modeling detail is a compromise between the required accuracy and computing limitations. For that reason, the treatment of ESS is often simplified. Similarly to GEP, detailed technical tools as ex-post analysis for checking the operational feasibility are also used in SEP, especially in the presence of large shares of both VRE and ESS. References [133–135] provide an exhaustive review of optimization methods applied to renewable energy and energy planning.

2.3. Methods

To derive the challenges and trends in storage expansion planning, we perform a systematic literature review comprised of two steps: gathering relevant publications and classifying the found models.

First, we collected a set of journal papers related to the topic. We set up a database with all journal papers that are indexed by *Google Scholar*, published online before 2016, and contained both the words “energy” and “storage” and “expansion”, and/or “planning” in their title. Particularly, in the first years of SEP (1970-1999), only a few results were found, which is why the reference list of each paper was checked for further publications. Only for this period, conference proceedings were also included due to the lack of online material. For the remaining decades, further references to those found by the above search criteria were added, aiming to evaluate as many related studies as possible. The found papers were skimmed, and those which did not provide sizing of ESS were discarded. This procedure resulted in a total of 87 considered papers, as shown in Table 1 [8,21,29,49,51–55,57–59,61,65,66,69,70,72,73,76–79,84–94,102,104,109,110,121–124,127–129,131,136–176]. The first 30 years (1970-1999) of SEP show only 13 publications, whereas the 2000s account for another 14. In the 2010s, SEP takes off: 60 studies are found until the end of 2015.

Table 1 Number of SEP publications found per decade.

Decade	Publications
Earlier	8
1990s	5
2000s	14
2010s	60
Total	87

These publications were then manually classified using the criteria mentioned in the previous section (modeled ESS, goal and planning perspective of models, modeled energy sectors and flexibility options, modeling of the network, modeling detail of ESS and power system, time treatment of investment decisions, time treatment of system operation, treatment of uncertainty, and solution methods). The overview of the resulting analysis can be found in Table 2.

Table 2 Overview and classification of the reviewed paper. *Abbreviations: Static (St), Dynamic (Dy), Sequential (S), Non-sequential (N), Central (C), Private (P)*

Year	First author	Reference	ESS	One node	Multinode	Inv. time treat.	Op. time treat.	Planning persp.	Deterministic	Scenarios	Montecarlo	Stochastic	Sectors
1973	Erlenkotter	[141]	HR	●		Dy	N	C	●				
1974	Gagnon	[143]	HR	●		St	S	C	●				
1981	Sorensen	[167]	HR		●	St	S	C	●				
1983	Bloom	[51]	PHS	●		St	N	C	●				
1986	Toyoda	[52]	Generic	●		St	N	C	●				
1986	Sanghvi	[87]	HR	●		Dy	N	C				●	
1987	Youn	[54]	HR, PHS	●		Dy	S	C				●	
1988	Yasuda	[53]	Generic	●		Dy	N	C	●				
1990	Hreinson	[149]	HR	●		St	N	C	●				
1990	Kandil	[55]	PHS	●		Dy	S	C	●				
1996	Schoenung	[127]	Multiple	●		St	N	P					
1997	Ito	[150]	HT, HP	●		St	S	C		●			Heat
1997	Protogeropoulos	[162]	BESS	●		Dy	N	P	●				
2003	Korpaas	[154]	G	●		Dy	S	P		●		●	
2004	Barton	[94]	FW, Flow BESS	●		St	S	C	●				
2004	Jaramillo	[151]	HR	●		St	S	P		●			
2007	Greenblatt	[146]	CAES	●		St	N	P		●			
2007	Kaldellis	[84]	Multiple	●		St	N	P		●			
2007	Meibom	[156]	HT, HP		●	St	S	C			●		Heat
2007	Swider	[169]	CAES	●		Dy	S	C		●		●	
2008	Lund	[70]	EV	●		St	S	C		●			Transport
2008	Brown	[109]	PHS	●		St	S	C		●		●	
2008	Garcia Gonzalez	[144]	PHS	●		St	S	P				●	
2008	Ummels	[65]	PHS, CAES, CHP		●	St	S	C			●		Heat
2008	Sullivan	[168]	CAES, PHS, BESS		●	Dy	S	C	●				
2009	Denholm-a	[177]	CAES	●		St	S	P	●				
2009	Mathiesen	[69]	HT, HP, CHP, EV	●		St	S	C		●			Heat, Transport
2010	Gutierrez-Martin	[147]	H_2	●		St	N	P	●				
2010	Heide	[148]	PHS, H_2	●		St	S	C	●				
2010	Kapsali	[152]	PHS	●		St	N	P		●			
2010	Kiviluoma	[153]	EV, CHP, HT, HP		●	St	S	C		●			Heat, Transport
2010	Pagliarini	[160]	HT, CHP	●		St	S	C		●			Heat
2010	Loisel	[78]	PHS, CAES	●		St	S	P		●			
2011	Brekken	[121]	BESS	●		Dy	S	P				●	
2011	Krajacic	[155]	PHS, HP, EV	●		St	S	C	●				Heat, Transport
2011	Dvijotham	[91]	Generic		●	St	N	C	●				
2011	De Jonghe	[138]	PHS		●	St	S	C	●				
2011	Oh	[159]	Generic		●	St	S	C				●	
2011	Tuohy	[171]	PHS	●		St	S	C				●	
2011	Denholm-b	[21]	Generic	●		St	S	C	●				
2011	Shimizukawa	[166]	BESS	●		St	S	C	●				
2012	Connolly	[137]	PHS, CHP, HP	●		St	S	C		●			Heat
2012	Fripp	[142]	CSP, EV		●	Dy	S	C				●	Transport
2012	Haller-a	[102]	Generic		●	Dy	S	C		●			

Year	First author	Reference	ESS	One node	Multinode	Inv. time treat.	Op. time treat.	Planning persp.	Deterministic	Scenarios	Montecarlo	Stochastic	Sectors
2012	Haller-b	[104]	PHS		●	Dy	S	C		●			
2012	Ramirez-Rosado	[163]	Generic		●	St	N	C	●				
2012	Makarov	[129]	Generic	●		St	N	C	●				
2012	Østergaard	[66]	BESS, CHP, Biogas	●		St	S	C	●				Heat
2012	Rasmussen	[77]	Generic	●		St	S	P	●				
2012	Sundararagavan	[128]	PHS, CAES, BESS	●		St	N	P	●				
2013	Fares	[92]	BESS	●		St	S	P	●				
2013	Zhang-a	[176]	PHS	●		St	S	C		●			
2013	Obara	[158]	HT, BESS, HP	●		St	S	C		●			Heat
2013	Papadaskalopoulos	[161]	EV, HP	●		St	N	C	●				Heat, Transport
2013	Pina	[131]	Generic	●		Dy	S	C	●				
2013	Steffen	[86]	PHS	●		St	N	C	●				
2013	Steinke	[8]	PHS, BESS, H_2		●	St	S	C		●			
2013	Tedeschi	[170]	Generic	●		St	S	C				●	
2013	Zhang-b	[175]	Generic			St	N	C	●				
2014	Batas-Bjelic	[136]	HT	●		St	S	P		●			Heat
2014	Bussar	[122]	H_2, PHS, BESS		●	St	S	C		●			
2014	Arabali	[88]	Generic	●		St	S	C			●		
2014	de Boer	[72]	H_2	●		St	S	C	●				
2014	Bertsch	[57]	Generic		●	St	S	C		●			
2014	Suazo-Martínez	[85]	Generic	●		St	S	C		●			
2014	Crossland	[93]	Generic			St	N	C			●		
2014	Mena	[61]	Generic, EV		●	St	N	C			●		Transport
2014	Schill	[165]	BESS	●		St	S	C		●			
2015	Saboori-a	[164]	Generic		●	St	N	C			●		
2015	Zerrahn	[174]	BESS, PHS, H_2	●		St	S	C		●			
2015	Das	[58]	CAES		●	St	S	C			●		
2015	Hajipour	[90]	Generic	●		St	N	C			●		
2015	Saboori-b	[123]	Generic		●	Dy	N	C		●			
2015	Good	[145]	HT	●		St	S	C				●	
2015	Han	[49]	BESS	●		St	N	P				●	
2015	Novosel-a	[157]	Rev. Osmosis	●		St	S	C	●				Water
2015	Novosel-b	[76]	PHS, Rev. Osmosis	●		St	S	C		●			Water
2015	Pellow	[29]	H_2	●		Dy	N	P	●				
2015	Qi	[59]	Generic		●	St	S	C				●	
2015	Viveka	[124]	BESS		●	Dy	N	P	●				
2015	Weitemeyer	[172]	Generic	●		St	S	C	●				
2016	Rajesh	[89]	BESS	●		St	N	C	●				
2016	Clegg	[73]	P2G		●	St	S	C					Gas
2016	Xing	[110]	Generic			St	S	C				●	
2016	Dehghan-b	[139]	Generic		●	St	S	C	●				
2016	Martinez	[79]	HT, HP, CHP	●		Dy	S	C				●	Heat
2016	Xiong	[173]	Generic		●	St	S	C				●	

2.4. Trends in storage expansion planning

The Section will analyze the found trends of SEP. We will follow the same structure as the one used in Section 2.2.2.

2.4.1. Modeled ESS

The need for energy storage is not new. In the beginning, operational flexibility in power systems was given by fossil power plants that stored their energy in the form of primary energy, mainly gas and petrol in tanks, and coal on adjacent yards. As long as that storage capacity is large enough (not imposing active constraints on the system), there is no need for modeling it. So, it comes as no surprise that SEP is born in the context of a more restricted primary energy source: hydropower reservoirs.

Fig. 4 Geographic evolution of SEP.
Based on author affiliation of the considered publications. Colors indicate the decades. Orange: earlier than 1990, green: 1990s, light blue: 2000s, grey 2010s.

The geographic development of SEP is illustrated in Fig. 4; whereas the technologies considered are shown in Fig. 5[6]. SEP is first performed in the '70s in the USA and Canada [141,143], although the first PHS installations already appeared in the 1890s in Italy and Switzerland [178]. During the following decade, Japan [52,53] and South Korea [54] join the topic, while the USA [51,87] keeps on adding publications. Also, Denmark appears, envisioning the role of storage for a Nordic "wind-hydro" system [167]. Mainly WR and PHS are sized, then first models for generic (G) storage emerge. During the 1990s, storage planning goes beyond the traditional hydropower nations. For instance, the first publications from Egypt and Libya show interest for PHS [55], while research elsewhere starts to look at a broader variety of ESS, including BESS [162], CAES, CAP, and FW [127]. Also, the first cross-sectorial models appear with the joint heat-power planning of heat tanks [150].

[6] In these kinds of figures, the y-axis shows the number of SEP publications that match a given criteria relative to the total number of SEP publications of a given decade. If a given criteria allows multiple answers, the y-axis becomes relative to the total number of answers of a given decade.

In the 2000s, SEP becomes a worldwide topic, and more studies focus on these emerging technologies, as well as on CHP [65,156] and EV [69,70]. The technology spectrum continues to grow in the 2010s, adding H_2 with a focus on P2G [72,73,174] and CSP [142]. Particularly, the BESS family receives attention with focus on developing technologies, such as Lithium-ion (Li-ion) [49,128,165], sodium-sulfur (NaS) batteries [128,165], and flow batteries [49,92,121,128].

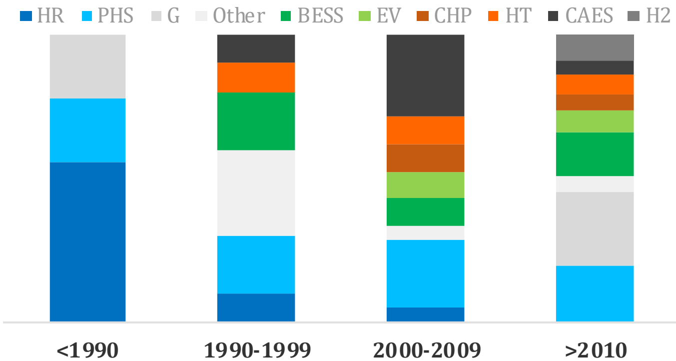

Fig. 5 Evolution of technologies considered in SEP.

Although diverse ESS are included in SEP over the decades, before the 2000s the focus is on one technology at a time. This changes in 2004, when Barton [94] introduces a simple spreadsheet to find short- and mid-term storage for a wind farm. The first optimization models that include multi-storage options appear as recent as 2014 [90,122,165]. Only a handful of studies analyzes more than two ESS at the same time. For example, reference [165] studies a combination of three ESS for a copperplate system, while reference [90] does the same for micro-grids. Bussar et al. [122] are the first ones to address multi-storage needs for a spatially distributed system: Europe-Middle East-North Africa with a 21-node resolution. One year later, Zerrahn et al. [174] focus on a storage mix with reserve constraints. Understanding such optimal ESS mixes will only become more relevant on the way to low-carbon power systems.

2.4.2. Goal and planning perspective of models

The planning goals of SEP have evolved over time. The overview and evolution of planning targets are given in Fig. 6. At first, cost and adequacy are the ruling planning criteria. During the 2000s, with rising concerns about climate change, the first SEP studies including CO_2 emission targets appear [65,70,94,169]. Nowadays, CO_2 targets or emission penalties are common criteria in SEP [18,57,58,86,102,142]. The increasing conviction towards green power as a solution for emission mitigation pushed many studies to include RES integration goals, in terms of minimizing energy curtailment or maximizing possible RES shares [8,21,29,121,122,172], although cost criteria are naturally still frequent.

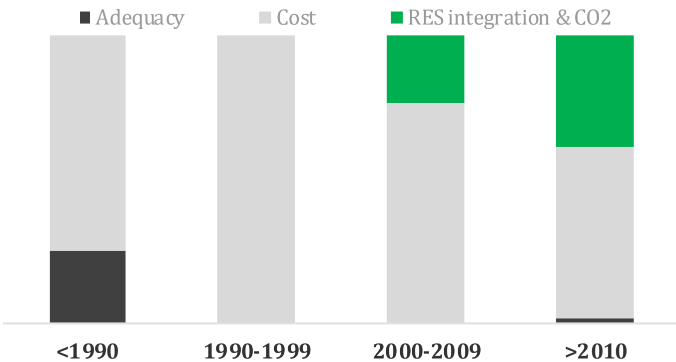

Fig. 6 Evolution of SEP planning target.

An important goal, but often neglected in the planning stage, is the reliability and security of supply that storage can provide. Recent relevant work in this regard [179] (but without sizing ESS) assesses the contribution of ESS to the adequacy of supply and the ability of DSM and ESS to displace conventional generation. Reference [180] defines the latter point formally in terms of a *capacity credit* of ESS.

The existence of diverse optimization goals has led to multi-objective formulations in many disciplines. In SEP, however, single-objective approaches are prevailing with only a few exceptions during the 2010s (e.g. [61,163]). The remaining studies focus on expressing their targets in a common (monetary) dimension or including them as constraints or as scenarios (e.g. SEP for a scenario of 100% VRE).

Before 1990, SEP is performed solely from a central planning perspective. In the following twenty years, with the liberalization of the energy sector, several studies from a private perspective emerge, involving models for attaining the production cost of technologies [84,127,146,151]. However, centrally planned SEP has not become obsolete. In fact, the vast majority of models of the 2010s is still based on such a perspective.

2.4.3. Modeled energy sectors and flexibility options

Until 1996, SEP focused only on the electricity sector. Since then, cross-sectoral planning has arisen, as shown in Fig. 7. The heat sector is the first one to be considered in SEP, particularly exploiting flexibilities in the heat storage of CHP [65,150,156]. A joint power-heat SEP has become more relevant with time [69,136,137,145,153,155,158,160,161]. For example, down to the level of individual buildings, there are clear examples of ESS able to support DSM mechanisms and to provide flexibility. They exploit low-cost thermal storage available in the building material and hot water tanks [145] when coupled with micro-CHP or electric heat pumps. Other recent studies focus on the operation of heat ESS. They include the thermal inertia of buildings and aim to highlight that the benefits from *virtual* energy storage available in residential applications potentially need to be traded off against the user's comfort level [181]. On the thermal energy storage side, this is also stirring a number of discussions and publications on the appropriate level of complexity of building simulation tools to capture the available thermal inertia and impact on comfort level [182]. Reference [67] shows the importance of coordinating electricity and heat in district energy systems and the possibility of thermal storage to support the provision of flexibility.

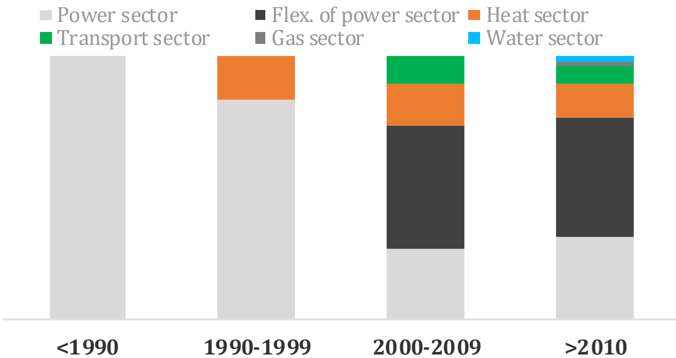

Fig. 7 Evolution of cross-sectoral planning in SEP.
Including flexibility options within the power sector.

Since the second half of the 2000s, the transport sector also starts to play an increasing role in SEP [69,70]. Consequently, it is becoming more frequent to assess the added value of coupling the transport-power-heat sectors [69,153,155,161]. Reference [161], for instance, shows an algorithm for demand response participation in distributed energy markets that considers both EV and heat pumps as key components to create flexibility and diversity in the demand side. Similarly, the coordination of storage in the transport-power-heat sector can be used to provide frequency services [183].

As a sector-connecting technology, P2G also shows increasing relevance in SEP [72,73,147,174]. Strictly speaking, these studies do not explicitly consider the gas sector, but model P2G only from the power sector point of view. Reference [73] is one of the few exceptions that models both the power and gas grid to study the benefits from P2G as seasonal storage. Another study [9], following that approach, focuses on the possibility of using P2G-based short-term storage to avoid electrical and/or gas network investment, even though no ESS sizing optimization is carried out.

With regards to the water sector (e.g. irrigation and drinking water supply) coupling, while its *operation* has been linked to the electricity sector for some decades [120,184], *investment* decision coupling has started to emerge only recently. For example, reference [185] includes in SEP the water demand and price as well as water network constraints. Also, the increasing demand for water desalination plants has triggered interest to understand their ability in providing flexibility to the power sector, e.g. through a special kind of PHS based on the resulting brines of reverse osmosis [76,157].

Within the power sector, joint expansion optimization of ESS and other flexibility options are frequently observed since the 2000s, e.g. ESS and transmission planning [93,102,122,139,142,153,168] and ESS planning with DSM options [21,57,69,182]. Energy curtailment [65,78,109,146,176] and investments in flexible generation technologies [77,104,131,142,146,168] are recurring flexibility choices in SEP, as well.

2.4.4. Modeling of network

The network modeling in SEP was strongly simplified for a long time. Indeed, studies before 2008 do not consider the transmission grid, with the exception of two papers [156,167].

More recently, SEP shifts towards multi-node approaches, accounting now for approximately 50% of the studies of the present decade. Most of these studies model the transmission system with anywhere from 5 to 30 nodes. Among the multi-node studies, the most frequent approach to model the transmission system is via transport models [57,59,116,122,142,153] and DC power flows [58,73,91,139,173,175]. In SEP, the AC approach is limited to a few studies about distribution grids [93,110,123,164].

Regarding the energy losses in transmission systems, little data could be found in the revised publications. The authors who do indicate their approach recur to model the losses as a constant proportion of demand [167], as a variable amount computed by iterations [123], or as an endogenous variable represented by piece-wise linear approximations [175].

2.4.5. Modeling detail of ESS and power system

SEP models have gradually gained detail over the recent decades (Fig. 8). The underlying equation of all studies is an energy balance, which in the simplest case is on an annual basis.

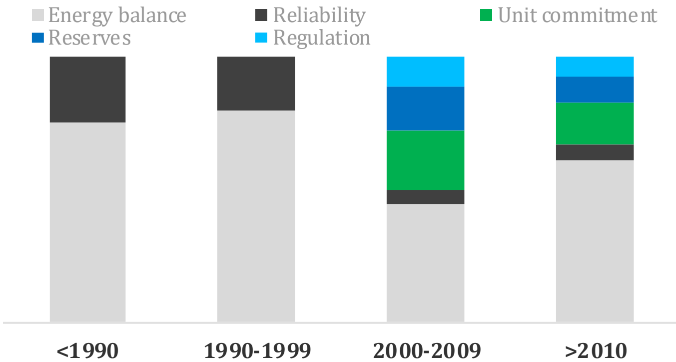

Fig. 8 Evolution of detail of power system modeling in SEP.

Before 1999, SEP is based on energy formulations only, with the exception of three publications that add reliability indices to their models [51,55,87]. The 2000s become interesting as the first SEP including UC formulations appear [65,156,169]. More detailed studies already include approximations for frequency [109] and voltage regulation [94]. In the 2010s, SEP approaches based only on energy balances still prevail. In absolute terms, formulations with UC [57,58,72,73,85,90,138,171,176], with reserves [89,174,176], and with voltage [93,110,123] and frequency [91,92] regulation proxies are becoming widespread. However, their application is limited to about one-third of the studied publications.

As for what concerns modeling of ESS, the vast majority of studies represents ESS by their energy and power capacity, and use a constant efficiency (roundtrip or dis/charge). A few exceptions use a variable efficiency, for example as a function of their state of charge [65] or their state and charge and operating current [92]. However, a variable efficiency in terms of their state of health or operating temperature has not been observed to date. Accounting for self-discharge is detected in some papers since 2013 [88,122,145,161,172]. Aging of the energy capacity and its effect on ESS lifetime is considered only in one publication [90].

Including a wide set of technical constraints of the power system, for example, reserves (primary, secondary, and tertiary reserve) was long hampered by the involved computational efforts. Recently, it was demonstrated how linear programming approximations might be used to significantly decrease simulation speed with minimum loss of accuracy in UC models for relatively large systems, such as for Great Britain [186].

2.4.6. Time treatment of investment decisions

Due to the clear advantages of modeling expansion paths of investment decisions (precise evolution of the energy system, including the end of life of existing facilities, delays due to constructing times, etc.), one would expect the number of SEP with dynamic planning formulations to increase over the decades in accordance with advances in computing capacity. But this is not what happened (Fig. 9). Instead, in the beginnings of SEP (before 1990), 50% of the models [53,54,87,141] had dynamic formulations, possibly conditioned by the long construction times of the main storage technologies of that time: hydropower reservoirs. Between 1990 and 2010, only two [168,169] out of 17 publications use a dynamic treatment for investment decisions. This trend is still valid today; about 10% of the publications target to find the expansion path of investments. In those approaches, the frequency of investment decisions (or milestone-years) has remained constant between one per year and one every five years.

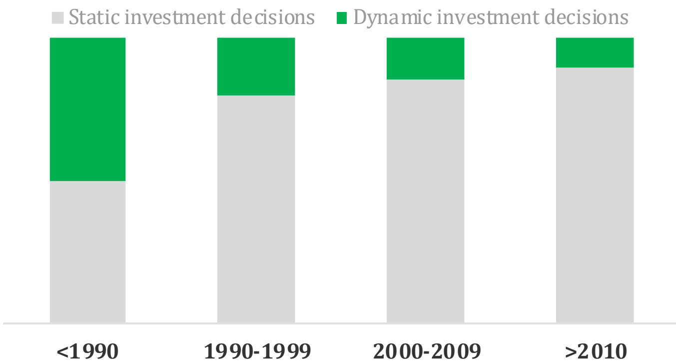

Fig. 9 Evolution of dynamic versus static formulations in SEP.

2.4.7. Time treatment of system operation

Due to limited computing capacity, SEP traditionally used non-sequential formulations. Just in the 2000s, the shift towards chronologic models starts. Nowadays, about 90% of SEP studies focus on preserving the chronology, out of which 30% use sequential type-day/weeks approaches to capture the time-dependent dynamics of ESS and VRE (Fig. 10).

The few non-sequential approaches that still remain usually correspond to particular research questions. For instance, one team aimed to make a gross economic evaluation for a wide spectrum of ESS, for which they only did a yearly balance (one time step) [128]. Others introduced a heuristic for sizing ESS relying on spectral analysis, which per definition interrupts the chronology [129]. Recently, screening curves were extended to SEP, which provide ease of solving the problem by graphical inspection, but again at the cost of the chronology [86]. Other non-sequential studies give up the chronology in trade of a longer planning horizon and a finer spatial resolution, e.g. reference [61].

Supported by advances in computing capacity and commercial solvers, time resolution in SEP has significantly improved over the last decades. Chronological models have increased their amount of time frames from about 10 in the beginnings of SEP, to 300 in the 1990s and 2000s, and to 8760 today. Furthermore, a year with hourly slices is the current standard, accounting for about 50% of the studies, even if this resolution usually requires spatially simplified systems.

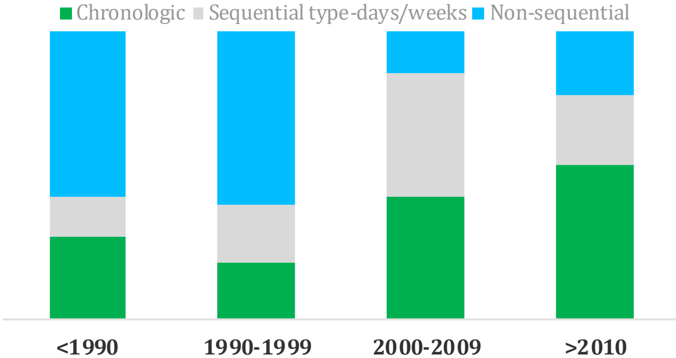

Fig. 10 Evolution of time treatment of system operation in SEP.

2.4.8. Treatment of uncertainty

Most SEP models follow a deterministic formulation, of which some use scenario analysis to account for uncertainty. Other recurrent methods to study uncertainty in SEP include Monte Carlo simulation and stochastic optimization. Their evolution over time is shown in Fig. 11.

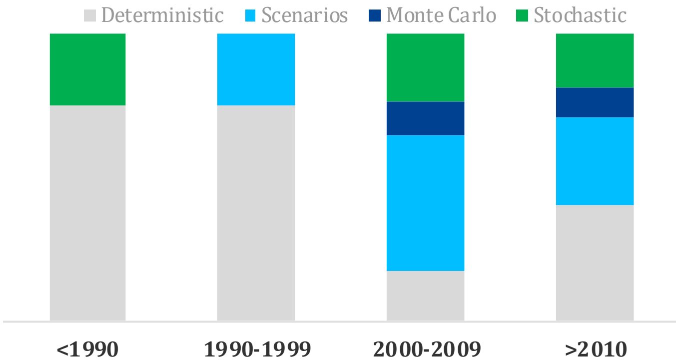

Fig. 11 Evolution of modeling of uncertainty in SEP.

Modeling of uncertainties has been part of SEP since the 1970s when stochastic optimization was the preferred tool to account for stochasticity of load [54] and -surprisingly already- of renewable energy availability (water inflows) [87].

Although during the 1990s no stochastic publication is found, a decade later it becomes a fundamental part of SEP to model uncertain energy profiles [59,109,110,121,142,144,154,159,170,171,173] and uncertain expansion paths in time (multi-stage SEP) [79].

Scenario analysis emerges in the 1990s to add sensitivities of capital costs [150]. Since a decade later, CO_2 emission prices [57,102,146], energy costs [84,152,160], VRE integration and maximum curtailment levels [78], and other technical parameters [85,122,153,165,174] are the main variables studied through scenarios.

With growing computing power, Monte Carlo simulation arrived during the 2000s, being used mainly for VRE levels and forecasts errors [90,93,156], as well as for outages of generators [61,65,90]. During the 2010s, the use of Monte Carlo expanded to other technical parameters, such as reliability levels [88,164] of the power system and efficiency parameters of ESS [58].

A recent publication relates to the liberalization of power markets. The emergence of trading agents has motivated SEP to include research based on game theory [49].

2.4.9. Solution methods

SEP has been formulated as mathematical optimization problems such as LP, MILP, NLP and MINLP, hybrid approaches, and other simulation techniques (Fig. 12). These are then solved with corresponding algorithms.

Until 1999, many different approaches are found without any dominant one. For instance, SEP are expressed as LP [51,55,87], NLP [141,143,149] –including one MINLP [53]–, hybrids [54,150], and other decision support methods [127,162,167].

In the 2000s, LP [109,156,168,169], including MILP [140], displace nonlinear formulations. Hybrids and other solution methods, with a focus on production cost models [84,146,151] and decision rules [69,70,94] account for more than half of the publications of that decade.

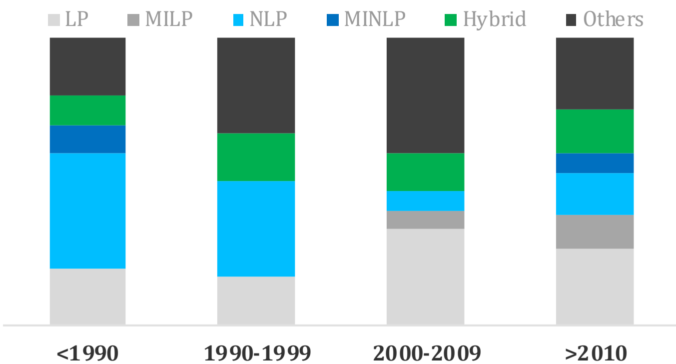

Fig. 12 Evolution of solution methods of SEP problems.

During the 2010s, LP keep being widely employed [8,57,156,159,169,170] and are frequently run with commercial solvers based on Simplex or Branch and Bound. NLP has become more frequent again, especially for solving multi-node systems, which is concurrent with the proliferation of nonlinear optimization heuristics, such as Particle Swarms [123,164], Genetic Algorithms [124], Simulated Annealing [93], Artificial Neural Networks [121] and so on. A new popular approach includes time series analysis [77,129,148].

In absolute terms, hybrids become more numerous. In SEP, these include i) optimizing the operation (with any of the above formulations) and through scenario inspection finding the optimal storage size [73,85,140,145,171]; and ii) optimizing the storage size, for which the operational costs are then attained by different methods (optimization or other solution methods) and fed back [122]. These approaches are in line with the fact that, given the complexity of future energy systems with increasing volumes of renewables, detailed simulations of power system operation will be more and more required in planning studies.

Motivated by the always limited computing capacity, model reduction techniques are applied to about a third of SEP publications. Decomposition approaches to reformulate the SEP into a master problem that determines the investments and a slave problem that calculates the operation, such as Dantzig-Wolfe [87] and Benders [51], emerge in SEP before 1990. Another early master-slave approach formulates the investment decisions as an optimal control problem and the operation decisions as an NLP [54]. Splitting the time horizon by means of Dynamic Programming corresponds to the earliest SEP publication found [141]. In the 2000s, the use of rolling horizons [154,156] and phenomenological model reduction techniques (including fuzzy clustering of load [109] and grouping of generation technologies [169]) are approaches with positive effects on solving times, especially relevant in stochastic environments. During the last years, SEP publications appear about defining the number of nodes that should be modeled as a function of areas free of transmission bottlenecks [8]. Other studies focus on warm starting the optimization problem, i.e. by finding a good initial solution [102,129].

2.5. Challenges for storage expansion planning

Research is consistent in that ESS will play a dominant role in VRE integration, as they can cope with the variability, uncertainty, and location-specificity of VRE. However, based on the findings of Section 2.4, in SEP several challenges arise in contrast to traditional expansion planning. These will be addressed as follows.

2.5.1. ESS' diversity needs to be addressed

In this review, we found that most of the studies represent ESS by using a handful of parameters (energy and power capacity, constant efficiency). However, there are other relevant and very dissimilar technical characteristics, which stand in great contrast with power generation plants. Some key features of ESS on this regard are reaction times, variable charge/discharge efficiency curves, operating/dead zones, variable lifetime, self-discharge, and ramping capacity [19,38,105]. A short review of the key characteristics of ESS and their main differences with conventional generators is explained as follows.

BESS may react to demand very quickly, providing high currents within seconds, and operate beyond their rated power (pulse rate capability). Their state of health, however, is strongly affected by cycling [19]. The life expectancy does not only differ significantly between the different types of BESS but also within a certain family. For instance, the cycles of Li-ion batteries range between 200 and 8000 under standard testing conditions, depending on the manufacturer [187]. Curiously, sodium-sulfur batteries maintain their operating temperature mostly through charging and discharging cycles [188]. On the contrary, CAES is quite insensitive to cycling, offer low self-discharge rates, but have lower efficiencies. PHS can conveniently shift energy in the day/night horizon, while large WR can accumulate energy over the seasons. Both may assist in frequency control [19]. However, they also possess forbidden operating zones given mainly by their pumps [189]. Small regulation tanks of run-of-river power plants, up- and re-powering of hydro reservoirs, and conversion of reservoirs into pumping facilities can provide additional operational flexibility. Electrolyzers offer good cycling capabilities, due to high efficiencies at partial load. The attained H_2 has good storage opportunities with very few losses even over long time horizons. The reconversion of H_2 to power via fuel cells is, however, limited by lower efficiencies (than other ESS) and very specific temperature requirements [35]. If a gas turbine is used for reconverting H_2, traditional modeling approaches may be used. EV have additional degrees of freedom. They can be connected or disconnected and may change location [61]. The literature provides exhaustive reviews of ESS qualities in power systems [4,19,190–194]. Two recently published books [47,195] in German may provide further insights on these topics.

Modeling the abovementioned technical characteristics within SEP can increase the solving times significantly and lead to a loss of linearity. The time-dependent constraints (starting times, energy balances, ramps) are especially challenging, as they require a sequential time treatment as well as a high temporal resolution. However, not modeling them accordingly may imply attaining suboptimal results in SEP.

2.5.2. ESS' complex lifetime and efficiency functions need to be modeled

The available of ESS differ vastly between each other, even within the same technology. The efficiency and lifetime functions that characterize them are particularly complex and dissimilar. Similar to power generators, ESS are affected by cycling [196], consequently impacting their operating and replacement costs. However, ESS are exposed to a larger number of cycles. For example, batteries could perform multiple cycles per day.

Lifetime as a function of cycling has been considered in expansion decisions of conventional generators [197], as well as in operation of small power systems [198]. In SEP, however, we detected that only one study has looked into cycling so far [90]. This implies that the *optimal* results found by the remaining studies may hide infeasible conditions. For example, nothing in the model would prevent BESS performing cycles beyond its lifetime expectations.

The efficiency of ESS is more dynamic than that of conventional power plants. It is sensitive to the state of charge, state of health, charging and discharging power flows, and operating temperatures, among others [19]. These complex dependencies provoke large deviations in their operating efficiency as compared to generators and hence lead to greater uncertainties. SEP blind to this phenomenon may over- or underestimate the actual efficiencies, as well as be indifferent to lower states-of-charge and the involved smaller efficiencies. If these relationships are implemented, the optimization problem frequently becomes nonlinear.

2.5.3. ESS require high temporal and spatial resolution

In modeling, coarse time scales may mask relevant short-term dynamics. This happens in GEP with VRE, but also in SEP. Furthermore, the technical differences among ESS (Section 2.5.1) can only be distinguished, if a matching temporal and spatial resolution is used. Moreover, important technical aspects of ESS, including ramping rates, variable efficiency, and reserve services, require sequential approaches. Although our review has shown that time resolution has improved significantly over the years, and is down to hourly resolutions, solving the entire planning horizon (e.g. 20 years) with that resolution is still not feasible in real power systems.

The chronology is frequently given up in trade of cross-sectoral planning, such as in the wide-spread expansion software MARKAL [96] and TIMES [199]. Here, VRE are mainly represented with capacity credits, which neglect their variable input. In power systems with high shares of VRE, ignoring their spatial and temporal variability leads to systematic errors, especially what refers to the need for ramp rates, forecast, and the quantification of operating reserves. As a consequence, simplified planning approaches may underestimate the real need of flexibility in the system [200–202]. In more recent versions of those programs, typical days or typical weeks are included as a possible solution to overcome these shortcomings [203]. Short-term storage systems can then be modeled with the time resolution they require. Nevertheless, type-days (or weeks) have two strong limitations: i) it becomes increasingly more difficult to identify them in the presence of many stochastic drivers (VRE) in the system; ii) the approach cannot deal with large storage capacities that exceed the length of the typical time period.

A potential solution to these issues is the use of hybrid models. As mentioned in Section 2.4.9, some hybrid SEP propose to optimize the operation and find the best ESS size by scenario inspection [85,172]. This nonetheless, depends strongly on the *good luck* of the planning expert and is hardly scalable to SEP with multi ESS, due to the numerous scenarios it would require. However, it may still provide a good initial solution for storage requirements. The other hybrids (which feed the operational costs back to the investment optimization [122]) are plagued by convergence issues and depend on configuring a good set of rules to describe the operation. Some researchers [131] propose to hard-link separated investment and operation programs. This means performing a long-term expansion planning (e.g. TIMES) followed by an operational model that feeds back constraints. So far they have been able to study the Portuguese power system. But, whether the framework holds for multi-storage, multi-sector, and nonlinearities, is unclear.

Similarly to VRE, many ESS rely on local resources, such as PHS in the mountains, CAES in special rock formations or EV in wealthy neighborhoods. Consequently, studying the local potentials becomes more relevant. Another corollary is that the transmission system and its expansion need to be modeled with more detail. But, this increases the computational burden.

In short, to capture the variable nature of VRE and the short-term dynamics of ESS, the temporal resolutions has to be further improved. Similarly, to address local potentials and bottlenecks, the spatial resolution needs to be enhanced.

2.5.4. ESS' multiple services need to be recognized

ESS can provide multiple services, from energy shifting and ramping capabilities to cope with VRE variability, reserves to compensate forecasting errors of VRE (uncertainty), improved frequency and voltage control, stability support, and black-start capability, among others. These applications are well documented [4,19,191,204] and some publications demonstrate that it is critical to properly consider what services ESS should provide from an operational point of view [205]. However, only few SEP publications include the pertinent benefits. Consequently, the value of ESS is systematically being underestimated.

More worryingly, current reserves, given primarily by conventional generators, are decreasing and being replaced by inertia-less converters (PV and wind power) [204]. In high VRE-shares scenarios, ESS might be the main source of reserves to deal with increasing levels of variability and uncertainties.

In the context of multi-sectorial planning (Section 2.5.5), more system services might emerge in time, which could be provided by ESS. For example, hydropower plants usually provide flexibility for VRE integration, but this operation (hydropeaking) [206–208] has detrimental effects on the ecosystems of rivers, such as washing out and stranding of species [209], life cycle, and food chain disruption [210]. Hence, if other ESS provide that flexibility, they could indirectly provide an ecosystemic service by reducing the hydropeaking.

In order to give the right price signals for investment decisions, the many services that ESS are able to provide in the power system, as well as across energy sectors, must be acknowledged. For this, the above-mentioned challenges need to be addressed.

2.5.5. ESS' presence in many energy sectors require multi-sectoral approaches

Within the electricity sector, investment decisions of the different flexibility sources are interdependent [18]. However, they are frequently planned separately. A holistic approach, instead, would enable identifying synergies. For example, a combined storage and transmission expansion planning allows for a more economic integration of VRE [102,122]. In other words, if the transmission is cheap, remote generation and ESS potentials can easily be accessed. Conversely, local generation and ESS resources would be preferred. Here, the value of ESS lies in decreasing transmission congestion and losses, as well as displacing its socially controversial expansion [18].

Nowadays, the economic potential of ESS transcends the electricity sector; also the heat, gas, water, and transport sector offer attractive ESS options. Reasons to include multi-sectors in SEP are at least the following: i) some cross-sectorial potential of ESS is convenient as it already exists or can be implemented through minor adaptions; for example, electric boilers for hot water and heat pumps for space heating may be a key low-cost option for providing flexibility [67,68]; similarly, H_2 attained from P2G can be stored and transmitted in existing gas infrastructure to some extent [9,73]; and ii) cross-sectorial SEP allows identifying synergies between sectors: for example, more gas storage can increase the sector's autonomy and simultaneously reduce the need for other long-term storage options, such as large reservoirs that often are controversial; or a desalination plant could perceive another stream of income when offering operational flexibility to the power sector [157]; iii) cross-sectorial SEP helps identify the possible issues that could arise when the coupling is *not* explicitly modeled: a recent work [9] (about the flexibility of an integrated electricity and gas network, considering the stored energy in the gas lines) highlights how the lack of storage flexibility in the gas network might cause issues with reserve commitment and delivery in the electrical sector. Moreover, as electrification of energy demand is envisioned by the International Energy Agency as a major solution for meeting CO_2 reduction goals [211], the electricity sector is no longer isolated and is growing closer together with the heat, gas, water and transport sectors.

Modeling more than just the power sector imposes computational burdens, just as the spatial and time resolution does. An open question is where the value of ESS lies. Is it in the multiple services that a mix of ESS can provide in the electricity sector, or is it the energy shifting ability across sectors and time?

2.6. Conclusions and future work

This chapter reviewed about 90 journal publications involving storage expansion planning (SEP). It classified them according to nine criteria, including modeled energy storage systems (ESS), goal and planning perspective of models, energy sectors and flexibility options, network modeling, modeling detail of ESS and power system, time treatment of investment decisions, time treatment of system operation, treatment of uncertainty, and solution methods. From this classification, trends in SEP were identified, and the outstanding challenges derived. These challenges are summarized as follows.

2.6.1. ESS' diversity needs to be addressed

Nowadays, SEP focuses on a wide spectrum of ESS, including short- to long-term, fixed and mobile, centralized and distributed ESS, all very dissimilar to each other. As the ideal ESS does not exist, the search for an optimum combination or mix of technologies seems natural. However, only now the first studies to identify that optimal ESS mix are appearing. So far, these studies limit the modeling details of ESS to a handful of parameters (state of charge, roundtrip efficiency, power, and energy capacity), neglecting other relevant dynamics.

2.6.2. ESS’ complex lifetime and efficiency functions need to be modeled

In contrast to conventional technologies in generation expansion planning (GEP), the lifetime of ESS is strongly affected by the many cycles to which they are exposed, and their efficiency depends on diverse phenomena making the model highly nonlinear. Modeling the lifetime in terms of cycling, as well as the efficiency functions of ESS remain scarce in SEP, but is required for not underestimating the costs.

2.6.3. ESS require high temporal and spatial resolution

The above mentioned technical diversity of ESS calls for a higher temporal resolution, whereas transmission constraints and local potentials of ESS call for a more detailed spatial resolution. Only a sufficient treatment of space and time and modeling their multiple services, as well as complete modeling of the power system operation (e.g. unit commitment and network constraints), will enable capturing the full value of ESS.

2.6.4. ESS’ multiple services need to be recognized

To integrate variable renewable energy systems (VRE), the flexibility of energy systems in terms of energy shifting, ramps, and regulation is needed. These are all qualities of ESS. However, current SEP focuses mainly on energy shifting, systemically underestimating their full value. This is relevant especially as ESS is a potential competitor to other flexibility sources, such as transmission and generation infrastructure, and demand-side management. Furthermore, only joint planning of them allows identifying the global optimum of flexibility in future energy systems.

2.6.5. ESS’ presence in many energy sectors require multi-sectoral approaches

ESS can be deployed in many energy sectors. Moreover, ESS may readily be available in other energy sectors, so that relatively low-cost options for power system flexibility provision may be accessed. Furthermore, the sectors are growing together as electrification of demand is widely envisioned as a solution for reaching climate change mitigation goals. Consequently, to find the cross-sectorial optima, the power, heat, gas, transport, and water sectors need to be planned in conjunction.

2.6.6. Future work

As future work, the aforementioned SEP challenges need to be addressed. In particular, elaborating a comprehensive ranking between them is pressing. For example, a benchmark for the trade-off between precision and computing time among the many technical ESS properties, time and space resolution, and detail of the power system is needed. Furthermore, towards multi-sectorial storage planning, a coordinated planning effort among the involved energy sectors is key.

Future SEP approaches might also emphasize agent-based modeling, stochastic programming, and multi-objective optimization, in order to capture market behavior, uncertainties, and multiple targets, such as environmental criteria, flexible planning, and resilience, of the energy sector.

Finally, the combination of a high resolution of time, space, technical phenomena, and market, along with multi-sectors -and all these under uncertainty- calls for advances in model reduction techniques and solving speed.

Chapter 3. How much energy storage do we need?

This chapter is based on the publication “*How much Electrical Energy Storage do we need? A synthesis for the U.S., Europe, and Germany*” by Felix Cebulla, Jannik Haas, Josh Eichman, Wolfgang Nowak, and Pierluigi Mancarella, published 2018 in the Journal of Cleaner Production.

This work was funded by the German Academic Exchange Service (DAAD), the Helmholtz Research School on Energy Scenarios, the German Research Foundation (DFG) through the grant DFG-NO 805/11-1, and the United Kingdom‘s Engineering and Physical Sciences Research Council (EPSRC) through the MY-STORE project (EP/N001974/1). Furthermore, the help of the authors of the inhere cited studies, who provided additional information to their publications, is highly appreciated.

Executive summary

In the last couple of years, many studies for ESS capacity planning have been produced. However, these resulted in a very broad range of power and energy capacity requirements for storage, making it difficult for policymakers to identify clear storage planning recommendations.

To clarify this issue, we studied 17 recent storage expansion studies pertinent to the U.S., Europe, and Germany. We then systemized the storage requirement per variable renewable energy (VRE) share and generation technology.

Our synthesis reveals that with increasing VRE shares, the ESS power capacity increases linearly; and the energy capacity, exponentially. Further, by analyzing the outliers, the ESS energy requirements can be at least halved. It becomes clear that grids dominated by photovoltaic energy call for more ESS, while large shares of wind rely more on transmission capacity. Taking into account the energy mix solves to a large degree the apparent conflict of the storage requirements between the existing studies. Finally, there might exist a negative bias towards storage because transmission costs are frequently optimistic (by neglecting execution delays and social opposition) and storage can cope with uncertainties, but these issues are rarely acknowledged in the planning process.

3.1. Introduction

During the last five years, many studies on planning storage requirements have emerged for the different regions of the world. Examples of studies that plan the required storage capacity for power systems with large shares of renewable energy (RE) are [212–217] for the U.S. or [57,174,212,213,218–221] for Europe. However, these studies result in a wide range of storage requirements, which makes it difficult for the policy maker to identify clear recommendations. As systemized in the previous chapter, many methods, assumptions, and modeling approaches in storage expansion planning exist, which may help explain the variances in the results.

To date, there are a few initial efforts in systemizing the flexibility requirements. One example is the book from Droste-Franke [222] which, based on studies from around 2010, comprehensively explains the flexibility requirements for Europe and Germany for different shares of renewables. Kondziella and Bruckner [223] follow that line and provide an updated review of flexibility demand. Koskinen and Breyer [28] provide a summary of global and trans-continental storage demand. Finally, Doetsch et al. [224] review different reports, which analyze the need for ESS in the German and European energy system. Most recently, Zerrahn and Schill [225] provide a comprehensive review of storage planning with a focus on the modeling approach. Unexplained differences in the prognosed ESS requirements remain, calling for a systematization of the many available storage expansion studies, particularly in the light of their derived storage capacity.

On the above premises, we analyzed and systemized recent ESS expansion studies for three regions with strong renewable targets (U.S., Europe, and Germany), including 17 studies and over 400 scenarios. This chapter makes three fundamental contributions to the literature:

- for each region, we compare the obtained storage energy and power capacity requirements for VRE shares;
- as these studies reveal a very broad spectrum of storage sizes, we further delimit the range of storage requirements by analyzing the main drivers, including the impact of different power mixes (photovoltaic- or wind-dominated);
- we discuss the impact of the electrical network modeling on the storage requirements.

Altogether, the findings provide direction to energy modelers regarding where to put effort when modeling future energy systems, as well as to decision makers towards a more precise understanding of the storage requirements.

The next section describes the methods about the analyzed studies. Section 3.3 presents the ranges of storage requirements found and discusses the main drivers. Finally, Section 3.4 draws the conclusions.

3.2. Methods

Our approach consists of three steps. First, we collect and systemize data from recent studies about storage expansion planning. Second, we analyze and coarsely describe the models of the selected studies to then synthesize the storage requirements and filter unfit scenarios in our third step. More detail on these steps will follow.

3.2.1. Data collection and systematization

Meeting environmental goals has triggered many studies about planning power systems with high shares of renewable technologies in the last couple of years. From the existing literature, we looked for studies that detail the storage requirements explicitly (storage expansion planning) and that range from 2009 to early 2017. A selected study should include scenarios with high shares of renewables and provide the specifics on the generation mix.

We decided to focus on the U.S. and Europe, as they are large continental grids and global drivers for storage demand. We also decided to contrast the results of such large grids with a smaller geographic region. Germany was chosen given the many available studies and the country's ambitious renewable energy target.

We paid special attention to the storage power capacity (in GWel) and energy capacity (TWhel), and the associated shares of VRE and generation mix. We defined VRE shares as the sum of all variable power generation (e.g. from photovoltaic (PV) or wind systems) over a time period (typically one year) divided by the overall power generation[7] [226]. Further, as a basis for systematization and synthesis, we recorded how the grid is modeled, whether other flexibility options were considered, and other relevant assumptions.

Most of the studies provided this information as part of their bodies or as supplementary materials. If absent, we contacted the corresponding author directly. All this data was compiled into a database.

3.2.2. Selected studies

Following the selection criteria explained above, we considered the following ESS studies: [57,86,174,212–221,227–233].

For the U.S., we considered the renowned studies "Renewable Electricity Futures" of the National Renewable Energy Laboratory (NREL) [216] and "Prospects for Energy Storage in Decarbonised Power Grids" from the International Energy Agency [213]. Relevant journal publications and PhD thesis are [212,214,215,227] and [217], respectively.

Selected studies for Europe include the recognized report "Roadmap Storage" [229] from Fraunhofer/RWTH Aachen/Environmental Law Foundation. Analyzed energy journal publications are [57,218–221]. The report from the International Energy Agency [213] and the journal publication [212] mentioned above also provide

[7] The VRE share can either refer to the gross power generation or the satisfied power demand. The former includes losses (e.g. from storage self-discharging or transmission losses) and the second neglects them.

scenarios for Europe.

Germany clearly is a region included in the models of the European studies. However, the studies frequently do not explicitly provide the results of one country; rather they refer to the continental storage need (with the exception of [57,229] that indeed provide the details for Germany). Hence, the following studies are specifically made for Germany. We included the well-known study from the VDE (Association for Electrical, Electronic & Information Technologies) [232], recent journal publications [86,174,230,231], comprehensive PhD theses on the topic [228,233], and the already mentioned publications of Europe that also detail Germany [57,229].

The summary of the considered studies is shown in Table 3 Overview of considered studies. Reprinted with permission from [234].. For a more detailed description, please consult the work of [234].

3.2.3. Admissible scenarios

The explored studies contain 527 scenarios. Not all scenarios are suitable, however, for comparison. We excluded those that differ significantly in their spatial scope from the majority of the reviewed body of literature. These are Bussar et al. [218,220], who combined Europe, Middle East, and North Africa; Mileva et al. [214] and Budischak et al. [227], which looked only at one U.S grid region (WECC[8] and PJM[9], respectively); and some scenarios of Frew [215,217] that focus on California and WECC. Additionally, we excluded those studies that do not size ESS (i.e. Brouwer et al. [221], which use only predefined ESS capacities), and those that lack the information required for our analysis (i.e. Kühne [228], where PV and wind shares are not explicit for some scenarios).

We finally ended up with 405 comparable scenarios for the U.S., Europe, and Germany. They will be processed as follows.

[8] Western Electricity Coordinating Council

[9] Pennsylvania - New Jersey - Maryland Power Pool

Table 3 Overview of considered studies. *Reprinted with permission from* [234].

Source	Year	Thesis	Report	Article	Model name	Optimi.	Simu.	Time res. (h)	Spatial scope	Regions	Storage techs.	Grid	Other flexibilities
Adamek et al. [232]	2012		●		N/A	●		1	Germany	1	Short and long-term ESS	Copperplate, w/o imports/exports	DSM[a], curtailment
Babrowski et al. [230]	2016			●	PERSEUS-NET-ESS	●		1	Germany	440	PHS, generic battery	Exogenous, w/o imports/exports	DSM, curtailment, controlled charging of battery electric vehicles (BEV)
Bertsch et al. [57]	2016			●	DIMENSION	●		1	Europe/ Germany	27	aCAES, PHS	Exogenous, based on scenario B of [235]	DSM, curtailment, controlled charging of BEV
Brouwer et al. [221]	2016			●	PLEXOS	●		1	Europe	6	aCAES, PHS[b]	Exogenous, six different cases analyzed	DSM[a], curtailment
Budischak et al. [227]	2013			●	RREEOM	●		1	U.S. PJM	1	Generic battery, H_2	Copperplate, w/o imports/exports	Curtailment, vehicle to grid
Bussar et al. [218,220]	2016/ 2015			●	GENESYS	●		1	Europe/ M. East/ N. Africa	21	PHS, generic battery, H_2	Endogenous	Curtailment
Frew [215,217]	2016/ 2014	●		●	POWER	●		1	U.S.	10	PHS, generic battery	Endogenous, additionally to existing grid	DSM[a], curtailment, controlled charging of BEV, concentrated solar power (CSP)
Hartmann [233]	2013	●			E2M2	●		1	Germany	1	PHS, CAES, aCAES	Copper plate, w/o imports/exports	Curtailment[c]
Inage [213]	2009		●		N/A		●	0.1	U.S./ Europe	12	Generic ESS	Copper plate	N/A
Kühne [228]	2016	●			MESTAS	●		1	Germany	1	PHS, aCAES, H_2	Copperplate, w/o imports/exports[d]	Curtailment
Mileva et al. [214]	2016			●	SWITCH	●		1	U.S. WECC	50	PHS[b], CAES, generic battery	Endogenous, additionally to existing grid	DSM[a], curtailment, controlled charging of BEV[e]
NREL Ref study [216]	2014/ 2012		●		ReEDS	●		1	U.S.	11	PHS, generic battery, CAES	Endogenous, additionally to existing grid	DSM, CSP, controlled charging of BEV
Pape et al. [229]	2014		●		SCOPE	●		1	Europe/ Germany	20	PHS, Lead-acid battery[e], H_2	Endogenous, additionally to existing grid based on [236]	DSM[a], curtailment, cBEV[f], flexible CHP
Scholz et al. [219]	2016			●	REMix	●		1	Europe	15	Redox-flow battery[e], PHS, H_2	Endogenous	Curtailment, CSP
Steffen & Weber [86,231]	2013/ 2012			●	N/A	●		1	Germany	1	PHS	Copperplate, w/o imports/exports	DSM[g]
Ueckerdt et al. [212]	2016			●	REMIND/ DIMES	●		1	U.S./ Europe	8	Generic short-term storage	Copperplate	Curtailment
Zerrahn & Schill [174]	2015		●		DIETER	●		1	Germany	1	PHS, aCAES, H_2, diverse batteries	Copperplate, w/o imports/exports	DSM[a], curtailment

[a] In some model runs DSM is not included (or only partially) to analyze its influence on ESS requirements. [b] Only existing PHS capacities. [c] Some sensitivity cases restrict curtailment. [d] Electricity surplus can be sold at a fixed price to the neighboring countries. [e] Different configurations of fixed energy-to-power ratios are used; i.e. no independent dimensioning of power and energy capacity of the ESS. [f] In some model runs controlled charging BEV is not included (or only partially) to analyze its influence on ESS requirements. [g] Load reduction in super-peak hours.

3.3. Results and discussion

This section systemizes and analyzes the need for storage capacities in the different regions recommended in the studies listed above. From the admissible scenarios, a broad spectrum of recommendations was found. For example, for VRE shares over 80%, the ranges of ESS requirements are 15–530 GW (0.2–6 TWh) for the U.S., 10–350 GW (0.2–22 TWh) for Europe, and 8–140 GW (0.05–83 TWh) for Germany. These variances make it challenging for policymakers to quantify the real need of ESS, which motivates us to systemize and analyze these figures, and then to synthesize a more specific recommendation with more narrow variances but with the most influential control variables revealed.

For this, we first organize the storage requirements per VRE shares. Second, we analyze the ESS needed according to the generation mix. Third and last, we discuss the impact of explicit electrical network modeling and other factors on the results.

3.3.1. Impact of renewable shares

Currently, the VRE shares (from wind and PV) in Europe, the U.S., and Germany are still small with about 13% (EU28), 7%, and 20% [237,238]. However, all three regions present strong VRE growth rates. By 2030, the overall renewable shares are expected to be around 44% [239], 15% [240], and 50%2 [241], although these numbers vary depending on the consulted study. Europe and Germany aim at renewable shares of over 56% [239] and 80% [241] by 2050. The U.S. has targets by states instead of national ones. Here, the projections are not too clear yet, but the U.S. Energy Information Administration expects at least 20% by 2050 [240]. As of 2016, the installed storage power capacities[10] in Europe, the U.S., and Germany are 52 GW, 24 GW, and 7 GW [22]. About 95% of this capacity is provided by PHS (50 GW, 23 GW, 6.5 GW) [22].

Now, in terms of demand for storage, we expected higher shares of VRE to yield larger requirements for ESS power capacity. However, the data points are scattered over the whole plot (of Fig. 13). The upper and lower bounds, nevertheless, show a clear trend. For the U.S., Europe, and Germany the minimum required ESS power capacity grows from 3 to 40 GW, 0.5 to 15 GW, and 2 to 10 GW for VRE shares of 50 and 90%. The upper bound is more varied. Here the ranges go from 50 to 145 GW for the U.S., 90 to 200 GW for Europe, and 40 to 85 GW for Germany.

In terms of ESS energy capacity requirements, a steady increase with VRE can be observed. For the U.S. and Europe, even studies which derive low ESS requirements suggest a quick increase after 40% of VRE shares and estimate a need from 16 to 235 GWh and 25 to 280 GWh for VRE shares between 40 and 90%. For the same range of VRE shares, publications which result in high ESS requirements depict values from 315–22,000, 500–5,900, 3,900–83,000 GWh.

Especially, the ESS energy capacity shows a large spread in all regions. The maxima are one order of magnitude larger than the averages. Hence, to further limit this range, we will identify and discuss the outliers for each region.

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[10] Discharging capacity, without thermal storage

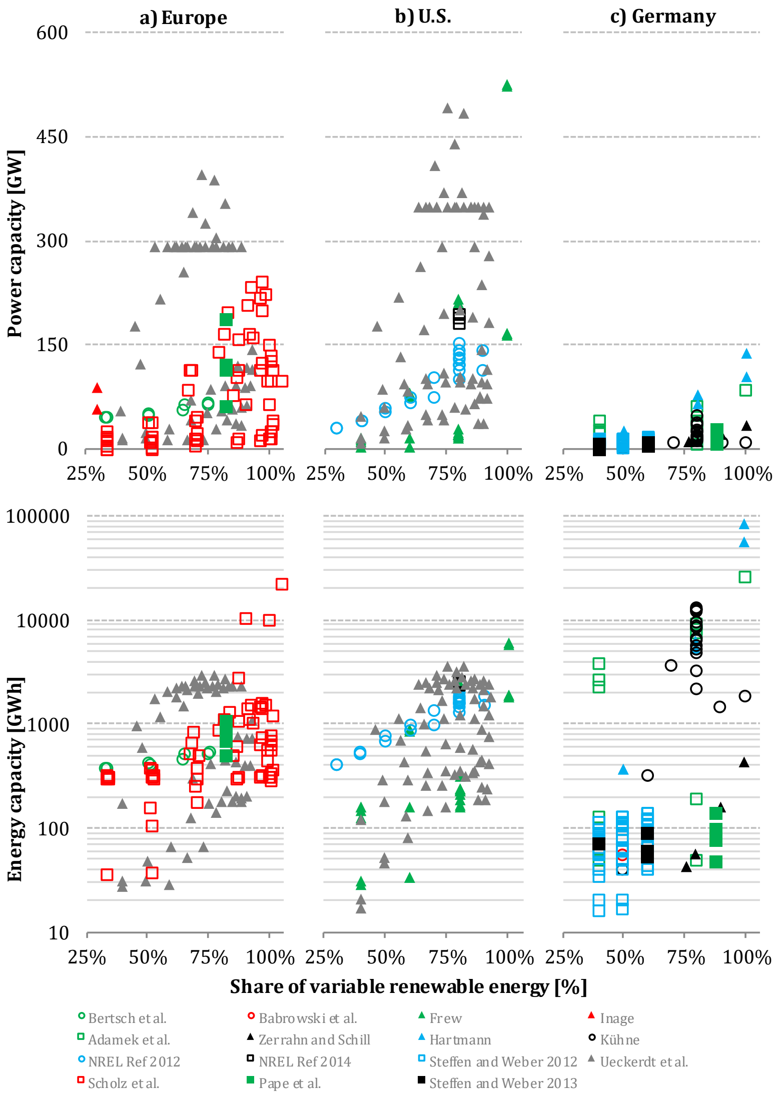

Fig. 13 Review on requirements of ESS capacities.

a) Europe, b) U.S., c) Germany. Note that the energy capacity is depicted on a logarithmic scale and that Inage does not provide values for energy capacities.

In the U.S., Frew [215,217] presents two scenarios with strong assumptions; the scenarios "independent FERC regions" -with/without electric vehicles- stipulate energy autarky among the regions. Hence, the overall ESS energy capacities are expected to be large. Excluding these two scenarios, the required national energy capacities are almost halved from 6 to 3.5 TWh.

In Europe, Scholz et al. [219] derive three extreme values for ESS energy capacities, which relate to scenarios of high VRE shares under extremely expensive CO_2 certificates (400 €/t). In these cases, the model tends to displace as much fossil generation as possible, which calls for balancing seasonal cycles via H_2 storage. If these cases are excluded, the European maximum ESS energy capacity requirements shrink from 22 to 3 TWh.

In Germany, outliers belong to Adamek et al. [232] and Hartmann [233]. The former exogenously prescribes ESS sizes and analyzes how the system operates. One of Hartmann's [233] extreme values forbids curtailment, which results in the need of storing all generated energy. His second outlier can be explained by the ratio between a rather expensive VRE and a relatively cheap ESS. Consequently, investing in CAES energy storage capacity is more economical than increasing generation capacities that lead to VRE curtailment. Once these cases are excluded, the needed ESS energy capacity in Germany is reduced from 83 to 12.5 TWh and the power capacity from 139 to 78 GW.

The resulting ESS energy capacity requirements for Europe and the U.S. are similar (about 3 TWh) for large VRE shares. This is coherent given the similarity in magnitude of their electric demand. However, Germany's ESS energy capacities are four times as large as those of other regions (over 12 TWh), for a system that is about five times smaller in terms of annual electricity demand.

With regard to ESS power capacities, Europe and the U.S. show similar values. Their respective maxima are close to 400 and 500 GW. Here, Germany lies, with about 80 GW, in the expected range. Nevertheless, the spectrum of storage requirements is large in all these regions. This might be caused by power mixes that strongly rely on a single technology.

3.3.2. Impact of generation mix

The generation profile has a large impact on flexibility technologies. Therefore, we distinguish the power mixes with a clearly dominant technology. We define the following categories: very PV-dominated (PV++), PV-dominated (PV+), very wind-dominated (Wind++), wind-dominated (Wind+), and balanced mixes. The limits between categories were defined as selected ratios between the installed capacities of PV and wind. These ratios are 6:1, 2:1, 1:3, and 1:1.5 for the *dominant* categories. The balanced cases are those in between PV+ and Wind+. For example, a system with 100 MW of PV and 10 MW of wind would be defined as PV++. The wind ratios are half of the PV ratios, to compensate for their higher capacity factor.

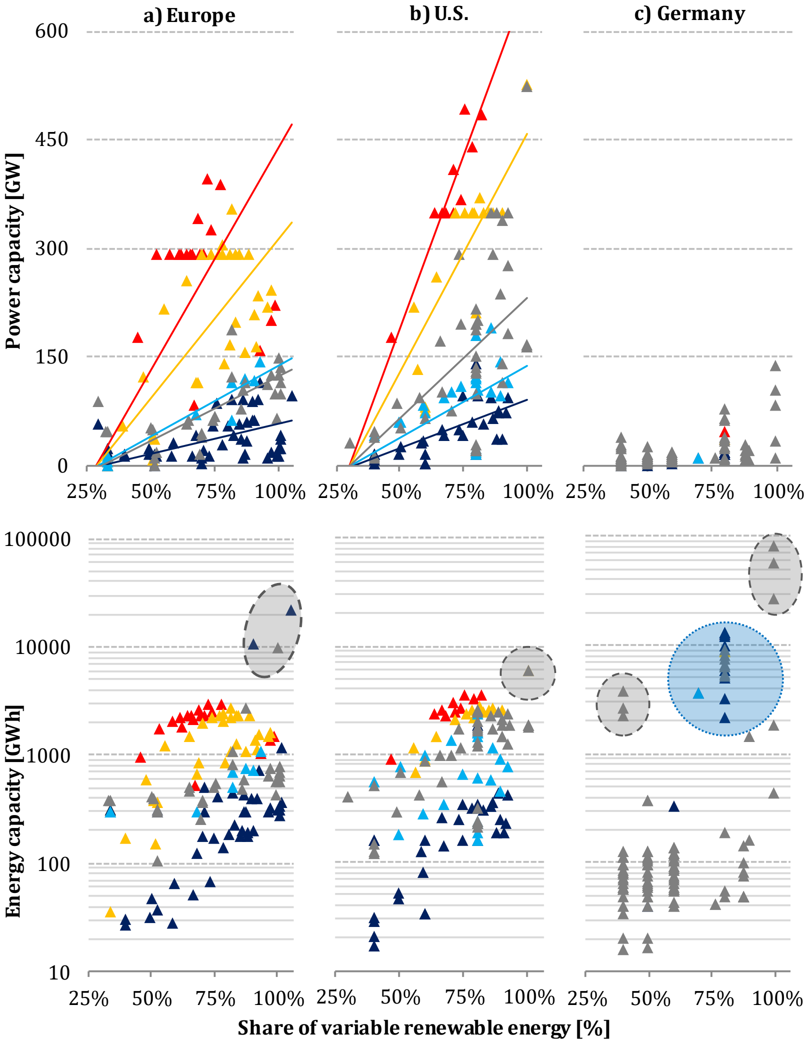

Fig. 14 Impact of power mixes on the requirement of ESS capacities.

a) Europe, b) U.S., c) Germany.

PV++ indicate publications with power mixes that are dominated by PV. Wind++ shows scenarios which are strongly wind-dominated. Note that the energy capacity is depicted on a logarithmic scale. The highlighted areas show the outliers (gray dashed area) and studies with unexpectedly high energy capacity needs (blue dotted area).

In Fig. 14, it can be observed that power systems with higher PV shares require the largest ESS. On the one hand, the very PV-dominated scenarios define an upper bound of storage requirements. PV+ also imposes a high need for ESS but show a much wider spread. Based on a linear regression, the required ESS power capacity is close to 6 and 9 GW/$\%_{VRE}$ for the PV++, and 4 to 6 GW/$\%_{VRE}$ for the PV+ scenarios in Europe and the U.S. However, in Europe, having a power system with ratios of PV to wind above 6:1 seems unlikely. For Germany, only very few scenarios show PV-dominated systems.

On the other hand, in wind-dominated mixes, the required storage power capacity also increases with VRE, but to a much lower extent than for PV scenarios. Wind-dominated mixes represent the lower bound of requirements for ESS power capacity. The necessary ESS power capacity in Wind++ scenarios shows a slight increase, while in Wind+ scenarios they grow more quickly, but with more of a spread. For both Europe and the U.S., the increase is about 1 GW/$\%_{VRE}$ for Wind++ and 2 GW/$\%_{VRE}$ for Wind+. Germany shows only a couple of Wind++ and almost no Wind+ scenarios. The former is characterized by a demand of 0.3 GW/$\%_{VRE}$.

The balanced scenarios are generally between the wind- and PV-dominated scenarios. In Europe, the U.S., and Germany these require 2, 3, and 0.6 GW/$\%_{VRE}$, respectively.

These findings are as expected. In fact, in contrast to wind power, PV generation shows a higher correlation in time over a region, e.g. Europe. In other words, even with unlimited transmission, the sun does not shine at night. Therefore, increased spatial flexibility through transmission can complement ESS to a certain extent. However, it is not able to completely substitute storage requirements [8,219,242], unless a global power grid is developed.

While the ESS power capacity shows a linear increase for the different mixes, the ESS energy capacity has an exponential behavior (note the logarithmic scale in Fig. 14; for the same reason we cannot apply the above-computed ratios here). The energy capacity requirements grow exponentially because storage has to gradually take care of the different cycles of the net load (and these cycles grow exponentially in terms of energy) as the renewable penetration grows and the conventional generation decreases. In other words, from lower to higher renewable shares, the role of storage changes gradually going from buffering small fluctuations in net demand to taking care of the main cycles of renewables (e.g. day/night of solar). And for systems with very high renewable shares, storage also needs to cope with extended periods of low renewable production (e.g. a week of slow winds or low solar generation in winter) [243].

Similar to the ESS power capacity, the required energy capacity is maximum in PV++ and minimum in Wind++ scenarios. Under increasing VRE shares, PV++ mixes require at most 1.0 to 2.9 and 0.9 to 3.5 TWh for Europe and the U.S. Systems strongly dominated by wind generation need at least 0.03 to 0.3 and 0.02 to 0.4 TWh for the same regions. These energy capacity requirements are quite bounded. For Germany, most of the studies are balanced mixes, which recommend ESS energy sizes of 0.02 to 12.5 TWh. This broad range in Germany has various causes. First, a small region has higher correlated wind resource than larger regions (such as Europe or the U.S). This results in a lower spatial smoothening for wind-dominated scenarios and subsequently in higher storage requirements (see area highlighted in blue of Fig. 14 - Germany). Second, neglecting power imports/export to neighboring countries reduces the available flexibility. This is the case of Kühne [228] and Hartmann [233]. When looking at the other recent studies for Germany, e.g. Zerrahn and Schill [174] or Pape et al. [229], which do not include such strong assumptions, the ESS energy capacity is estimated between 0.04 and 0.44 TWh. This range does scales with the continent's storage requirements.

3.3.3. Impact of grid modeling

Typically, in expansion planning, three approaches of grid modeling can be found in the literature, with some explicit consideration of the electrical network infrastructure. One is considering transmission infrastructure as a decision variable. This endogenous approach allows for finding the optimal combination of the future grid, storage, and other flexibility options. As transmission expansion is usually cheaper than storage, this approach might result in lower ESS requirements. However, in practice, grid expansion is usually plagued by delays, thus resulting in costs larger than those as planned. Alternatively, a transmission plan (topology and line capacities) can be prescribed and used as inputs to the optimization. This exogenous approach can be more realistic in terms of project execution since social and regulatory aspects might have been taken into account. Finally, not modeling the grid (i.e. copper plate) equates to assuming that no bottlenecks exist nor will exist (i.e. free and unlimited grid). This assumption may generally lead to a systematic underestimation of storage requirements.

For Europe and for PV-dominated scenarios, endogenously modeled grid expansion or copper plate approaches do not translate into less storage. In should be noted that although Figure 3 seems to imply that copper plate modeling goes in hand with large storage needs, this is actually caused by the high shares of PV (as explained in the previous section) and not by the grid modeling. It is also worth mentioning that, if most of solar were to come from PV connected to the distribution network, it is likely that bottlenecks at that level might emerge too, which is typically neglected in system-level expansion studies.

For wind-dominated and balanced scenarios, the above-mentioned relations between grid modeling and storage requirements are not observed for Europe (see Fig. 15). The data points are quite mixed, which can have to do with the low cost associated with expanding the grid, allowing it to adapt to any potential bottleneck. Therefore, some flexibility-transfer might be allowed through regions, with transmission expansion allowing energy arbitrage in space and partially substituting energy arbitrage in time (which alternatively ESS could provide).

The relevance of the grid modeling approach can only be confirmed in scenarios within a given study [219,242,244]. Reference [244] finds that gradually constraining the transmission grid transfer capacity in Europe leads to scenarios with higher shares of PV and the associated (large) storage requirements. On the contrary, if more grid infrastructure is allowed, the models derive higher shares of onshore wind (with less storage requirement).

It is also worth mentioning that, in many cases, the transmission cost functions used for expansion studies might in practice not apply (e.g. common delays in project completion, social opposition, and uncertainty in the evolution of various parameters) so that some negative bias towards storage might arise. In this respect, recent work [245] clearly shows how *smart* technologies (such as storage) emerge in expansion planning exercises as economic solutions *against* conventional technologies (such as transmission grid reinforcement). There is a need to explicitly model operational flexibility requirements and details, time delays in project realization, and various factors that can introduce investment uncertainty in the planning scale.

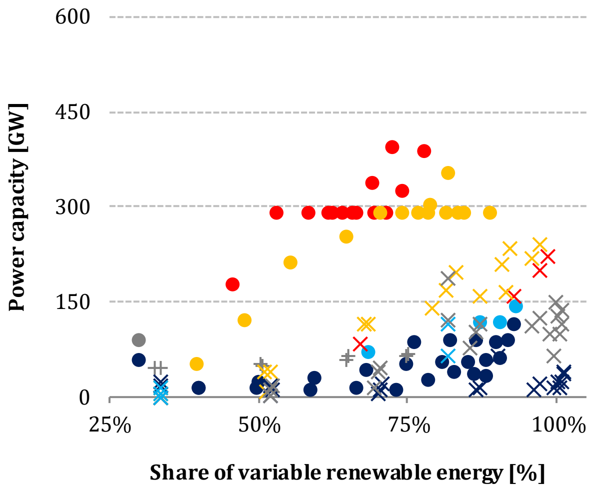

Fig. 15 Grid modeling and ESS power capacity in Europe.
The color code is the same as in the previous figure, depicting PV++, PV+, Wind++, Wind+ and balanced mixes, whereas the different markers show the grid model approach (circle for copperplate, plus for exogenous, cross for endogenous).

3.4. Conclusions

In this chapter, we analyzed the energy storage system (ESS) requirements arising from 17 recent storage expansion studies involving over 400 scenarios. For the U.S., Europe, and Germany, we first systemized their recommendations in terms of storage needs per share of variable renewable energy sources (VRE) and discussed the outliers. Second, we studied how the dominance of a given generation technology (i.e. PV or wind) can help explain the storage needs. And third, we discussed the relevance of the detail of grid modeling. This synthesis helps to provide clarity for policymakers and energy system modelers.

3.4.1. Storage capacity as a function of renewables

With growing VRE shares, the demand for storage increases linearly in terms of power capacity and exponentially in terms of energy capacity. Although data is wide-spread, the trend for the lower and upper bound is relatively clear. By identifying and understanding outliers, the requirements for ESS energy capacity can be halved. Particularly strong assumptions that lead to these outliers involve: dictating energy autarky for smaller regions, forbidding (or setting very low limits of) energy spillage, and using extreme costs inputs. Examples of the latter are low ratios between ESS costs and VRE cost (causing the model to over-invest in storage instead of renewable generation) and very expensive CO_2 certificates (making it more attractive to invest in storage than fossil backup).

3.4.2. Generation mix is main driver for storage requirements

In general terms, PV-dominated grids directly correlate to high storage requirements, in both power capacity and energy capacity. Conversely, wind-dominated scenarios require significantly lower storage power and energy capacities, if grid expansion is unlimited or cheap. Focusing on the energy mix solves, to a large degree, the apparent conflict between existing studies in the prognosed storage requirements. Therefore, we recommend that future studies should invest more effort to explicitly quantify the effect of energy mix assumptions on their results.

3.4.3. Need of storage in high-renewable scenarios

The U.S. and Europe present similar storage requirements in both energy and power capacity. Germany shows about a third of that power capacity requirements, but in terms of energy capacity, the studies show a broad spread, even exceeding the whole European needs. For both Europe and the U.S., the increase in ESS power capacity is about 1–2 and 4–9 $GW/\%_{VRE}$ for wind- and PV-dominated scenarios, respectively. The studies about Germany focus on more balanced generation mixes, attaining additional ESS power capacities of 0.3 $GW/\%_{VRE}$. In terms of ESS energy capacity, for VRE shares over 80%, PV-dominated grids require about 1.0 to 3.0 TWh for Europe and the U.S. Systems strongly dominated by wind generation need at least 0.2 to 1.0 TWh. Most of the studies for Germany are balanced mixes, and those which include other flexibility options (e.g. curtailment, exports/imports to neighboring countries) recommend 0.05 to 1.1 TWh.

3.4.4. Impact of grid modeling on storage needs

When considering *all* evaluated studies, no general conclusion can be drawn regarding the impact of grid modeling on storage requirements. However, the fact that unlimited or vast transmission capacities (i.e. copperplate models) lead to less storage is consistent within a *given* study. Furthermore, in practice, grid infrastructure is commonly delayed. Therefore, storage requirements are likely to be higher than those forecast by the studies. Finally, deterministic studies that do not consider planning uncertainty naturally create a significant bias towards transmission investments and against storage and other smart grid solutions.

3.4.5. Future work

We recommend to continuously update the developed database, especially in the light of the numerous studies emerging since five years. Furthermore, the storage requirements strongly depend on the considered flexibility sources, such as interconnecting with other energy sectors. Inter-sectoral planning is particularly recent and will impact the needed storage quantities.

Part II – New energy storage planning model

Chapter 4. Multi-service energy storage expansion planning

This chapter is based on the publication “A multi-service approach for planning the optimal mix of energy storage technologies in a fully-renewable power supply” by J. Haas, F. Cebulla, W. Nowak, C. Rahmann, and R. Palma-Behnke, accepted September 2018 in the Journal of Energy Conversion and Management.

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Executive summary

Energy storage expansion planning approaches tend to focus on balancing the energy fluctuations from renewable technologies but are usually blind to the need for specific additional services required for dealing with forecast errors. Hence, they underestimate the real operating costs of the future power system and lead to suboptimal investment recommendations. In response, we propose a multi-service storage expansion approach.

We have developed a linear programming optimization, called LEELO, to find the optimal investments in a 100% renewable system (based on solar photovoltaic and wind power) deciding on renewable generators and storage systems. In our formulation, we explicitly model the provisioning of power reserves and energy autonomy as additional services. In a case study, we apply our model to Chile considering four regions and the (existing) hydropower park, for a complete year with an hourly resolution. We systematically assess how our novel multi-service planning differs from conventional energy-based planning in terms of total costs, operation, and investment decisions (with a focus on ESS).

We found that considering power reserves and energy autonomy reveals on average 20% higher costs that otherwise would not be captured in the expansion planning process. Regarding operation, ESS show only slight differences in the two planning models. All ESS participate in the provision of energy. As might be expected, batteries are the main provider of (short-term) power reserves, assisted by pumped-hydro, whereas hydrogen storage is responsible for providing (long-term) energy autonomy. However, the storage investment decisions differ significantly between both models. In our multi-service model, the attained power capacities and energy capacities are up to 1.6 and 3.2 times larger, respectively than in conventional planning. The resulting storage mix changes even more strongly: a general shift towards hydrogen systems is observed. Mainly batteries are substituted, while pumped-hydro capacities stay relatively constant. The trend of the above results is consistent for various scenarios of wind and photovoltaic generation and for sensitivities of service parameters.

Our findings underline the importance of modeling multi-services in the planning of renewable-based power systems.

Symbols

Table 4 Nomenclature of model: Sets and variables.

	Name	Units	Description
Sets	t		Time steps
	z		Zone of the power system
	r		Renewable power plants
	s		Storage technologies
	h		Hydropower plants
Variables operation	$p_{t,z,r}$	MW	Power generated by renewable plant r in zone z at time t
	$p_{s,t,z}^{charge}$, $p_{s,t,z}^{discharge}$	MW	Power charged to or discharged from storage s in zone z at time t
	$p_{t,h}$	MW	Power generated by hydropower plant h at time t
	$p_{z,t}^{unserved}$	MW	Power unserved in zone z at time t
	$p_{z,t}^{curtailed}$	MW	Power curtailed in zone z at time t
	$p_{zz,z,t}^{imp}$	MW	Imported power from zone zz to z at time t
	$p_{z,zz,t}^{exp}$	MW	Exported power to zone zz from z at time t
	$oRes_{t}^{system}$	MW	Operational reserve (total) prescribed by the system at time t
	$oRes_{t,z,s}^{S}$	MW	Operational reserve from storage s in zone z at time t
	$oRes_{t,h}^{H}$	MW	Operational reserve from hydropower at time t
	$fRes_{t}^{system}$	MW	Contingency reserve (total) prescribed by the system at time t
	$fRes_{t,z,s}^{S}$	MW	Contingency reserve from storage s in zone z at time t
	$fRes_{t,h}^{H}$	MW	Contingency reserve from hydropower at time t
	$autonomy_{s,z,t}$	MWh	Autonomy from of storage s in zone z at time t
	$autonomy_{h,t}$	MWh	Autonomy from of hydropower h at time t
	$stored_{s,z,t}$	MWh	Stored energy of storage s in zone z at time t
	$stored_{h,\mathrm{t}}$	m^3	Stored water of hydropower h at time t
	$loss_{s,z,t}^{storage}$	MW	Energy loss (self-discharge) of storage s in zone z at time t
	$loss_{s,z,t}^{reserves}$	MW	Energy loss (provision of reserves) of storage s in zone z at time t
	$loss_{h,t}$	m^3	Water losses (infiltration, evaporation) of hydropower h at time t
	$q_{h,t}^{turbined}$	m^3/s	Flow turbined by hydropower h at time t
	$q_{h,t}^{diverted}$	m^3/s	Flow diverted by hydropower h at time t
	$q_{h,t}^{reserve}$	m^3/s	Flow used for reserve provision by hydropower h at time t
	$q_{h,t}^{fictitious}$	m^3/s	Fictitious flow of hydropower h at time t (used for tuning purposes)
	$q_{h,t}^{turbined\ upstream}$	m^3/s	Flow turbined upstream of hydropower h at time t
	$q_{h,t}^{diverted\ upstream}$	m^3/s	Flow diverted upstream of hydropower h at time t
Variables investment	$P_{r,z}^{ins}$	MW	Installed power capacity of renewable technology r in zone z
	P_{l}^{ins}	MW	Installed power capacity of transmission lines l
	$P_{s,z}^{ins\ dis.}$, $P_{s,z}^{ins\ charge}$	MW	Installed power capacity (discharging, charging) of storage s in zone z
	$E_{s,z}^{ins}$	MWh	Installed energy capacity of storage s in zone z

Table 5 Nomenclature of model: Inputs.

Inputs	$Load_{t,z}$	MW	Load (demand) in zone z at time t
	P_h^{ins}	MW	Installed power capacity on hydropower h
	$P^{largest\ unit}$	MW	Power capacity of largest (hydro)power generator
	$Profile_{r,t,z}$	%	Profile of renewable source r in zone z at time t
	$P_{max}^{curtailed}$	%	Maximum amount of renewable energy to be curtailed
	$PVtoWindRatio$	%	Proportion between power capacity of PV and wind plants
	$\eta_{charge}, \eta_{dis}$	%	Charging and discharging efficiency of storage s
	$F_s^{Min\ E2P}, F_s^{Max\ E2P}$	%	Minimum and maximum energy to power ratio of storage s
	$F^{used\ fRes}, F^{used\ oRes}$	%	Ratio between the deployed and committed power reserves
	$AutomyHours^{system}$	h	Ability of the power system to operate autonomously, in hours
	$Autonomy^{system}$	MWh	Ability of the power system to operate autonomously, in energy
	$E_{s,z}^{potential}$	MWh	Technical potential of energy capacity of storage s in zone z
	k_h	MW/(m^3/s)	Yield of hydropower h
	$Q_{h,t}^{inflow}$	m^3/s	Inflow to hydropower h at time t

4.1. Introduction

There are many studies available that size the general storage need in renewable systems. The previous chapter [246], for example, compares almost 20 publications [57,86,174,212–221,227–233] about the ESS requirements in the U.S. and Europe for increasing shares of renewables. Many of these publications do not account for the different storage technologies, although they strongly differ from each other. Batteries, for example, show low costs per power capacity but high costs per energy capacity. The opposite is true in long-term storage technologies, such as hydrogen systems. As no single ESS outperforms all others, the resulting question is what combination of storage technologies can offer the least-cost and most reliable solution for future power systems. Thus, more recent studies have included multiple storage devices into their planning programs in the last couple of years. For example, reference [243] focuses on the short-, mid-, and long-term storage needs of Europe. Reference [218] also looks at the Middle East and Northern Africa (in addition to Europe) in their studies. The team of Breyer has studied different regions, including Ukraine [247], Turkey [248], and Australia [24]. Many more approaches of storage planning can be found in the literature; reference [2] systemized about 100 publications, including the current challenges.

Three main challenges need to be tackled when planning storage systems for high shares of renewable technologies: variability (in time), site-specificity (or variability in space), and uncertainty (or forecast errors) of renewable generation [2]. The first challenge is frequently addressed by using a sequential time treatment. In generation planning this used to be representative weeks, but current storage planning models tend to plan full years with hourly resolution (i.e. 8760 continuous time steps) [2]. The second challenge can be handled by considering multiple sites for potential projects (where care has to be put on the correlation of the resources), which also implies that the transmission infrastructure has to be modeled (i.e. losses and bottlenecks). The third and last challenge can be tackled by using scenario analysis (e.g. assessing the system's reliability in different meteorological years), robust programming (i.e. finding designs that work for many different conditions —which are already taken into account during the investment planning—), and stochastic optimization.

Stochastic optimization treats uncertainties endogenously by using probabilistic descriptions of the random processes. In other words, the profiles of renewable production are generated within the optimization under the assumption of imperfect foresight [249]. Although this is the most complete approach to handle uncertainties, it is also intensive in computing times; thus, stochastic optimization is mainly found when planning smaller systems, such as distribution grids. Here, the literature shows to be more advanced. Reference [250], for example, introduces an explicit stochastic formulation to deal with forecast errors of load and wind, when sizing distribution system components (like substations or feeders). Reference [251] puts more emphasis on the sources of uncertainty, extending them to emission prices and demand growth. Finally, also with explicit consideration of stochasticity, storage systems and demand response [252], and capacitor banks [253] have been sized. However, when it comes to sizing larger power systems, explicit stochastic approaches are (still) uncommon. In fact, most of the above-cited studies, including the ones analyzed by the reviews in references [254] and [246], either neglect uncertainty, or treat it with scenario analysis.

An emerging alternative to (implicitly) treat uncertainty in large power systems is modeling system services, for example power reserves. Here, the model would request to allocate a buffer among generation and storage units to accommodate for short-term forecast errors (which, in turn, can be described with a statistical parameter, say 10% of the forecasted energy). One of the few examples is reference [255], that sized a single storage technology while taking into account power reserves and security requirements. In this line, the most complete work found is reference [256], which presented a detailed formulation of power reserves for planning a thermal-based system (but without considering the transmission system) with increasing shares of renewables. Modeling such system services can strongly impact the final investment recommendations, and is not fully understood yet.

From the above state of the art, it becomes clear that modeling diverse power system services in planning exercises is a still incipient topic. Consistently, we extend the existing body of literature by understanding how the need for multi-services impacts the optimal combination of storage technologies in a fully-renewable system when including the transmission system. Concretely, we contribute by:

- Assessing how accounting for power reserves and energy autonomy in a storage expansion tool for a multi-nodal system impacts the sizing of multi-storage technologies. We systematically explore these services, focusing not only on the overall costs and investments but also on the crossed-effects among the different storage technologies.
- Studying the optimal combination of storage technologies for a projected 100% renewable-based power system that is in line with the Paris Agreement. Beyond wind and solar technologies, we modeled the existing hydropower plants (flow routing) because this technology can alleviate the storage requirements. Including hydropower in such detail and constellation is the first attempt, according to our literature review.
- Performing a case study about the Chilean power system. Whereas for Europe and the U.S. there are several studies on fully-renewable power systems, for South America —and Chile in particular— there are transition scenarios only [246]. In those publications, the focus is typically on the trade-off between conventional technologies and renewables, where storage devices play a minor role only, given the sunk cost of conventional plants. Furthermore, Chile has ambitious renewable targets, including a political goal of reaching 70% of renewable generation by 2050 [257] and research visions of becoming a net solar energy exporter to Latin America [258].

Our findings for a 100% renewable system reveal new and essential long-term insights for planners, modelers, and policy-makers.

The next section details our optimization model for planning energy storage systems considering a multi-service approach. Section 4.3 presents the description, inputs, and scenarios of the case study (Chile), while Section 4.4 discusses the results. Finally, Section 4.5 concludes and lines out the future work.

4.2. Methods

Our hypothesis is that including power reserves and energy autonomy services in a storage expansion model significantly impacts the final storage investment recommendations. In other words, we seek the optimal mix of ESS that offers a combination of services. We will study the impact of modeling these multi-services on: i) the system operation, ii) the total costs, and iii) the investment decisions for each storage technology. We will illustrate the resulting numbers for a multi-nodal fully-renewable power system (Chile in the year 2050) that includes an important share of hydropower.

4.2.1. Introduction to the model

We develop a tool for finding the optimal energy storage mix, called Long-term Energy Expansion Linear Optimization (LEELO). It minimizes the investment and operating costs of a power system, deciding the capacities of storage and renewable technologies.

We base the design of LEELO on the learnings from Chapter 2 and 3. Concretely, the former made the following five recommendations when planning storage expansion: (1) to acknowledge the diversity of the many available storage devices; (2) to capture their complex lifetime and efficiency curves; (3) to use a high spatial and temporal resolution; (4) to recognize the multiple services they can provide; and (5) to plan with multiple energy sectors (as storage and flexibilities might readily be present in other energy sectors) [2]. Items (1), (2), and (3) were implemented in LEELO following the state of the art, whereas item (4) extends the current body of knowledge by integrating multiple services into the optimization tool. Chapter 3 found that assumptions with a particularly strong impact on storage sizes are: forbidding energy curtailment, and limiting or overestimating the energy exchange between regions (by assuming island operation or copper plate, respectively). In response, LEELO captures the existing grid, allows transmission expansion, and tolerates a certain amount of curtailment.

More specifically, LEELO can include power reserves and energy autonomy as services, beyond the classical energy balance or arbitrage. Our approach considers a one-year modeling horizon with hourly resolution (i.e. 8760 sequential time steps). The electrical power system is represented by multiple nodes, where the transmission system is modeled as a transport model. Flow routing is modeled to capture cascading hydropower. LEELO can handle any number of storage devices, but in the case study we will consider three types: Li-ion battery systems, pumped-hydro systems, and hydrogen systems (more details provided in Section 4.3.4). We will not model the distribution grid, nor the heat and gas sectors (helpful formulations for those aims are found in references [123] and [259], respectively). As we focus on a 100% renewable-based power system, unit commitment constraints are not necessary (e.g. minimum online/offline times of fossil generators). LEELO is formulated as a linear program in GAMS [260] and can be solved with a barrier (interior point) algorithm, e.g. from CPLEX [261].

We produced two versions of LEELO, one without and one with multiple services:

- Model B (for “basic”) is a classical storage expansion problem with energy balance as the main constraint. Relevant inputs are the (projected) load, (projected) costs of deploying and operating storage and renewable technologies, and the primary energy profiles (solar, wind, water) for renewable generation. The model also captures cascading hydropower systems.
- Model M (for “multi-services”) extends the previous model by including the following power system services: a) operating power reserves to cope with forecast errors, following grid operator’s practices of leaving operational margins as a function of the renewable production. And b) energy autonomy, i.e. leaving energy reserves in storage devices to deal with major, unexpected drops in energy production (e.g. weeks of extremely low renewable generation as when compared to the typical weather year, sometimes referred to as dark doldrums).

The most generic formulation of such an optimization problem is shown in Eq. 1, where d_{opt} is the optimal design that we want to find such that the objective function f_{costs} is minimum, and D is the domain of possible decisions (i.e. solutions that fulfil the model’s equations/constraints). In the following subsections, we describe LEELO, starting with the objective function and continuing with the constraints that cover the modeling of the overall system, including the power system, storage technologies, hydropower plants, and renewable technologies. The complete nomenclature including sets and decision variables, and parameters are shown in Table 4 and Table 5.

$$d_{opt} = \arg\min_{d \in D} f_{costs}(d) \qquad \textit{Eq. 1}$$

4.2.2. Objective function and decision variables

The objective function is a minimization of investment and operating costs including:

- annualized investment costs of storage in terms of energy capacity and power capacity,
- annualized investment costs of renewable generators,
- variable operating costs of storage for charging and discharging,
- variable operating costs of renewable generators and transmission lines,
- fixed operating costs of storage in terms of installed energy capacity and power capacity,
- fixed operating costs of renewable generators and transmission,
- other costs, such as penalties for unserved energy, curtailed energy, and fictitious inflows.

On the investment side, decisions are related to the power capacity and energy capacity of the storage devices, and the power capacity of the renewable power plants.

For the operation, the *main* decision variables are the generated renewable energy, the charged and discharged energy of the storage units, and the transmitted power between the zones. For model M, further operational decision variables include the power system services (see section 4.2.3.3 and 4.2.3.4).

4.2.3. Modeling of power system

Transmission

The transmission system is modeled using a transport model (i.e. only active power flows are considered, and the angle difference of the voltage phasors are not), such as in references [8] or [102]. We assume the losses to be proportional to the transmitted power. This proportion is a combination of a fixed term (transformer) and a variable term (line length). The resulting losses are allocated equally at both ends of the line. The involved equations are not shown here for the sake of brevity. Expansion of transmission is not considered. Although this is a common simplification storage expansion publications [49,89,157], it might also be a strong one [8]. However, planning transmission infrastructure usually involves other dimensions beyond costs, such as social opposition that results in delays and cost overruns. These are being dealt with in more detail in an ongoing study.

Nodal energy balance

The energy supplied by renewables r (including hydropower plants h) and storage systems s must match the demand for every time step t at each zone z of the network (Eq. 2). In case of energy shortage or energy surplus, the model gives the option for unserved energy (as this variable is heavily penalized in the objective function, it does not become positive but is useful for tuning purposes) and curtailed energy, respectively. Energy can be exchanged (imports, exports) between nodes or zones.

$$\sum_{r} p_{r,t,z} + \sum_{s} (p_{s,t,z}^{charge} - p_{s,t,z}^{discharge}) + p_{t,z}^{unserved} - p_{t,z}^{curtailed} + \sum_{zz} \left(p_{zz,z,t}^{imp} - p_{z,zz,t}^{exp}\right) = Load_{t,z}, \forall t, z \qquad \text{Eq. 2}$$

In traditional expansion planning models, adequacy used to be the other main equation. Essentially, it ensures that the installed generation capacity exceeds the peak demand. However, in systems based on variable renewable generation, the investments are triggered by critical conditions of the net-load (which is highly variable) along the year. In our model, adequacy is, hence, captured in the set of equations represented by Eq. 2.

Power reserves

There are many reserve definitions available in the literature, related to power system security. Here, we distinguish between contingency reserves and operational reserves. The former are needed during contingencies to compensate for the unexpected loss of a generation unit. The latter deal with hourly forecast errors of renewable generation (i.e. steady-state from a power system regulation perspective).

The contingency reserves are equal to the installed capacity of the largest generation unit (Eq. 3). To avoid formulations with integers, we assume that the largest unit is always online. The operational reserves (Eq. 4) are modeled as a percentage of the forecasted renewable energy production. We treat demand as a deterministic process, because its behavior is already well-understood by transmission system operators, and smart systems will only improve the controllability on the demand side. Note that the above ways of sizing the power reserves do not include network allocation's criteria (i.e. independent of the location). Thus, the index z does not appear in the equations.

$$fRes_t^{system} = P^{largest\ unit}, \forall t \qquad \textit{Eq. 3}$$

$$oRes_t^{system} = F^{renewables} \sum_{z,r} P_{r,t,z}^{ins} Profile_{r,t,z}, \forall t \qquad \textit{Eq. 4}$$

In our formulation, storage devices and hydropower reservoirs can endogenously decide what reserves to offer. The sum of reserves offered must always be larger than the reserves requested by the whole power system (Eq. 5 and Eq. 6). The total committed power output of a generator (i.e. the sum of dispatched power, committed operational reserve, committed contingency reserve) has to be smaller than its power capacity. Eq. 7 exemplifies this for a hydropower reservoir. Eq. 8 makes sure that ESS and hydropower offer reserves only if they have enough energy stored to provide them for at least one time step.

In contrast to our linear formulation of reserves, in unit commitment tools they are usually modeled with integer variables (just as it is the case of on/off states of thermal generators). These formulations are relevant when only a few generation units can provide reserves, and their level of flexibility is poor (large minimum offline times, slow reaction times, etc.). In our system, we assume that many distributed storage devices will exist in a 100% renewable power system. For these situations, operational planning literature shows that linear formulations are a good approximation for integer models [225,262,263], which confirms our choice for a linear formulation for the sake of solving times.

$$\sum_{z,s} oRes_{t,z,s}^{S} + \sum_{h} oRes_{t,h}^{H} \geq oRes_t^{system}, \forall t \qquad \textit{Eq. 5}$$

$$\sum_{z,s} fRes_{t,z,s}^{S} + \sum_{h} fRes_{t,h}^{H} \geq fRes_t^{system}, \forall t \qquad \textit{Eq. 6}$$

$$oRes_{t,h}^{H} + fRes_{t,h}^{H} + p_{t,h} \leq P_h^{ins}, \forall t, h \qquad \textit{Eq. 7}$$

$$(oRes_{t,h}^{H} + fRes_{t,h}^{H})\Delta t \leq stored_{t,h}, \forall t, h \qquad \textit{Eq. 8}$$

Energy autonomy

Energy autonomy (or energy reserves) are helpful to cope with (unexpectedly) prolonged periods of low generation. They are analogous to the previously described operational reserves but are expressed in terms of energy instead of power. So, instead of dealing with short-term forecast errors, energy autonomy is a way of dealing with long-term forecast errors or with situations worse than the ones considered in the typical-weather year. In that sense, they relate to term *adequacy* applied to power system planning.

The amount of the energy autonomy requested by the system (e.g. 1 week) is not well established in the power sector yet, as it is currently not a common service in planning. It will need to become more frequent when designing 100% renewable-based systems, especially under the influence of climate change or when merging with other energy sectors. The German fuel sector, for example, imposes an autonomy equal to a three-months demand [264].

$$Autonomy^{system} \geq Load_{average}^{system} AutomyHours^{system} \qquad \text{Eq. 9}$$

$$\sum\nolimits_{s,z} autonomy_{s,z,t} + \sum\nolimits_{h} autonomy_{h,t} \geq Autonomy^{system}, \forall t \qquad \text{Eq. 10}$$

$$autonomy_{s,z,t} \leq stored_{s,z,t}, \forall s,z,t \qquad \text{Eq. 11}$$

$$autonomy_{s,z,t} \leq P_{s,z}^{ins\ discharge} AutonomyHours^{system}, \forall s,z,t \qquad \text{Eq. 12}$$

The level of autonomy requested by the system is expressed in hours (in which the system has to be able to satisfy demand without generation) and is transformed into units of energy with Eq. 9. The different storage devices and hydropower reservoirs act together to meet this level at all times (Eq. 10). The amount of energy autonomy that each ESS can offer (in MWh) during a period is bounded by its stored energy (Eq. 11) and by its converter, which limits the energy it is able to evacuate during the respective time horizon (Eq. 12). Eq. 11 and Eq. 12 are analogous for hydropower reservoirs but are not shown for the sake of brevity.

4.2.4. Modeling of storage technologies

Charging and discharging capacity and energy capacity

The power output (discharge capacity) of an ESS is limited by its installed power capacity (e.g. power of the turbines) in Eq. 13. The charging capacity is assumed to be symmetric (i.e. installed charging capacity equals the installed discharging capacity). Similarly, the stored energy is limited by the installed energy capacity (e.g. volume of the reservoir) in Eq. 14. The power capacity and energy capacity are independent decisions (i.e. disjoint) [265].

$$p_{s,z,t}^{discharge} \leq P_{s,z}^{ins\ discharge}, \forall s,z,t \qquad \text{Eq. 13}$$

$$stored_{s,z,t} \leq E_{s,z}^{ins}, \forall s,z,t \qquad \text{Eq. 14}$$

Energy-to-power ratio

To make sure that the resulting storage investments are of reasonable sizes (i.e. that the ratio between the energy and power capacity is economically meaningful), we limit the energy-to-power ratio with Eq. 15. This constraint avoids, for example, batteries with oversized energy capacities, say 24 hours.

$$F_{s}^{Min\ E2P} P_{s,z}^{ins\ discharge} \leq E_{s,z}^{ins} \leq F_{s}^{Max\ E2P} P_{s,z}^{ins\ discharge}, \forall s,z \qquad \text{Eq. 15}$$

Cycling and state-of-health

Some storage technologies have to be replaced after a limited amount of cycles, e.g. batteries. Eq. 16 accounts for this issue by constraining the maximum amount of yearly cycles (discharged energy divided by installed energy capacity) of each storage technology. For example, if the battery system has a lifetime of 10 years and 10,000 cycles, then Eq. 16 makes sure that batteries deliver less than 1000 cycles/year. Note that to keep the linearity of the program, the term corresponding to the installed energy capacity actually goes on the right-hand side.

$$\sum_t p_{s,z,t}^{discharge} / E_{s,z}^{ins} \leq Cycles_s^{max} / Lifetime_s, \forall s,z \qquad \textit{Eq. 16}$$

Furthermore, state-of-health refers to the decrease of the storage performance due to aging. Examples are lower storage capacities in batteries (degradation) and lower power capacities in turbines (mechanical wear). Our model does not account for this issue, which is a common simplification in static planning [2].

Energy balance, own losses, start and end conditions

The energy balance in the ESS (Eq. 17) takes into account the energy taken from the grid for charging (decreased by its charging efficiency) and the energy delivered to the grid for discharging (increased by its discharging efficiency). The stored energy is also decreased by self-discharge, calculated as a fraction of the stored energy (Eq. 18). Another loss occurs when providing power reserves (Eq. 19). This equation ensures two things. First, it tells the model that the storage technologies with higher round-trip efficiencies might be the first ones in providing these reserves. And second, it accounts for the energy lost in that process (e.g. batteries dedicated to providing frequency reserves is a net energy consumer). These storage conversion losses arise from balancing a sub-hourly cycle (or noise) related to forecast errors, which is superposed to the hourly energy commitment. Furthermore, the offered reserves are not always fully deployed, which is captured with a factor that represents the frequency of fully deploying these (offered) reserves.

$$\begin{gathered} stored_{s,z,t+1} = stored_{s,z,t} + \\ (\eta_{charge} p_{s,z,t}^{charge} - 1/\eta_{dis}\, p_{s,z,t}^{discharge} - loss_{s,z,t}^{storage} - loss_{s,z,t}^{reserves})\, \Delta\mathrm{t}\,, \forall s,z,t \end{gathered} \qquad \textit{Eq. 17}$$

$$loss_{s,z,t}^{storage} = (F_{s,z}^{losses}/24)\, stored_{s,z,t}, \forall s,z,t \qquad \textit{Eq. 18}$$

$$\begin{gathered} loss_{s,z,t}^{reserves} = \left(oRes_{t,h}^{S} F^{used\ oRes} + fRes_{t,h}^{S} F^{used\ fRes}\right) \\ \left(1 - \eta_{discharge}\eta_{charge}\right)\ , \forall s,z,t \end{gathered} \qquad \textit{Eq. 19}$$

The start and end conditions of the stored energy are decision variables. Both are set to be equal to avoid the optimization from draining the stored energy towards the end of the time horizon.

Resource potential

The maximum capacity of to-be-installed storage technologies might be limited. For example, pumped-hydro is constrained to available height differences. These bounds (for energy capacity and power capacity) are expressed by Eq. 20 and Eq. 21.

$$P_{s,z}^{ins\ discharge} < P_{s,z}^{potential}, \forall s, z \qquad \textit{Eq. 20}$$

$$E_{s,z}^{ins} < E_{s,z}^{potential}, \forall s, z \qquad \textit{Eq. 21}$$

4.2.5. Modeling of cascading hydropower

Cascading hydropower systems are more complex than other storage technologies. The following equations are specific to the former and are additional to the storage equations of Section 4.2.4. Here, we use a unit-sharp representation for hydropower plants. This approach generates more decision variables but is necessary for capturing the cascades. Technically, it also triggers the need of distinguishing hydropower plants from other storage devices in all equations of the model, but for the sake of simplicity, we tried to group hydro reservoirs and other ESS whenever possible.

Water to power yield

The conversion from water to power depends on many factors (e.g. efficiency, head). These are all summarized in the yield k, which we assumed to be constant (Eq. 22). This value is unique to each reservoir.

$$p_{h,t} = k_h q_{h,t}^{turbined}, \forall\ h, t \qquad \textit{Eq. 22}$$

Flow routing

The connectivity of cascading hydropower plants is modeled with connectivity vectors (a simplified formulation of connectivity matrixes), one for the turbined flows and one for the diverted flows. These indicate from where to where the flows (turbined or diverted) go. For instance, if the hydropower plant hh is immediately upstream of plant h, the corresponding entry in the connectivity vector (row hh) would show the identifier of h.

The turbined flows that come from upstream are computed in Eq. 23. The expression for the diverted flow is analogous.

$$q_{h,t}^{turbined\ upstream} = \sum_{hh} q_{hh,t}^{turbined}, where\ hh\ are\ upstream\ of\ h, \forall\ h, t \qquad \textit{Eq. 23}$$

Water balance

The water balance (Eq. 24) is analogous to the energy balance of the storage devices but involves more terms. The water additions (Eq. 25) contain the natural inflow, the diverted and turbined flows from upstream (as explained above), and the fictitious flows. The latter is a tuning variable with correspondingly high penalties in the objective function. Clearly, in the results of the case study, this variable needs to be zero. The water output (Eq. 26) includes the turbined and diverted flow (by the corresponding hydropower plant), and the flow used for the provision of the power reserves (analogous to Eq. 19).

$$stored_{h,t+1} = stored_{h,t} - loss_{h,t} + \left(q_{h,t}^{in} - q_{h,t}^{out}\right) \Delta t, \forall\, h,t \qquad \text{Eq. 24}$$

$$q_{h,t}^{in} = Q_{h,t}^{inflow} + q_{h,t}^{diverted\ upstream} + q_{h,t}^{turbined\ upstream} + q_{h,t}^{fictitious}, \forall\, h,t \qquad \text{Eq. 25}$$

$$q_{h,t}^{out} = q_{h,t}^{turbined} + q_{h,t}^{diverted} + q_{h,t}^{reserve}, \forall\, h,t \qquad \text{Eq. 26}$$

4.2.6. Modeling of renewable technologies

Max. power capacity

Wind, solar PV, and run-of-river hydropower are modeled as follows (for cascading hydropower, read above). The generated power is limited by the installed capacity in Eq. 27 (which also is decided by the model). It is further constrained by the available natural resource (wind, sun, water), which has a resolution in time and space (Eq. 28). To reduce computing time, we set the generated power equal to the available energy profile. All energy excesses are handled with the variable for energy curtailment, which is indexed per node (recall Eq. 2) instead of per generator and thus reduces the computational effort.

$$p_{r,t,z} \leq P_{r,z}^{ins}, \forall\, r,t,z \qquad \text{Eq. 27}$$

$$p_{r,t,z} = P_{r,t,z}^{ins} Profile_{r,t,z}, \forall\, r,t,z \qquad \text{Eq. 28}$$

Curtailment

We limit the maximum amount of curtailed energy since large quantities could render the investment unattractive (Eq. 29). In other words, instead of installing excessive generation that could be curtailed, this equation makes sure that the produced energy is preferably used or stored. Limits extremely close to zero seem to produce biased results towards the energy capacity of storage [246], but values between 5% and 20% have shown to be reasonable in the literature [246]. The curtailed energy is (slightly) penalized in the objective function.

$$\sum\nolimits_{z,t} p_{z,t}^{curtailed} \leq P_{max}^{curtailed} \sum\nolimits_{r,t,z} Profile_{r,t,z}\, P_{r,z}^{ins} \qquad \text{Eq. 29}$$

PV-to-wind ratio

Previous studies show that one of the leading drivers of different storage requirements is the power mix [246]. To explore a wide range of possible future power systems, we impose the proportion of the to-be-installed capacities between PV and wind (Eq. 30). The model still decides where to invest but needs to respect this PV-to-wind ratio.

$$\sum\nolimits_{r=PV,z} P_{r,z}^{ins} = PVtoWindRatio \sum\nolimits_{r=wind,z} P_{r,z}^{ins}, \forall z \qquad \text{Eq. 30}$$

Resource potential

The resource potential is expressed in the same way as for storage technologies (Eq. 20). The corresponding inputs are typically taken from existing resource-mapping studies.

4.3. Case study

This section will describe the inputs of the case study. Following the structure of the previous section, we will first present an overview of the system under study, and then detail main inputs and assumptions for the optimization model. At last, we will define the scenarios considered for the model runs.

4.3.1. Description of system

We used a brownfield planning approach to design Chile's power system in 2050, deciding the investments of renewable generation and storage technologies. However, the subsequent analysis of results will focus on the storage decisions only. From the current power system, we assumed that only the existing hydropower plants and transmission lines -given their long lifetime- will be present in 2050, while thermal power plants will be fully decommissioned. We modeled Chile in four zones (see Fig. 16 for those zones, including main results). Each zone includes three profiles (or locations) for both wind and solar technologies and two profiles for run-of-river plants. From south to north these zones are:

- Southern Chile (z_1): with large cascading hydropower capacity, outstanding wind sites, but only limited potential for solar technologies. The demand is mainly residential.
- Central Chile (z_2): many cascading hydropower plants, good sites for wind and PV generation. Most of the country's load is concentrated here, presenting a mix of residential and industrial profiles.
- Southern Atacama (z_3): excellent wind and outstanding solar potential. The demand is small and mainly industrial.
- Northern Atacama (z_4): excellent wind and outstanding solar potential. The load is industrial.

4.3.2. Inputs for the objective function

Here we describe the main parameters. The complete set of values can be found in online [266].

Costs parameters

The costs and lifetime of the different storage technologies and renewable technologies are taken from reference [247]. This database uses experience curves to project costs to the year 2050 and has been validated in numerous journal publications [24,25,28,247,248,267]. For pumped-hydro, we used a capital cost for power and energy capacity of 1100€/kW and 10€/kWh, which is consistent with reference [190].

Penalties

The penalty cost for unserved energy is set to 10k€/MWh. Fictitious inflows are punished more strongly to avoid them becoming positive. A cost of 5€/MWh is used for curtailed energy.

4.3.3. Inputs for the power system

Transmission

The existing power transmission capacities are based on the databases of the power system operator [268]. Each zone is interconnected to the adjacent ones by transmission lines of approximately 1.5–2.0 GW of capacity. We modeled linear losses equal to 1.5% (of the transmitted power) per 1000 km [267].

Load

The yearly load profiles (with hourly resolution) of zones z_1, z_2, and z_3 are based on data of [269], and of zone z_4 on [268]. These are then projected to 2050 using the growth rates given by Chile's National Energy Commission [270][11]. This results in an average demand of 3, 12, 2 and 6 GW (23 GW) for the zones z_1 to z_4 and a total peak load of 29 GW.

Power reserves

The contingency reserves are set equal to the installed capacity of the largest generation unit, which is a hydropower reservoir of 0.7 GW. Our first simulations showed that the results are not sensitive to variations from 0.5–1.0 GW. Therefore, the amount of contingency reserves remains fixed during all simulations.

For the operational reserve, we evaluated four cases ranging from 5% to 20% of the forecasted renewable energy production. The upper bound is close to the current practices of some system operators, whereas the lower bound can be understood as a future setting when the forecasts become more precise (better tools and more knowledge).

Energy autonomy

We explored four scenarios of autonomy, specifically 1, 7, 30, and 90 days. The 1-day scenario aims to account for the worst day (e.g. day with very low wind and PV production), which might not be captured in the time series (typical-year) used in this planning exercise. The other extreme, 90 days, is used in the fuel sector of Germany [264]. A substantial autonomy would avoid an energy crisis similar to Chile's in 2007 when it could no longer import gas from Argentina.

4.3.4. Inputs for the storage technologies

We considered the following storage systems: Li-ion battery systems (BESS), pumped-hydro storage (PHS), and hydrogen systems (H_2). For hydropower reservoirs, please see the next section. We included Li-ion because of its rapid growth in deployment, PHS because it is a well-established technology, and H_2 as a promising technology in future multi-energy (power-heat-transport) systems.

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[11] This source projects the loads until 2036. To obtain the demand of 2050, we assumed that the growth rate of 2035 would remain constant.

The technical potential of BESS is virtually unlimited. In the model, we only limit the energy-to-power ratio between 1 and 6 hours. These values are based on the currently installed BESS that show an average of 2 h and an upper limit of 4 h [22]; allowing some room for growth for this ratio as the technology matures.

Regarding PHS, we assumed that about 5 GW of projects could be realized in those zones with already large deployed hydropower capacities (z_1 and z_2). We assumed 3 GW in the zones of the desert (z_3 and z_4), where the main source of water is the ocean (i.e. PHS installed on the cliffs). This equals about ten projects of the size of the ongoing PHS project in the Atacama Desert [271]. We assumed the same costs for both freshwater and seawater PHS systems. We bounded the energy-to-power ratio between 1 and 20 h. The upper limit avoids larger reservoirs (which may face strong social opposition [272]).

For H_2 storage, we considered a chain of systems composed of an electrolyzer (produces H_2 with electricity), a methanizer (converts H_2 to methane for easy storage), a gas tank, a open cycle gas turbine (for reconverting the methane back to electricity), and a CO_2 scrubber (for capturing the CO_2 from the gas turbine and feeding it to the methanizer). The potential of these technologies is unconstrained.

4.3.5. Inputs for cascading hydropower

We modeled the existing hydropower park given the long lifetime of the technology and the fact that in Chile water licenses do not expire. We assumed that the installed capacity would not grow beyond the existing park [268] because the hydropower sector in Chile has lately shown major difficulties in deploying new projects. Especially large projects are hampered by environmental concerns and social opposition [272,273].

The modeling of the existing hydropower cascades and their connectivity (flow routing) and inflows is based on references [268,269] and [274], respectively. More information can be found in our previous publications [206,207]. The ecological flow is assumed to be ten percent of the maximum power output for the lowest power plant of each cascade. In total, we captured over 40 hydropower plants, with capacities distributed about equally in zones z_1 and z_2.

4.3.6. Inputs for renewable technologies

The power generation mix of our case study consists of 100% renewable technologies. We modeled the expansion of solar PV and wind power. We also considered existing run-of-river (in addition to the previously mentioned hydropower cascades), grouped into an equivalent hydropower plant per zone, attaining 0.1, 0.3, 0.1, and 0.0 GW for z_1 to z_4, respectively. Their profile is based on [269]. Geothermal and biomass energy in Chile have shown a negligible increase when compared to PV and wind. Hence, they are not included in this study.

We considered single-axis tracking PV plants and onshore variable-speed wind farms. The profiles are generated with the online tools *Solar and Wind Energy Explorer* [275,276]. Details on these tools can be found in [277]. We used 3 locations for solar and 3 for wind in each zone (thus totalizing 24 profiles in the model). Given the vast extension of Chile, the potential of solar and wind are not constrained by space (an overview of other challenges that the solar sector is facing can be consulted in references [278] and [279]).

We study five scenarios varying the ratio between installed PV and wind plants (but all are 100% renewable). These include solar dominated scenarios (PV++ and PV+ with ratios of 3:1 and 2:1) and wind dominated scenarios (Wind++ and Wind+ with ratios of 1:3 and 1:2). The last scenario is a balanced mix (1:1).

4.3.7. Summary of scenarios

Altogether, we subjected the following parameters to sensitivities: PV-to-wind ratio, autonomy requirements, and reserve requirements. Table 6, provides an overview of the resulting scenarios. The nomenclature of the first column will be used later on in the discussion.

Our base case consists of a balanced mix. Model B does not consider autonomy and reserves, whereas model M prescribes an autonomy of 7 days and operational reserves equal to 10% of the forecasted renewable generation (contingency reserves are always equal to the largest generation unit).

To systematically explore differences in storage decisions as a function of different generation portfolios, we defined a set of scenarios varying the PV-to-wind ratio. In these scenarios, the service parameters are kept constant (same as in the base case). Here, we compared the results from model B with model M.

Table 6 Definition of scenarios.

	ID	Model	PV to Wind	Autonomy	Reserve[a]
	Base Case (B)	B	1:1	-	-
	Base Case (M)	M	1:1	7 days	10%
Diff. power mixes	PV+ (B)	B	2:1	-	-
	PV+ (M)	M	2:1	7 days	10%
	PV++ (B)	B	3:1	-	-
	PV++ (M)	M	3:1	7 days	10%
	Wind+ (B)	B	1:2	-	-
	Wind+ (M)	M	1:2	7 v	10%
	Wind++ (B)	B	1:3	-	-
	Wind++ (M)	M	1:3	7 days	10%
Diff. service parameters	Autonomy 1-day (M)	M	1:1	1 days	10%
	Autonomy 1-month (M)	M	1:1	30 days	10%
	Autonomy 1-quarter (M)	M	1:1	90 days	10%
	Reserve 5% (M)	M	1:1	7 days	5%
	Reserve 15% (M)	M	1:1	7 days	15%
	Reserve 20% (M)	M	1:1	7 days	20%

[a]Percentage of forecasted renewable generation; additional to a reserve equal to the largest unit.

The second set of scenarios explored different parameters for the services in a balanced mix. Here, we compared the resulting differences from the scenarios with the base case of model M (and not with model B).

4.4. Results and discussion

In this section, after a brief overview of the system, we will analyze the impact of modeling multi-services in storage expansion planning. We will first contrast the operation of the storage devices between the two models. We will then analyze their cost difference and, finally, study the effect of modeling multi-services on the storage investment decisions.

Before starting with in-depth analysis, we will first show the main investments to get a general impression of the system. Fig. 16 shows, per zone, the installed capacities of the generation technologies (including existing hydropower cascades), the existing transmission infrastructure, and the planned storage mix. Panel a) shows the base case and panel b) the PV++ scenario, (which we decided to show because it is one of the most cost-effective scenarios).

In the base case, we see how zone z_1 only installs wind turbines supported mainly by the hydropower park and H_2. Zone z_2 has more PV than wind generation and requires vast storage facilities of all kinds to supply the main load center. Zone z_3 is based more on wind than PV power and needs mainly H_2 assisted by smaller PHS and BESS for balancing renewable generation. Zone z_4, is dominated by PV and requires important shares of all storage technologies. We see that H_2 is present in all zones with an energy capacity of around one month, whereas PHS and BESS show capacities of 12-20 h and 2-4 h, respectively.

The PV++ scenario, per definition, relies on solar generation, which compared to the base case creates differences in terms of the storage requirements. Zone z_1 decreases the amount of needed H_2 power capacity, which is offset in zone z_2. Zone z_3 now relies more strongly on PHS. In zone z_4, H_2 and PHS remain constant, but batteries double to deal with the fluctuations of a *solar pole*. Along the four zones, the energy capacities suffer only small changes regarding the base case. In all scenarios, the model does not recommend run-of-river hydropower plants under the used cost assumptions.

This kind of analysis could be deepened, following references [243] or [218], for example. However, now we will focus on the novelty of the present work, which is understanding how accounting for multi-services offered by multi-storages in a multi-nodal system impacts the expansion decisions.

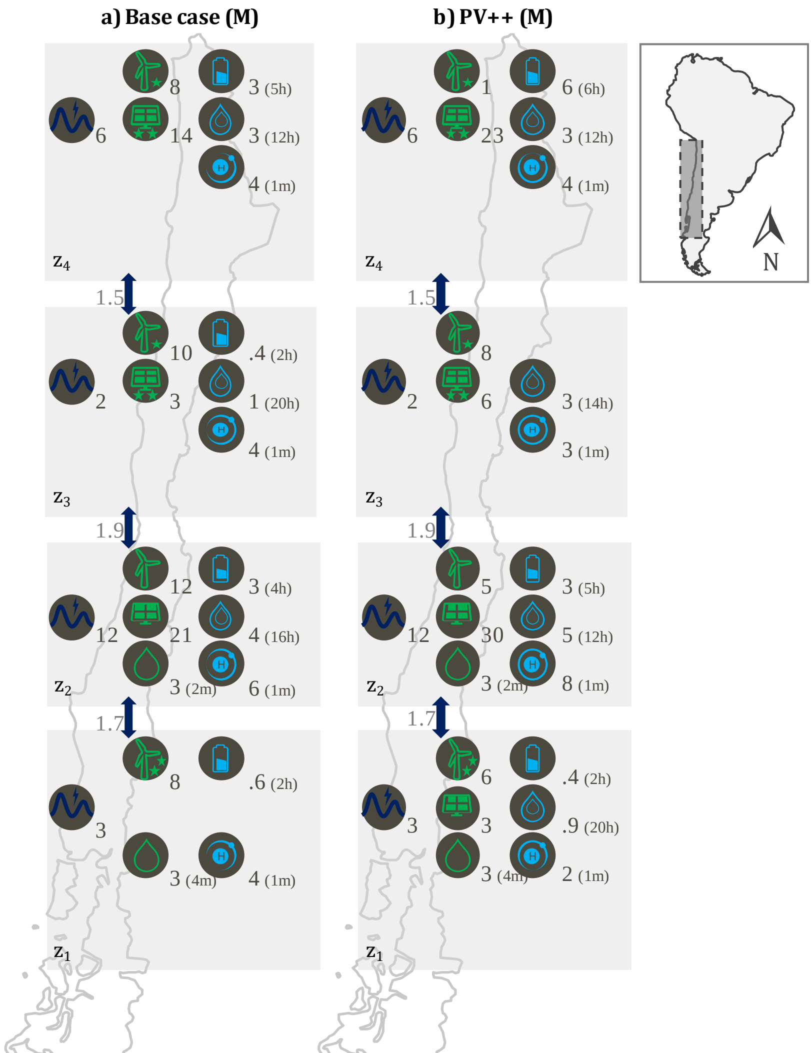

Fig. 16 Main investment decisions for the Chilean power system in 2050

(a) base case and (b) PV++ of model M. Green icons show the generators (solar PV, wind, and existing hydro; zones marked with one/two stars indicates that the resource is excellent/outstanding), light-blue the storage systems (BESS, PHS, and H_2), and dark-blue the load. Numbers show installed power capacities in GW (and in brackets the storage capacity in full-load hours (h) / months (m)).

4.4.1. Operation of storage technologies

Here, we will compare the operational results of model B with model M, to identify what service is provided by each kind of ESS. Fig. 17 summarizes the operation of the different ESS in the base case (of model B and M). Each row corresponds to one storage technology (all storage devices of a same technology – along the four zones– are now grouped). All values are normalized by the installed capacity of each storage technology.

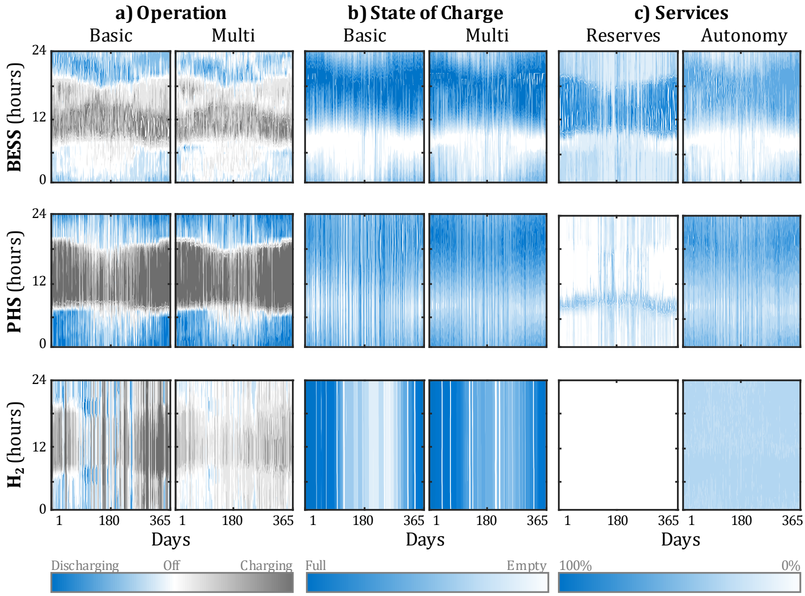

Fig. 17 Operation of ESS (BESS, PHS, H_2).

a) Power output, left: model B, right: M. b) State of charge, left: model B, right: model M. c) Services, left: power reserves in model M, right: energy autonomy in model M. Numbers are relative to the capacity (energy or power) of each ESS.

Panel a) and Panel b) of Fig. 17 compare the energy delivery and the state of charge, respectively. From here we can see how in both models B and M, BESS and PHS respond to the day-night cycle of solar generation. BESS also follows the variability of wind, presenting an overall more fluctuating behavior. Whereas BESS is fully depleted during the nights, PHS tends to be steadier. H_2 has a more seasonal operation showing high states of charge during summer and low ones during winter. It charges during longer periods (full days or weeks) of solar availability and discharges during shorter times of low energy availability. It contributes to some extent to balancing the day-night cycles. H_2 follows a similar operational pattern as in both models, but consistently operates below its installed capacity in model M. In other words, model M recommends more H_2 converters (triggered by the autonomy criterion) without fully using them. Furthermore, in model M, H_2 is never completely empty (for the same reason).

Panel c) of Fig. 17 shows the provision of power reserve and energy autonomy in the left and right column, respectively (both for model M only). It becomes clear that BESS is the main technology in providing power reserves, assisted by PHS before sunrise (moments of low state of charge). Energy autonomy is steadily provided by H_2 throughout the year and by PHS during the day (except the early morning). BESS seems to help after noon (once they reach a higher state of charge).

Up to this point, we have shown the operation of each storage technology, normalized to its respective installed capacity. Fig. 18 instead normalizes to the total service requested by the power system. It shows one dimensionless index for the provision of energy[12], power reserves[13], and autonomy[14], in the subplots a), b), and c), respectively. Figure 3 clearly illustrates that more than half of the energy is delivered by PHS; followed by BESS and H_2. BESS, despite its small energy capacity (Fig. 19), is still able to provide vast quantities of energy given by a large number of cycles. Power reserves (contingency plus operational) are primarily provided by BESS and PHS. Energy autonomy is virtually only delivered by H_2. This stands in apparent conflict with what we saw on Fig. 17; although the provision of autonomy by BESS and PHS can be measured when relative to their installed capacities, the absolute magnitude is not relevant from a system perspective.

As a general remark, the intuition that H_2 should focus on energy delivery and that only BESS will provide power reserves does not show to be true. All ESS participate with important shares in delivering energy. Power reserves are met by BESS and PHS. H_2 is the main technology for energy autonomy. When subjecting the parameters of these services to sensitivities, the found operational trends remain consistent (not shown for the sake of brevity).

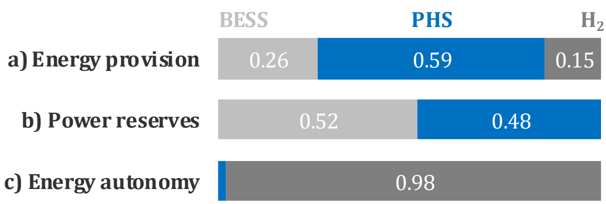

Fig. 18 Service provision by the different storage technologies.
Numbers are relative to the total service requested by the power system.

[12] Energy provided by one ESS divided by the total energy supplied by all ESS.

[13] Ratio of provided reserves by one ESS and the system-wide requested power reserves (frequency and operational reserves are grouped).

[14] Ratio of autonomy provided by one ESS and the total autonomy offered by all ESS.

4.4.2. Impact of multi-services on the system costs

In this section, we will look at the cost difference between both models and how these differences are consistent across scenario variations. By definition, model M must show costs greater than (or equal to) model B, because it has more constraints. This difference, however, has to be understood as the error or cost-underestimation of model B. In other words model M shows a cost closer to reality, which is simply not captured by model B. Table 7 summarizes the total costs obtained by model B and M, divided by the total energy demand (€/MWh).

The impact of planning with multi-services translates into over 20% of total costs difference. We see that this magnitude is consistent for different power mixes (different ratios between PV and wind power), ranging from 16–22%. The smallest difference occurs for mixes based on wind power. Balanced and PV-dominant scenarios are on the other extreme.

Table 7 Total costs for different scenarios of PV-to-wind ratios.
For model B and M.

Case	Cost B (€/MWh)	Cost M (€/MWh)	Ratio M/B (-)
Balanced mix	36.5	44.4	1.22
PV+	35.8	43.8	1.22
PV++	36.2	44.0	1.22
Wind+	39.3	46.6	1.19
Wind++	41.7	48.3	1.16

When analyzing the sensitivity of different service parameters, we see that the cost difference (shown in the last column of Table 8) is minor. Energy autonomies smaller and larger than one week (base case) impact the costs by -4% and +3%, respectively. Different power reserve parameters have a cost difference below 1%. Hence, the parameters used in the base case (BC) seem robust because further parameter variations produce only slight (additional) cost differences.

Table 8 Total costs for different service parameters.
For power reserves and energy autonomy, for model M.

Case	Cost M (€/MWh)	% (rel. to BC)
Autonomy 1-day	42.8	0.96
Autonomy 1-week (BC)	44.4	1.00
Autonomy 1-month	44.8	1.01
Autonomy 1-quarter	45.6	1.03
Reserve 5%	44.3	1.00
Reserve 10% (BC)	44.4	1.00
Reserve 15%	44.5	1.00
Reserve 20%	44.7	1.01

In short, considering energy autonomy and power reserves in expansion planning reveals costs that in traditional planning would remain hidden. These costs are on average 20% and are robust for different parameters of these services.

As a general remark, the (mis-) planned power system by model B would need further adaptions or else it may suffer from a poorer quality of service, e.g. unserved energy. This, in turn, implies costs greater than (or equal to) those of model M. In the literature, this is typically assessed by Monte Carlo approaches that test many operating conditions for the recommended investments [40,280]. In our work, however, we did not study the cost overruns of model B, to focus on the impact on the investment decisions, which we will see now.

4.4.3. Impact of modeling multi-services on the investment decisions

Base case

We will now analyze the investment decisions when modeling multi-services. For this purpose, Fig. 19 shows the resulting storage investment decisions of the different storage devices for all scenarios (energy capacities in panel (a) —note that the axis is discontinuous for H_2— and power capacities in panel (b)). For example, in the base case, model B suggests a total storage requirement of 3.4 TWh and 20.7 GW, while model M recommends 10.7 TWh and 32.1 GW. This is an increase by a factor of about 3.2 and 1.6 for the energy and power capacity, respectively.

Furthermore, when we look at the recommended storage mix, we find more deviations. For BESS, PHS, and H_2, the power capacities in the base case of model B are 10.0, 8.2, and 2.5 GW, respectively, and of model M are 6.5, 8.1, and 17.5 GW. In relative terms, this is a modification by a factor of 0.7, 1.0 and 7.1 for the respective three storage types. This means that H_2 substitutes BESS, while PHS remains invariant. This behavior also holds for the energy capacity. Here, we observe how model B recommends 40, 140, 3220 GWh and model M suggest 25, 124, 10580 GWh for BESS, PHS, and H_2, respectively. Again, in relative terms, this means strong changes between both models: 0.6, 0.9, and 3.3 for the three storage technologies. Perhaps, the increase in energy capacity of H_2 could be expected given its low (energy) investment costs. The substitution of the power capacities (cheap BESS by expensive H_2) is counter-intuitive at first but is related to the multi-services and will be discussed and explained in Section 4.4.3.3. For the remainder of the discussion, we will work with relative numbers.

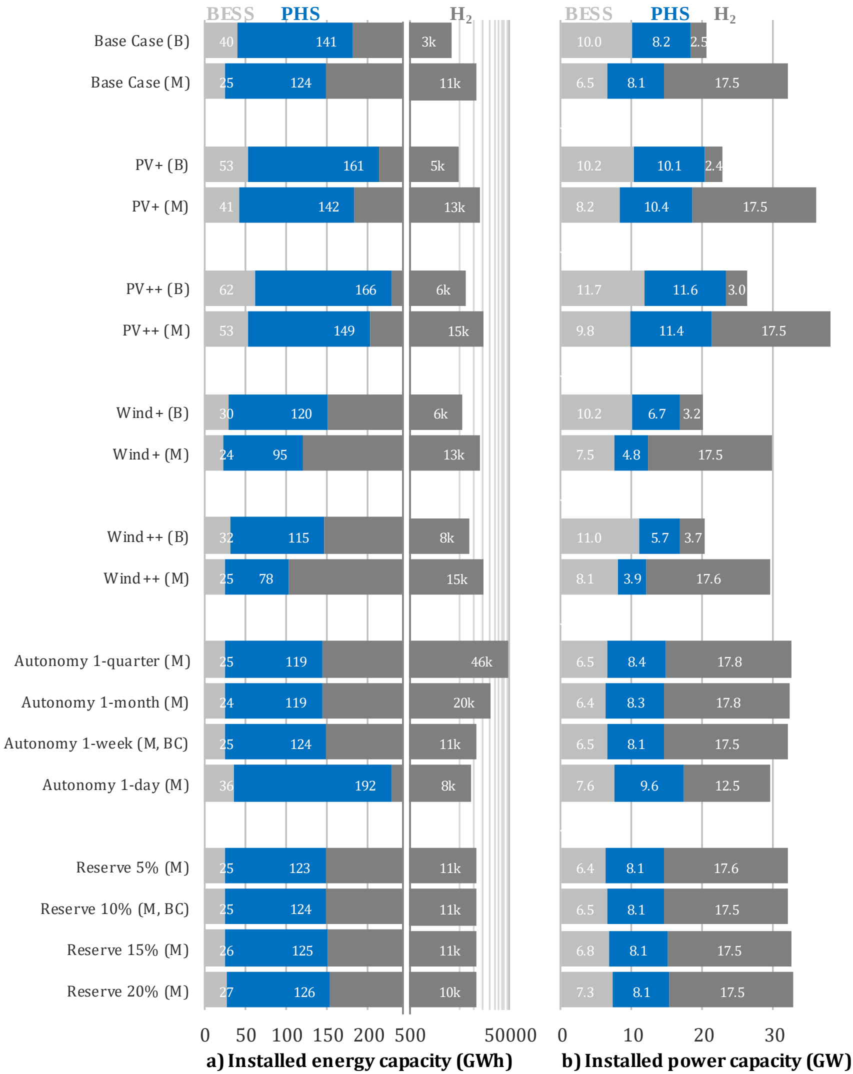

Fig. 19 Investment decisions of ESS (BESS, PHS, and H_2)

(a) energy capacity and (b) power capacity, for the different scenarios.

Note that (a) shows a discontinuous x-axis, which is first linear and then logarithmic.

Sensitivity to PV-to-wind scenarios

The resulting power and energy capacities of ESS for the different renewable scenarios are shown in Table 9 and Table 10. From there we see how the total power capacity resulting from model M is around 1.4–1.6 times larger than in model B, for all scenarios. The resulting deviations in energy capacity are even larger. These range from 1.9 in wind-based scenarios (which do not need as much storage, being consistent with previous studies [246]) and 3.2 in the balance mix scenario. Solar-dominated grids are in between.

Regarding the resulting mix, again, H_2 takes over in all scenarios when including multi-services. Its energy capacity tends to double/triple and its power capacity grows over a factor of five. H_2 displaces the energy capacity of BESS and PHS. In power capacities, H_2 substitutes BESS and PHS up to 30% each. PHS only suffers substantial changes in the wind dominated scenarios.

Table 9 Power capacities for different PV-to-wind ratios. *Model M, relative to model B (%).*

Power capacity	**BESS**	**PHS**	**H_2**	**Total**
Base Case (M)	0.7	1.0	7.1	1.6
PV+ (M)	0.8	1.0	7.2	1.6
PV++ (M)	0.8	1.0	5.8	1.5
Wind+ (M)	0.7	0.7	5.6	1.5
Wind++ (M)	0.7	0.7	4.8	1.4

Table 10 Energy capacities for different PV-to-wind ratios. *Model M, relative to model B (%).*

Energy capacity	**BESS**	**PHS**	**H_2**	**Total**
Base Case (M)	0.6	0.9	3.3	3.2
PV+ (M)	0.8	0.9	2.7	2.6
PV++ (M)	0.8	0.9	2.4	2.4
Wind+ (M)	0.8	0.8	2.2	2.2
Wind++ (M)	0.8	0.7	1.9	1.9

Sensitivity to service parameters

In this part, we will analyze how the investment decisions are impacted when considering different parameters for the services. Table 11 shows the resulting differences in power capacity and Table 12 in energy capacity (all changes are here measured relative to the base case of model M, i.e. they are additional to the base case of model M). Recall that energy autonomy is leaving a level of stored energy, and power reserves is leaving a margin in the converters (see Section 4.2.3.3.).

Table 11 Power capacities for different service parameters.
Model M, relative to the base case of model M (%).

Power capacity	**BESS**	**PHS**	**H_2**	**Total**
Autonomy 1-day	1.2	1.2	0.7	0.9
Autonomy 1-week (BC)	*1.0*	*1.0*	*1.0*	*1.0*
Autonomy 1-month	1.0	1.0	1.0	1.0
Autonomy 1-quarter	1.0	1.0	1.0	1.0
Reserve 5%	0.98	1.00	1.00	1.00
Reserve 10% (BC)	*1.00*	*1.00*	*1.00*	*1.00*
Reserve 15%	1.04	1.00	1.00	1.00
Reserve 20%	1.12	1.00	1.00	1.00

Table 12 Energy capacity for different service parameters.
Model M, relative to the base case of model M (%).

Energy capacity	**BESS**	**PHS**	**H2**	**Total**
Autonomy 1-day	1.4	1.5	0.8	0.8
Autonomy 1-week (BC)	*1.0*	*1.0*	*1.0*	*1.0*
Autonomy 1-month	1.0	1.0	1.9	1.9
Autonomy 1-quarter	1.0	1.0	4.3	4.3
Reserve 5%	0.99	0.99	1.00	1.00
Reserve 10% (BC)	*1.00*	*1.00*	*1.00*	*1.00*
Reserve 15%	1.03	1.01	1.00	1.00
Reserve 20%	1.08	1.02	0.99	1.00

As expected, larger amounts of energy autonomy demand more ESS energy capacity because that service hard-constrains the energy to be stored. How this service impacts the mix is not clear a priori. When requesting more autonomy, H_2 emerges as the most cost-efficient solution (see how its energy capacity in Table 12 grows from 0.8 to 4.3). Once larger H_2 is installed, it can provide other services as well. Consequently, H_2 displaces BESS and PHS. Different parameters of autonomy have essentially no impact on the total power capacity, except when using a small value (1 day) for autonomy. This scenario favors investments in BESS and PHS by about 20% each because they are more cost-efficient on that time scale as opposed to H_2 which is rather long-term.

Variations of power reserve parameters do not show large alterations in the total power and total energy capacities. Furthermore, the resulting mix is only slightly affected. Basically, BESS takes care of stricter operating reserve requirements, without affecting the other technologies. The most stringent power reserve requirement favors the investment of BESS up to 12% and 8% in terms of power and energy capacity, respectively.

As a concluding remark of Section 4.4.3, including energy autonomy and power reserves in expansion planning strongly impacts the investment decisions. Total power capacities and energy capacities turn out to be about 1.4–1.6 and 1.9–3.2 times larger than in traditional planning, for the different scenarios of renewable shares. Using different service parameters creates additional and significant changes in the total energy capacity but more limited ones in total power capacity. The recommended mix is heavily affected under all scenarios, observing a general shift towards hydrogen.

4.5. Conclusions and future work

In this paper, we developed a novel optimization for planning the expansion of storage and renewable technologies, called LEELO, in which the provision of power reserves and energy autonomy is modeled endogenously. Recall that power reserves and energy autonomy are mechanisms of coping with short-term and long-term forecast errors, respectively. Although these services are relevant for the adequacy of power systems and potentially impact the investment recommendations, they are not usually considered in expansion planning. We applied LEELO to a case study about a 100% renewable grid: the Chilean power system in the year 2050. We modeled the whole year with an hourly resolution, considering three storage (battery, pumped-hydro, and hydrogen) and three generation technologies (wind, solar photovoltaic, and existing hydropower cascades). We evaluated different scenarios, varying the ratio between wind and solar generation and the service parameters. By implementing two versions of our model, we compared how multi-service planning differs from the conventional energy-based planning.

4.5.1. Storage technologies and participation in services

In terms of operation, ESS show minor differences between both models. All ESS participate in balancing energy fluctuations. As might be expected, batteries (low energy-to-power ratio) provide most of the power reserves (short-term operation), complemented by pumped-hydro during the nights. Hydrogen storage (high energy-to-power ratio) takes care of the energy autonomy (long-term operation).

4.5.2. More storage in multi-service planning; mix is affected

However, the investment recommendations for storage technologies from our multi-services model differ significantly compared to those from conventional planning, attaining power capacities and energy capacities up to 1.6 and 3.2 times larger, respectively. Moreover, the resulting storage mix is profoundly affected. In our multi-service model, we observe that batteries are substituted to a large extent by hydrogen storage. Pumped-hydro remains mostly invariant. These findings are consistent for the explored power mixes. Using different parameters for the modeled services changes none of the identified trends, under the considered cost assumptions.

4.5.3. Multi-services planning reveals higher costs

Furthermore, we found that considering power reserves and energy autonomy reveals about 20% higher (total) costs. These costs remain hidden in the traditional energy modeling approach. Therefore the solutions found by traditional planning are suboptimal and cause additional unexpected costs, such as ex-post modifications for upgrades to meet the required levels of service.

Our findings underline the importance of modeling multi-services in the task of planning renewable power systems. Not including these services means in practice obtaining systems that are either unreliable or suffer from large adaptation costs. These results are relevant for all entities that in the aim of meeting the Paris Agreement deal with highly renewable power systems, such as governments, power system planners, regulation entities, and generation companies.

4.5.4. Future work

Future work can extend our approach to interactions with other energy sectors (e.g. heat and transport) or by considering other flexibility options in the power sector. We also recommend a more precise definition of the service levels, which is both a technical and political task. Environmental services (life cycle emissions [281,282] or ecological flows in hydropower operation [207]) could also be evaluated, including the corresponding future pricing mechanisms. Finally, further research on stochastic- or robust-based programming approaches is recommended for additional evaluation of the uncertainty from renewable generation.

Chapter 5. Multi-objective energy storage planning

This chapter is based on the publication “Multi-objective planning of energy storage technologies for a fully renewable system: implications for the main stakeholders in Chile” by Jannik Haas, Wolfgang Nowak, and Rodrigo Palma-Behnke, accepted November 2018 in the Journal of Energy Policy.

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Executive summary

Energy storage systems can cost-effectively balance fluctuations from renewable generation. Also, hydropower dams can provide flexibility, but often cause massive fluctuations in flow releases (hydropeaking), deteriorating the ecology of the downstream rivers. Expanding transmission infrastructure is another flexibility source but is frequently plagued by social opposition and delays.

As the decision-making process transcends costs, we developed a multi-objective framework to design a fully renewable power system, such that the tradeoffs between total costs, hydropeaking, and new transmission projects can be assessed from a multi-stakeholder perspective. We planned the Chilean power system for the year 2050 and, based on the obtained trade-off curves (Pareto Front), we identified the following implications for the different stakeholders.

Avoiding new transmission generates little costs (avoiding 30%/100% of transmission increases costs by <1%/>3%), which is positive for planners but negative for transmission companies. Hydropeaking can be mitigated for about 1% of additional costs if transmission is deployed. Avoiding both hydropeaking and transmission is the most extreme scenario, costing 11%. The less the transmission and hydropeaking, the more solar and storage technologies are installed. Cheap solar and storage systems enable policymakers to cost-effectively limit hydropeaking and new transmission, which makes the system greener and more socially acceptable.

5.1. Introduction

Storage expansion planning aims to find the sizes, types, and locations of storage systems that minimize total costs (investment and operation). There are different modeling approaches, such as those systemized in Chapter 2 [2] and in reference [225]. Further, Chapter 3 [246] (which, based on existing studies for storage expansion, synthesized the storage requirements for Europe, U.S., and Germany based on over 400 scenarios) found that, for renewable shares above 50%, the storage park will need to grow strongly beyond the existing capacities. This holds true, especially if the generation is based on solar photovoltaic rather than on wind. What also became clear from the above references [2,225,246], which analyzed in total over 150 sources, is that most studies rely only on techno-economic models. While the technical detail is continuously increasing and complex formulations can be found (including stochastic planning approaches [145,170], high technological [139] and temporal resolutions [121], or multiple technical objectives [283]), the environmental dimensions are frequently neglected. We believe that these environmental dimensions, such as carbon emissions, social opposition, ecosystem health, or material availability, are extremely relevant when planning future power systems, not only because of their inherent importance but also because considering these dimensions can impact the optimal system design.

Since the 2000s, there have been increasing efforts to include environmental criteria in planning. To date, the most common environmental target is the minimization of carbon emissions. For example, the team of reference [78] planned storage devices and took a closer look at avoided energy curtailment and carbon prices in scenario-sensitivities (i.e. ex-post analysis of environmental impacts). Reference [166] went one step further and endogenized CO_2 emissions in the objective function when sizing storage technologies for power systems with high shares of renewables. This approach, i.e. decision making in the presence of multiple targets that frequently compete with each other, is called multi-objective optimization. Another example is reference [171], which included minimizing renewable energy curtailments in the objectives, as a proxy for maximizing the integration of renewable technologies. Further multi-objective approaches (but in distribution systems) have accounted for pollution, energy losses, and reliability in reference [284]; and for greenhouse gas emissions and grid energy losses in reference [285].

When planning the deployment of energy storage for large power systems, using multi-objective frameworks (beyond technical targets) is very rare. This is confirmed by the three literature reviews on storage planning mentioned earlier [2,225,246]. Additionally, a recent search (as of July 2018) on *Google Scholar* (for the combination of “multi-objective”, “energy”, and “storage” in the title) only revealed 50 publications. Dismissing the ones that deal with operational scheduling (e.g. optimal control), single-storage design (e.g. residential or vehicle storage sizing), and micro- or distributions grids, we are left with three contributions. The first one [286] sized battery storage, tested in a 162-bus system, minimizing costs, duration of blackouts and number of circuit breaker operations. The second one [287] calculated distributed storage systems from the viewpoint of an independent system operator. It minimized wind curtailment and transmission congestion while maximizing the profit of storage owners. Only the third study included environmental impacts [288]. Besides optimizing for costs and technical suitability for the different power system services (here: bulk and customer energy management, transmission and distribution support), it included an aggregated lifecycle analysis indicator, called ReCipe [289]. This indicator summarizes the impacts of the storage devices on climate change, human toxicity, particulate matter, and fossil depletion. However, when studying the need for storage, there are other impacts that have not yet been considered in the literature.

5.1.1. Storage planning and hydropower (hydropeaking)

Hydropower reservoirs have several externalities. One of them relates to their operation. Conventionally, they buffer fluctuations in the net energy demand. This highly variable operation scheme is called hydropeaking and provokes ecosystemic harm because the generated power directly translates into strong and unnatural flow fluctuations in the downstream rivers [290,291][15]. Some flow variability is healthy and required to sustain life in rivers [292]. In fact, the natural flow regime is variable over different timescales: minutes to hours during flood peaks, days during high flows, seasons due to precipitation patterns, several years due to extended droughts, and decades because of climate change. [292,293]. However, the water flow downstream of hydropower plants can be extremely altered, exhibiting several peaks per day and flow rates even beyond the strongest natural floods. The literature shows ample evidence on how these severe fluctuations of water levels and flow velocities threaten the lotic communities. These include severe changes in food webs and vegetation [294], stranding, drifting, and washing out of entire populations [295], physiological constraints and problems in reproduction [208,296], life-cycle disruption [210], and many more. Altogether, these altered flows degrade the river habitat and stress its aquatic communities, deteriorating their abundance and diversity up to complete extermination [292,297]. More details on these impacts can be consulted in the review of references [298] and [299].

The conventional way of measuring hydrologic alteration is with the Indicators of Hydrological Alteration [290]. This set of metrics relies on five groups related to the flow's monthly magnitude, magnitude and duration of annual extreme water conditions, timing of extreme annual conditions, frequency and duration of pulses, and rate and frequency of water changes [290]. However, these indicators rely on daily flow resolutions which mask the effect of subdaily patterns [300]. Subdaily and even sub-hourly fluctuations, however, have become more intense due to the integration of renewable generation [206,301] as well as new market structures [302]. In response, more recent studies have proposed eco-hydrologic indicators based on higher temporal resolutions. The Richard-Baker index [303] is one of them and computes the flow's flashiness (sum of all –up and down– fluctuations normalized by the total flow) [206–208,302].

[15] Pumped hydro storage is safe from this issue as its turbined flows are usually not released into rivers

Although research from recent years has shown increasing efforts in quantifying hydropeaking in the operation of power grids, so far it has been ignored in expansion planning exercises. The issue is that when ignoring hydropeaking, the optimization tends to recommend a specific infrastructure but is short-sighted to complications that arise during or after its deployment. In the case of hydropower, there are at least two reasons for acknowledging hydropeaking during the infrastructure planning. One is that a compatible ecological operation (less hydropeaking) can help find socially and environmentally sound solutions while decreasing social opposition, making the recommended projects more likely to be built. Secondly, when integrating renewables, we need flexibility, and a more constrained hydropower operation opposes that goal. This tradeoff between both targets has not been captured in the storage planning literature thus far.

5.1.2. Storage planning and social opposition to transmission

Another socio-environmental impact that is usually neglected when planning storage devices, has to do with transmission infrastructure. Around the globe, social opposition plagues grid deployments [304–306]. This opposition is considered to be the major bottleneck [307], although other aspects are making the development of new transmission lines difficult. Some of these factors include the many actors inherently involved in such large-scale projects (local governments, federal governments, regulators, residents), substantial investments (and their difficulty to justify and recover the costs), and rights of way, among others [308]. The main concerns relate to the visual impact of the lines and pylons [309], endangerment of bird populations [310], noise [311], decrease of property value [312], and electromagnetic-field health concerns —although there is no clear scientific evidence for this issue— [313]. Altogether, these issues can result in delays, cost overruns, and even cancellation of the projects. The resulting underinvestment and delays in transmission directly increase congestion costs, energy curtailment, energy losses, and systems maintenance [308], and can indirectly lead to suboptimal investments in renewable and storage technologies [104].

From social sciences, there are several studies about public acceptance of energy infrastructure; reference [314] for example. They conclude that transmission, in contrast to wind turbines, is not perceived as green technology, thus facing more resistance. Another study [315] picked up this idea and tested whether the transmission lines required to support the energy transition would increase social approval. Although their findings were positive, informing this link (power lines needed for integrating renewables) is challenging. In the end, when it comes to transmission, competitive electricity prices alone are insufficient to gain social support; the public wishes to better understand the need for transmission and alternatives for it [307]. One technical alternative is underground lines. Although they are more costly [316], their social benefits have shown to outweigh their costs in populated areas [316]. If this solution is targeted, clearly, its cost should be considered in the planning.

Within storage expansion literature, transmission lines have been considered from a technical point of view only. In the extreme, storage and transmission can be competitors. If storage is to become very cheap (and in presence of local generation options), all energy could be stored locally. And vice-versa, affordable transmission could eliminate the need for storage because somewhere in the world there is always wind blowing and sun shining. Nevertheless, both extremes seem unpractical from today's perspective, which is why transmission storage systems are perceived as complements [8]. For example, storage can smoothen the fluctuation of a solar power plant and, thus, optimize the utilization of a transmission line [59]. Similarly, having a strong grid allows transmitting energy from different regions to the storage devices, which buffer the received fluctuations [104,218]. Delaying investments in flexibility sources leads to overall suboptimal decisions, including lower renewable generation and higher emissions from fossil sources [104].

From the analyzed studies, it becomes clear that the externalities of transmission lines have not widely been dealt with when planning the deployment of storage systems. Maybe it is because these externalities are difficult to forecast and, thus, challenging to be translated into economic terms (which would then be used in the optimization models). Not including them in the optimization process is similar to the conflict of hydropeaking, in the sense that a model recommends solutions that in practice will face unforeseen inconveniences. A direct response would be treating transmission investment as a separate dimension in multi-objective optimization.

5.1.3. Contribution and research questions

The above literature review shows that multi-objective optimization for storage planning is scarce. However, there are relevant dimensions beyond economics that have to be considered, even when planning 100% renewable power systems. In fact, the practice has shown that transmission infrastructure and hydropeaking are such dimensions. Our working hypothesis is that limiting new transmission infrastructure and constraining hydropeaking are aspects that strongly impact the component-sizing of future power systems, and that explicitly considering both aspects allows for finding cost-effective mitigation strategies. Consistently, in this chapter, we formulate a multi-objective framework for optimizing energy storage expansion decisions. Beyond the framework itself, we concretely contribute by answering the following questions for the involved stakeholders:

- Transmission and generation companies: How relevant is additional transmission infrastructure and what would it cost to avoid new lines? And, is there a bias towards a certain generation technology when relying on weaker grids?
- Storage companies: What happens to the overall storage requirements when costs are minimized next to transmission and hydropeaking? How does the demand for specific storage technologies change?
- Environmental organizations: Can we mitigate hydropeaking at reasonable costs? And, is that cost still bearable if at the same time the society opposes all new transmission lines?

We illustrate the above points in a real power system. We chose Chile as a case study because it has a significant hydropower park (susceptible to ecological alteration), vast distances between generation and load centers (potentially requiring intensive transmission investments), and ambitious renewable targets (triggering the need for storage). These targets include an official political goal of reaching 70% of renewable generation by 2050 [257] and a research vision of becoming Latin America's solar exporter [258].

The following section will detail our methods, including the description of our case study. Section 5.3 will discuss the results, explaining the found tradeoffs from the perspective of the different stakeholders. Finally, Section 5.4 will conclude, show the policy implications, and outline the future work.

5.2. Methods and data

To design the optimal storage and 100% renewable generation mix including externalities, such as from building transmission lines and hydrologic alteration from hydropower operation, we propose a multi-objective framework consisting of four steps. These are multi-objective formulation, power system expansion tool, inputs, and multi-objective analysis, as shown by the blocks i, ii, iii, and iv in Fig. 20. We will briefly introduce these steps in the following paragraphs and then provide a more detailed description in Subsections 5.2.1 to 5.2.4.

1. *Multi-objective formulation*: The main concerns of the involved stakeholders need to be identified. The conventional target is energy equity (affordability and accessibility), i.e. delivering power to all users at minimum costs. There are also socio-environmental concerns related to power system planning. Our framework is general enough to include most types of externalities, but in this work, we focus on two: minimizing hydropeaking and minimizing new transmission facilities. From a modeling perspective, these can be implemented in two equivalent alternatives: penalizations (in the objective function) or bounds (in the constraints).

2. *Power system expansion tool (LEELO)*: Here we use a linear optimization tool, called LEELO (Long-term Energy Expansion Linear Optimization), for planning the power system. The main outputs involve the investments (sizes and location of storage, generation, and transmission), the operation of the system, and the socio-environmental parameters. The tool can handle the design of a multi-nodal power system with a detailed representation of hydropower.

3. *Inputs*: The main inputs relate to technical parameters (power plants, storage technologies, transmission infrastructure and projections of electricity demand), cost projections (capital and operational cost), and renewable resources (profiles). We set up a database to plan the system of Chile in the year 2050, based on a full milestone year with an hourly resolution. We considered three kinds of storage devices (batteries, pumped hydro, hydrogen), and three kinds of renewable generation (solar photovoltaic, wind, existing hydropower cascades).

4. *Multi-objective search and analysis*: First, the outputs of the tool are compiled and processed into a set of key indicators. Then, the tool is run multiple times to systematically form the Pareto Front, with which we analyze the tradeoffs between cost, hydrologic alteration, and new transmission lines. We adopt the

perspective of the involved stakeholders of the power system (transmission and generation companies, energy storage companies, environmental organizations) to address the main implications when planning with multiple dimensions.

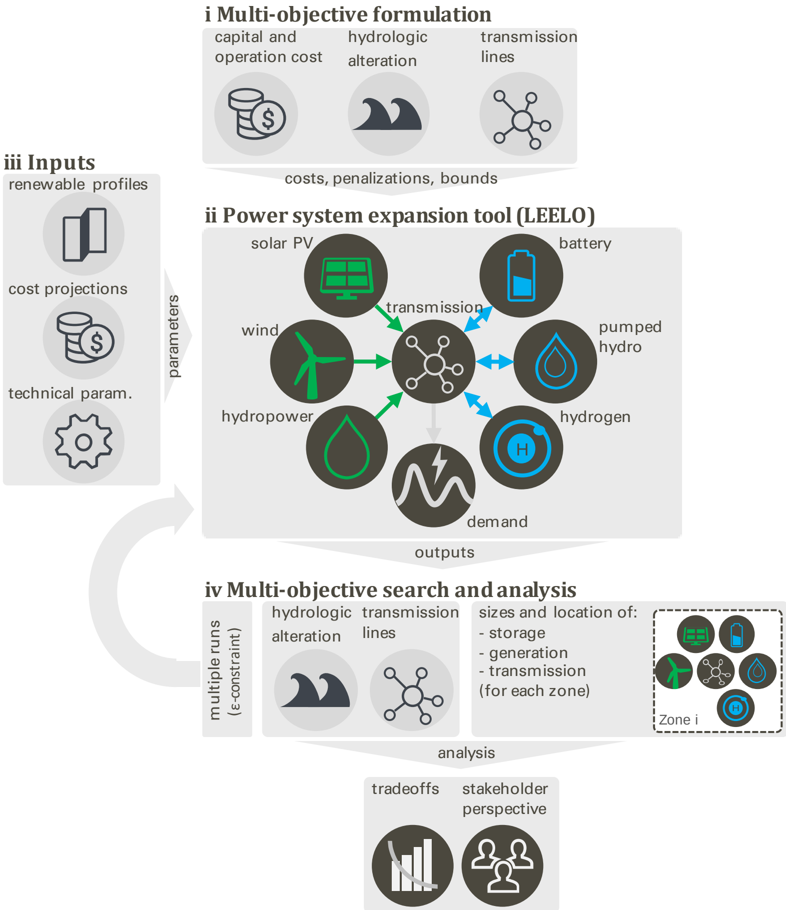

Fig. 20 Multi-objective optimization framework.
i) multi-objective formulation, ii) power system expansion tool (LEELO), iii) inputs, and iv) multi-objective search and analysis.

5.2.1. Multi-objective formulation

We aim to find the design of the power system (d_{opt}) that minimizes the different components of the objective function. These objectives, shown in Eq. 31, are composed of costs (f_{costs}), hydropeaking ($f_{hydropeaking}$), and transmission ($f_{transmission}$), which we will explore now. The decision space of feasible designs (D) is given by the power system expansion tool (see Section 5.2.2).

$$d_{opt} = \arg\min_{d \in D} \begin{bmatrix} f_{costs}(d) \\ f_{hydropeaking}(d) \\ f_{transmission}(d) \end{bmatrix} \qquad \textit{Eq. 31}$$

Objective A: minimize costs

One objective is minimizing the total costs, composed of investment and operating costs. Investment cost includes building energy storage systems, generators (solar photovoltaic and wind power plants), and transmission lines. The investment costs are treated as annuities, which is a function of each technology's lifetime and a given interest rate. Operating, variable, and fixed costs are mainly the maintenance costs of all the built infrastructure.

Note that the *cost* of transmission infrastructure is part of this objective function. Yet, to confront other complications that transmission faces during its deployment, it is additionally treated as a separate dimension.

Objective B: minimize hydrologic alteration

We measure hydrologic alteration with the Richard-Baker (RB) index. Recalling its definition from the introduction, for one hydropower plant, this is the sum of the flow variations divided by the total flow over a given time horizon. Here, the time step is one hour, and the horizon one year (i.e. 8760 flow variations are summarized into one index, per hydropower plant). To summarize the operation of the whole hydropower system (our case study includes over 40 cascading hydropower plants) into one index, we computed the weighted sum between the RB index of a hydropower plant and its installed capacity.

Modeling the RB index endogenously in the optimization would implicate losing the linearity of the model (which would burden the solving times) because both the hourly flows and the total flows are decision variables that would be dividing each other. As a proxy to the RB index in the optimization, we decided to minimize the ramps of the hydropower park (i.e. the numerator of the RB index). As a side note, modeling ramps in linear optimization requires using two auxiliary variables. One for the sum of the positive ramps and another for the negative ramps. Once the optimum is found, we used the RB index for analysis (Section 5.2.4).

Objective C: minimize new transmission lines

The deployment of new transmission lines is frequently burdened by severe execution delays –if built at all–, and social opposition. In combination with other factors, this tends to result in much higher costs than the projections originally considered in the optimization. Treating additional transmission infrastructure as a separate dimension allows understanding how much the other dimensions (here: costs and hydrological alteration) would suffer if only a given level of transmission can be built.

Concretely, this objective is defined as the sum of (new) transmission capacity to be built, measured in MW. Recurring to life-cycle analysis literature, more complex treatments can be found, for example land use, especially in sensitive territories. However, as a first approximation, especially in a tri-dimensional objective function, we decided to take the simplest expression (MW) for the ease of communicability. This also implies that a, say, 1 MW line of 1 km has the same relevance (for the model) as a 1 MW line of 1000 km (note that in our case study the length of all potential lines are of the same order of magnitude, making this issue less relevant than in other cases).

5.2.2. Optimization tool (LEELO)

LEELO is an optimization tool to design fully-renewable multi-nodal power systems. The main objective of LEELO is sizing and siting energy storage, renewable energy, and transmission systems. In contrast to other available models, LEELO's strengths are: having a detailed representation of cascading hydropower (flow routing), the option to include different power system services (power reserves and energy autonomy), and considering multiple-objectives (an extension we performed for the present publication). LEELO is based on cost minimization, i.e. it adopts a welfare-planning perspective (this also means that the market feasibility of the recommended solutions is out of scope). Below, we will provide a general overview of LEELO's main characteristics. For further detail, we recommend consulting our previous publication [254].

LEELO is multi-nodal, meaning that it captures different geographic zones. The zones are interconnected with transmission infrastructure, which we represented with a transport model (i.e. voltage differences and phase angles are ignored, which is a common simplification when planning nation-wide grids). Energy losses due to transmission are considered to be proportional to the transmitted energy. Each zone is modeled as a copper plate (i.e. sub-transmission and distribution systems are not captured). Other energy sectors, such as heat, transport, and gas, are not included.

Storage systems are modeled in terms of their capacities, energy-to-power ratio, cycling, and energy balance. The former refers to the (maximum) energy capacity and power capacity, which are two independent decision variables. More specifically, the costs for energy capacities refer to the effective capacity (e.g. in order to have an effective energy capacity of 100 MWh for a device with a maximum depth of discharge of 80%, 125 MWh have to be purchased). Limiting the energy-to-power ratio makes sure the model avoids infeasible configurations (for example batteries with, say, weeks of storage capacity). The cycling is captured in terms of a maximum number of yearly cycles coherent with their lifetime (e.g. 10.000 cycles in 10 years results in 1.000 cycles per year), in order to (indirectly) capturing the aging of the battery.

The model considers different profiles for the renewable generators, depending on their location. The amount of energy curtailed is verified ex-post to make sure economically unattractive projects are avoided.

Cascading hydropower (hydropower plants that are constructed in series, one downstream of another) are modeled with connectivity vectors to capture the flow routing. Some hydropower plants have reservoirs. Thus, they have an energy balance equation similar to the energy storage systems. To convert from turbined water to power, we assumed a constant yield.

Regarding the multiple power system services, the most fundamental one in available models is energy balance, meaning that in each time step supply needs to meet demand. In our previous publication/chapter [254], we proposed to include further services: power reserves (leaving capacity to ramp-up and ramp-down) for tackling short-term forecast errors and energy autonomy (leaving energy reserves) to confront long-term deviations in the used weather inputs. We found that both services impact the final storage investment decisions. Also in the present study, we used this more complex model.

5.2.3. Inputs

The main inputs include technical parameters, cost projections, and renewable profiles, and can openly be accessed online [266]. For even further details, please consult our previous publication [254]. We follow a brownfield approach that considers the existing transmission lines and hydropower park as inputs and assumes that the current thermal power plants will be fully decommissioned by 2050. As follows, we will only explain the main assumptions and data sources after briefly introducing the main characteristics of the Chilean power system.

Chile is a country with extremely high potential for renewable technologies (see Fig. 21 for a simplified schematic of the main topology and zones of our case study). The Atacama Desert in the north with the world’s highest levels of irradiation is ideal for a solar pole (zones z_3 and z_4) [278]. The high Andes combined with precipitation, offer in the center and south a strong hydropower resource (z_1 and z_2). And the Pacific Coast refreshes the almost 4300 km long country with fast winds for turbines (z_1 to z_4). These resources are not only high but also virtually unconstrained in space. The load is distributed quite unevenly, most of it being concentrated in Chile’s center close to the largest cities (z_2). The north is sparsely populated and requires electricity mostly for copper mines (z_3 and z_4), whereas the south exhibits many touristic landscapes (social opposition) and is characterized mostly by a residential demand (z_1). Altogether, this configuration makes planning the future electricity system a challenging task.

For the definition of the zones, we segmented the country across the main transmission bottlenecks. The corresponding (existing) transmission capacities come from the database of the national power system operator [268]. From here it results that the four zones are interconnected by lines of capacities ranging from 1.5–2.0 GW, totaling 5.1 GW.

Regarding generation technologies, we considered solar PV (single-axis tracking) and wind turbines (onshore). The resource profiles were obtained from validated online tools (*Solar and Wind Energy Explorer* [275–277]). In each zone, we considered three locations for each technology. We also modeled the existing hydropower park, consisting of about 20 cascading installations in each zone z_1 and z_2.

Their connectivity and inflows are based on references [269,274]. For the last hydropower plant of each cascade, we assumed an ecological flow equal to ten percent of the nominal turbine flow. Hydropower plants (reservoirs and run-of-river) are not expanded.

For storage technologies, we chose to model Li-ion batteries, pumped hydro storage, and hydrogen systems (with gas turbines for reconversion back to electricity, and CO_2 scrubbers).

To obtain the load of 2050, we took the current demand profiles of zones z_1, z_2, and z_3 from reference [269], and of zone z_4 from reference [268], and applied the yearly growth rates as estimated by the National Energy Commission of Chile. This resulted in a (total) average load and peak load of 23 and 29 GW, respectively. For context, these numbers imply tripling Chile's current load. This challenge is additional to making the system 100% renewable. We considered a penalty for unserved energy of 10.000 €/MWh.

As what refers to costs, we used the database from Breyer's team [247]. Based on experience curves and projections of to-be-deployed capacities, they forecast the costs of the main renewable and storage technologies. This forecast has been widely used in scientific publications in the last years [24,25,28,247,248,267]. For pumped hydro, we recurred to values compatible with reference [190]. For calculating the annuities of capital expenditures, we took the expected lifetime of each technology [247] and a yearly interest rate of 5%, which is in line with other equivalent studies (i.e. when the focus is on mature technologies in regions with high geopolitical stability) [234].

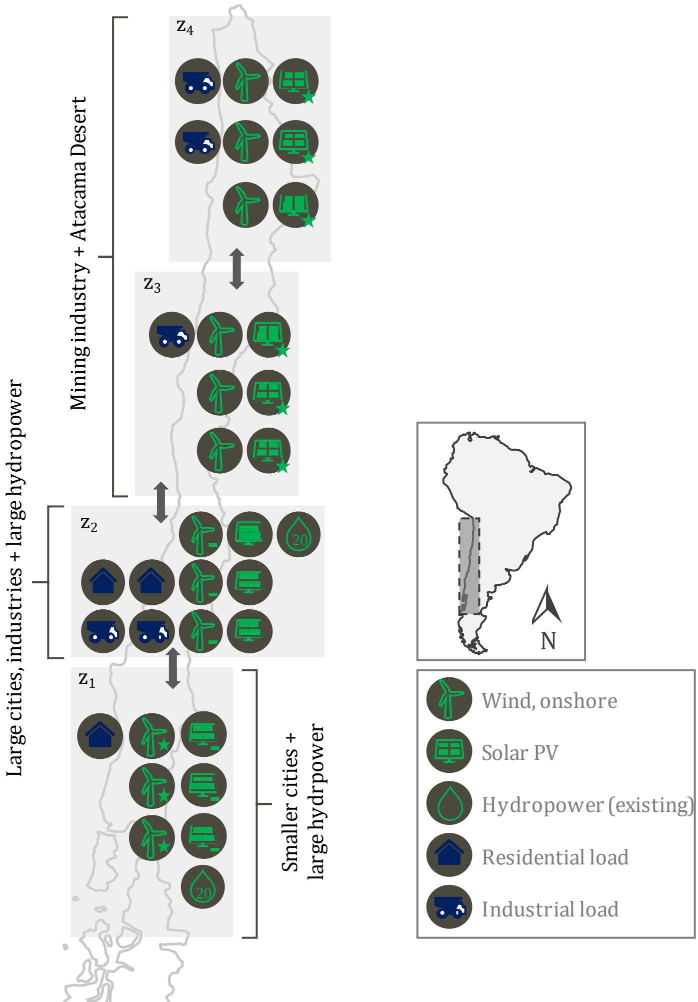

Fig. 21 Schematic of the Chilean power system.
Solar PV and wind resource, as well as existing hydropower plants in green (outstanding resources marked with a star, and lower resources with a minus-sign). Residential and industrial load in blue.

5.2.4. Multi-objective search and analysis

Each model run gives us one solution consisting of a recommended generation mix (wind, solar), storage mix (batteries, pumped hydro, hydrogen), additional transmission lines, and the operation of the whole system for the simulated year. To systematically screen the space of pareto-optimal solutions, the model is run multiple times. We follow the *ε-constrained method* , which consists of minimizing one dimension of the objective function while constraining the ranges of the remaining ones. Note that the literature shows other options for exploring the Pareto Front, such as Monte Carlo (randomly weighting each part of the objective function), the *augmented ε-constrained method* (a more efficient formulation of *ε-constrained*) [317], or *Borg* (for evolutionary computing frameworks) [318]. The two latter become especially relevant when computing time is limited (i.e. to produce the best front with few runs). In our case study, computing times were not critical, which is why using the *ε-constrained method* was enough.

By definition, each found solution is optimal (given the used range of the objective function). This case is direct for the dimensions of costs and additional transmission, where the target to be minimized is explicitly modeled in our tool. In the case of mitigating hydrologic alteration, we recall that our model minimizes total hydropower ramps in the objective function as a proxy for the ecological index (the ecological index is only computed during post-processing). Due to this proxy, it could happen that some of the found solutions are not pareto-optimal. For this reason, we test each solution for Pareto-Optimality and filter out the non-dominant ones.

For the final analysis, we will adopt the perspective of the different stakeholders involved in power system planning. Decision making in multi-dimensional spaces is inherently complex, which is why we focused on providing a small set of well-selected indicators for each stakeholder. Namely, for the transmission companies and generation companies, we will describe the tradeoffs related to transmission investments and the resulting generation mix (with the ratio between installed solar photovoltaic and wind power capacity). For the storage companies, we will focus on the power capacities of the total storage requirements and the individual storage requirements. Finally, for the environmental organizations, we will analyze the tradeoffs between mitigating hydropeaking, new transmission, and costs.

5.3. Results and discussion

In this section, we will first present a general overview of the results. We will then analyze the findings in perspective of the different stakeholders in a power system: Section 5.3.1. will describe the implications for transmission and generation companies, Section 5.3.2 for storage companies, and Section 5.3.3. for environmental stakeholders. Section 5.3.4 comments about uncertainties and future work.

To find the surface of optimal solutions (the Pareto Front), we run our model about 100 times. Each scenario takes around 30 minutes to solve on an i7-7700 (4 cores of 3.6 GHz), 32 GB of memory, with CPLEX v12.8. As a comment about the feasibility of the recommended power system design, in all scenarios, 100% of the energy demand is met (no unserved energy) and the amount of curtailed energy is below 3%.

The resulting Pareto Front is shown in Fig. 22. The three axes correspond to the three objectives to be minimized: costs, transmission, and hydropeaking (in x, y, and z, respectively). Costs range between 34.6 and 38.5 €/MWh, additional transmission between 0 and 7.0 GW (which is about doubling the current capacity), and hydropeaking between 0.00 and 0.16 (measured with the Richard-Baker flashiness index, where the upper extreme is at least one order of magnitude more flashy than a natural regime). The green dot at the lower left corner is the point where we would like to be: low cost, no hydropeaking, and no new transmission systems. In practice, we cannot achieve that point, and as a consequence, the solutions are distributed around it. The color code indicates investment decisions, in the case of Fig. 22 that is the ratio between solar PV and wind capacities.

In general terms, the found Pareto Front has the following shape. It is asymptotic to the plane of hydropeaking/transmission and cost/transmission. This means that, on the one hand, the first efforts of reducing hydropeaking are very cheap, and that, on the other hand, the last efforts are expensive. Furthermore, the front side of the Pareto Front is rotated outwards, and all cross-sections in the cost-hydropeaking plane are hyperbolic. This rotation means that if new transmission facilities are not built, the costs increase but the overall behavior remains similar. Or in other words, for a given level of hydropeaking, the resulting costs are higher if less transmission is built. Let’s now discuss what the results mean for each stakeholder in particular. Some selected scenarios to be discussed are displayed in Table 13.

Table 13 Main investment decisions.
For selected scenarios from the Pareto Front.

Level of transmission/ hydropeaking	Costs (Eur/MWh)	Cost (rel. to base case)	Hydropeaking (RB)	Transmission (added GW)	Solar to wind (GW_{PV}/GW_{wind})	BESS (GW)	PHS (GW)	H_2 (GW)
TX_100%, HP_max (Base Case)	34.6	100%	0.16	5.5	1.8	6.9	9.6	13.1
TX_0%, HP_max	35.7	103%	0.16	0.0	2.1	11.6	9.6	12.8
TX_100%, HP_min	37.2	107%	0.00	7.0	1.6	7.9	9.6	13.2
TX_0%, HP_min	38.5	111%	0.00	0.0	1.9	12.9	9.6	13.3
TX_70%, HP_max	34.6	100%	0.16	5.0	1.9	7.0	9.6	13.1
TX_15%, HP_max	35.4	102%	0.16	1.0	2.0	10.1	9.6	13.1
TX_0%, HP_0.01	36.1	104%	0.01	0.0	2.1	12.5	9.6	13.1
TX_15%, HP_0.01	35.8	103%	0.01	1.0	1.9	11.2	9.6	13.2
TX_100%, HP_0.01	35.0	101%	0.01	5.9	1.7	7.7	9.6	13.2

5.3.1. Transmission and generation companies

Here, we will first explore the implications of our findings for transmission companies, followed by generation companies. Here, we will first explore the implications of our findings for transmission companies, followed by generation companies. When comparing the different solutions of the Pareto Front, we will use the minimum cost solution (upper left point, where both transmission and hydropeaking are maximum) as base case.

Recall from the methods, that transmission infrastructure is captured in the cost dimension (capital and operational), as well as in its own dimension (to account for its externalities). When trying to minimize the main transmission facilities, avoiding (the last) 30% of transmission can come at almost no additional cost (<1%). This fact can be seen in Fig. 22, where all solutions that have over 5 GW of grid expansion are close to the axis of minimum cost. The costs of avoiding 85% of new transmission start around 2%. Building new transmission shows an important impact on costs only between 0 and 1 GW (the first 15%). Renouncing to all new transmission increases total costs between 3% and 11% depending on the desired level of hydropeaking. These costs seem small in the context of social externalities.

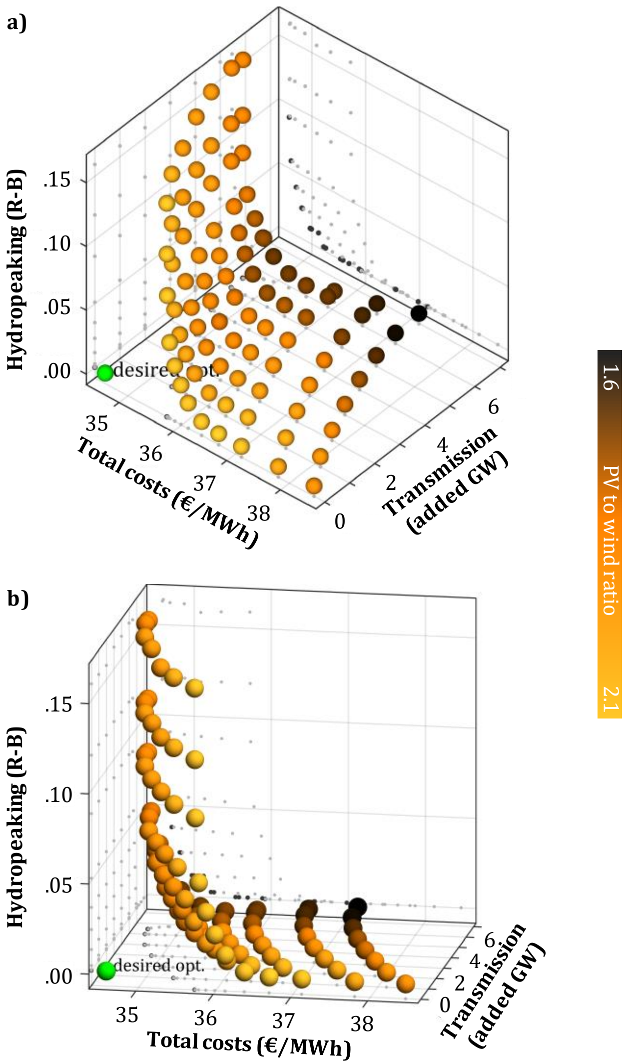

Fig. 22 Pareto Front and the resulting generation mix.

Color shows investments in renewable systems (solar to wind ratio). Each solution (sphere) is projected on the faces of the cube in grey, or in black if the projection is pareto-optimal on the corresponding face. Both figures show the same solutions but from a different angle.

Given that the business model of transmission companies relies on building and operating grid infrastructure, are the found results good or bad news for them? The answer has different components. First, given the difficulty of decreasing social opposition of transmission lines, even in the context for the energy transition [315], it is unlikely that the least-cost point can be achieved in practice anyways. Secondly, the marginal cost saving of the last GWs of transmission capacity is very low, which allows the transmission companies to focus on key-projects, without letting go of valuable business opportunities. Such projects could include power lines in less populated areas such as a corridor in the Atacama Desert or optimizing existing lines without affecting their visuals (e.g. replacement of conductors) in more conflictive regions. In conclusion, the fact that *some* of the new transmission can be avoided for cheap is good news for transmission planners. However, the *overall* saving potential of new transmission (only <11% of total system costs when transmission is doubled) is inconvenient for transmission companies that want to grow. Especially after installing the first 2 GW, the marginal savings are meager under the made cost-assumptions. However, other factors not considered here could also play a role. For example, interconnecting energy sectors [24], Chile becoming an H_2 exporting country [319], or planning systems that are also robust, resilient, and adaptive [320] are elements that could impact the relevance of transmission infrastructure. Furthermore, we underline that we refer to investments of the main transmission system only, while sub-transmission and distribution systems are beyond our scope.

To understand the tradeoffs for generation companies, we need to take a look at the color scale of Fig. 22, which indicates the ratio between the installed capacities of solar and wind power plants (from grey to yellow, the solutions rely more strongly on solar generation). From here we see that, when new transmission capacities are constrained, the system relies more on solar. This relates to the fact that solar with storage can be cost-effective in most regions, whereas wind needs to be transmitted from the good spots to the load centers. In the extremes, when the maximum transmission is deployed, solar exceeds wind capacity by 60% (ratio of 1.6), and when no transmission is installed, solar exceeds wind by 110% (ratio of 2.1). It becomes clear that the solar sector has a lot to gain if the transmission system is not fully expanded. In general, renewable generation companies are currently exposed to intensive discussions about the integration costs (direct and indirect) needed for achieving highly renewable systems. Transmission lines are one of these externalities [316], which, as shown above, can be avoided for little costs. Yet, integration costs remain in the form of storage, but these face less social opposition. Overall, that is good news for generation companies.

In short, transmission can be avoided for little economic effort, in the presence of a robust solar-storage strategy. Based on this analysis, the business case for future transmission lines seems limited. For planners and policymakers, especially in zones with strong social opposition, this is good news. They can focus on the development of transmission in less sensitive regions. Finally, when not investing in transmission, the system relies more on (local) solar which, in turn, may trigger the need for more storage, as we will see in the next subsection.

5.3.2. Energy storage companies

Below, we will first analyze the total storage needs, followed by the implications for each storage technology. The figures used in this section are similar to Fig. 22 shown above. They all plot the same solutions (spheres) on the same dimensions (axes), but with a different color code for the necessary power capacities: total storage in Fig. 23, battery energy storage systems (BESS) in Fig. 24-a, pumped hydro storage (PHS) in Fig. 24-b, and hydrogen systems (H_2) in Fig. 24-c.

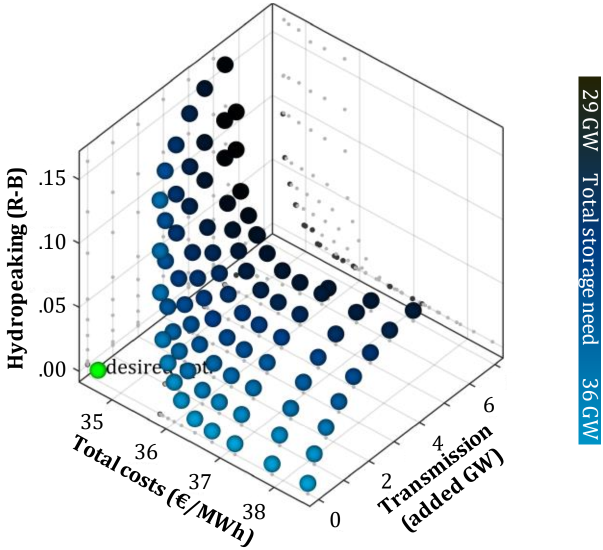

Fig. 23 Total energy storage requirements (power capacity).

In the presence of flexible hydropower (hydropeaking) and a strong new transmission system, storage systems are less needed. Here our multi-objective optimization reflects existing knowledge. This is shown in the upper-right part of the Pareto Front in Fig. 23 by the black spheres. In this area, the total storage requirement is about 29 GW of power capacity. As we move to regions with more limited transmission, the need for storage increases strongly. Also, when hydropeaking becomes very constrained, the total storage demand grows systematically. When both sources of flexibilities are absent, storage requirements peak at 36 GW. All futures rely on storage systems, which stands in high contrast to new transmission that can be avoided entirely (see previous section). Furthermore, the changes along the whole solution space are very smooth, meaning that small variations in constraining transmission and hydropeaking generate small changes in total storage requirements.

BESS (Fig. 24-a) are least needed in scenarios with strong transmission and allowed hydropeaking, constituting around 24% of peak demand. As these flexibility sources become more constrained, BESS requirements proliferate, culminating at 44% (of peak demand).

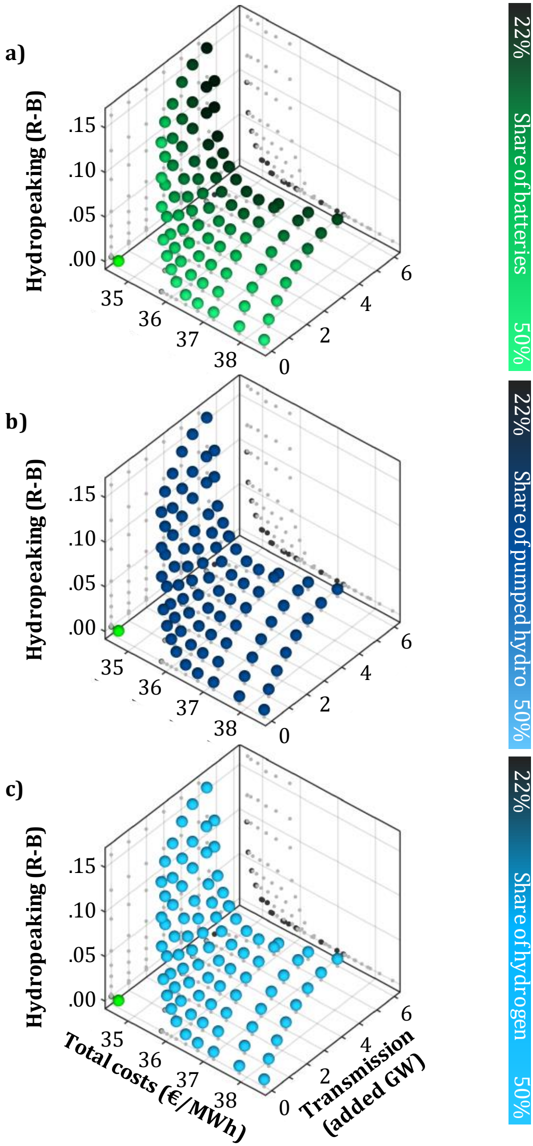

Fig. 24 Storage requirement per technology.
Power capacity, normalized by peak demand. a) BESS, b) PHS, c) H_2.

PHS (Fig. 24-b) sizes show to be constant for all scenarios. This relates to the fact that the model recommends deploying all the available (energy capacity) potential of PHS (and then, for this energy capacity, the converter size is optimized). This is in line with other studies, which also have reported PHS to deplete the whole potential [243].

H_2 (Fig. 24-c) exhibits only small variations of its recommended power capacity: between 44% and 46% of peak demand. Here, the main driver is the energy autonomy service (similar to fuel security) from the model. This long-term constraint is most easily met with H_2 storage. Note that providing this service also is the reason for the total storage capacities to exceed the peak demand; this can be seen equivalent to current power systems where peakers provide backup.

In summary, all futures rely on energy storage. BESS requirements grow when transmission and hydropower are more limited in direct response to lower levels of system flexibility, and also because those systems rely more on solar.

5.3.3. Environmental organizations

Next, we will focus on how ecological alteration —in rivers downstream of hydropower reservoirs— can be mitigated. First, we will explore the tradeoff between transmission and hydropeaking, and then between costs and hydropeaking. Finally, we will identify a set of promising solutions in terms of all three considered dimensions.

For this section, we need to recall the shape of the Pareto Front from any of the above figures. Between hydropeaking and transmission, there is no *direct* competition. In fact, there is a solution where both dimensions are minimum. There, hydropower flexibility cannot be transferred to buffer the fluctuations of the zones strong in solar generation. All the remaining points (not pareto-optimal in the dimensions of transmission and hydropeaking) are generated by the existence of the cost-dimension. It so happens that many solutions, especially for substantial transmission additions, rely on severe hydropeaking. There are also solutions, which keep hydropeaking close to the natural flow regime no matter the level of added transmission. It is all a matter of costs. However, under budget constraints, avoiding hydropeaking and transmission do compete.

To reach a flashiness close to the natural regime, a reduction of hydropeaking by one order of magnitude is needed (our base case exhibits an RB~0.160, and natural streams can have values between 0.005 and 0.050 [206]). As the natural flashiness is different for each basin, we can only provide a first number in the direction of restoring the natural flow regime (and no final recommendation). RB values below 0.01 cost from 1%. The most extreme is targetting RB values close to zero, which has costs starting from 7% if transmission is present, and up to 11% if transmission is not.

An interesting solution region is where both hydropeaking and transmission are small but not zero. Having hydropeaking *close* to the natural regime (e.g. RB<0.01), while investing only little (<1 GW) transmission costs 3%. Avoiding the last GW of transmission costs another 1%. Very low values of hydropeaking generate the cost increase of 11% that we just mentioned in the previous paragraph. For this region (recalling Fig. 22 about the generation mix), the optimal system of 2050 will be based mostly on PV, with strong back up from BESS. From a technological point of view, what exact solution from that region is finally chosen does not seem to matter as the Pareto Front is smooth. Even if the flashiness tends to zero, the storage mix remains stable. This solution-robustness is practical when negotiating with the other stakeholders.

Two paragraphs earlier, we mentioned that transmission and hydropeaking could compete, which becomes relevant only under very constrained budgets (<3%). Here, we can observe two extreme scenarios: low hydropeaking (RB=0.01) while avoiding most (85%) transmission, or extreme hydropeaking while avoiding all transmission. Nevertheless, constraining the budget to such low limits seems somewhat unreasonable in the light of the potential benefits of mitigating both hydropeaking and transmission for one additional percent. A previous study showed that using BESS for peaking purposes, thus, reducing hydropeaking, can easily be profitable already in 2025 [321]. In other words, a clear investment strategy in solar and storage technologies (mainly BESS) is needed as soon as possible for reaching low values of hydropeaking and —at the same time —transmission.

To conclude, the main messages for environmental organizations are the following. Severe hydropeaking can be avoided for little costs (1%). If both transmission and hydropeaking are to be avoided, the cost increases by around 11%. This is enabled by affordable solar and storage systems. Communicating this link clearly (solar and storage allow avoiding hydropeaking and transmission) to society might help create a future based on strong solar and storage technologies (i.e. easier to tolerate).

5.3.4. Comments about uncertainties and future work

In the present work, we derived the tradeoff curves between total costs, hydropeaking, and new transmission infrastructures, when planning a fully renewable power system. The two latter are subject to deep uncertainties, which is why we treated them as separate dimensions, as opposed to modeling them as given hard-constraints. But there are other sources of uncertainty that we did not address, as briefly discussed below.

Regarding the reliability of the proposed solutions; recall that reliability has two components: adequacy (“ability to meet peak demand over time” [192]) and security (“ability to withstand contingencies” [192]). The former was taken care of endogenously by considering hourly nodal power balances. The latter we treated by requesting ancillary services (power reserves to tackle forecast errors of renewables; and energy autonomy to cope with long periods of low renewable production), which also are modeled endogenously [254]. These services are still not an explicit treatment of contingencies but serve as a proxy. If further verification is desired on the secure operation of the solutions (e.g. with *n-1* simulations), the numbers from Table 14 in the appendix (section 5.5), showing the main component sizes, can be used.

In expansion planning exercises, cost assumptions are an inherent and important source of uncertainty. For solar PV and wind, cost projections are widely available, reducing the involved errors. However, batteries and, even more so, hydrogen systems are more incipient with correspondingly large deviations to be expected between their cost forecasts and actual future costs. For this reason, we decided to quantify the uncertainty of the most extreme scenario of our Pareto Front (the solution without new transmission and hydropower flexibility that resulted in the largest storage demand). For this purpose, we performed a Monte Carlo simulation, varying the investments costs of batteries, pumped-hydro (which we decided to include given their large cost spread across projects), and hydrogen system[16]. From Fig. 25-a, we see that the total costs and total power capacity of storage converge after about 50 Monte Carlo runs. What we found is that the different storage investment cost can impact the total system costs by ±8% (Fig. 25-b), and the recommended total storage power capacity by -20% to 15%, relative to our selected scenario (Fig. 25-c). These ranges, in the context of the wide range of investment cost considered, seem rather small. Most importantly, all scenarios from the Monte Carlo simulation have no unserved energy and present only small levels of curtailment (<3%). In short, the uncertainty from storage investment costs on the resulting total storage requirements is limited, in our setup.

In terms of hydropeaking mitigation, we found that total costs are sensitive when the (system-wide) hydrologic flashiness index approaches values close to zero. What precise value we should target is not entirely clear, because we condensed all rivers into one single index and, in practice, each basin has a different natural flashiness. Also from an environmental perspective, further dimensions could be included in the future, such as mineral sufficiency, life-cycle emissions [322], and land use.

Concerning our planning approach, we designed one milestone year (static planning). However, in practice, systems evolve gradually. This implies that past decisions might burden the future configurations, which in turn makes it more difficult to actually achieve the theoretical optimum. In this context, our found costs could be understood as lower bounds.

Market feasibility of the recommended solutions is another topic for the future. In general, the discussion of pricing mechanisms in fully renewable systems is very complex and incipient. Future power/storage companies will probably rely on incomes besides the energy market, for example from reserve markets or fuel security services. Even the energy market itself could suffer changes, evolving, for example, from marginal pricing of short-term costs to marginal pricing that include long-term costs (investment signals).

[16] For lower and upper bounds of battery costs (energy and power capacities), we used the *high development* and *low development* scenarios from [25] adapted to 2050 based on [248] . For hydrogen systems, we varied the power capacity cost by ±50% (relative to our originally assumed inputs) for all components except for the already-mature gas turbine (the energy capacity costs for methane storage was kept constant for the same reason). For pumped hydro, we assumed a cost range of ±10% for the power capacity. We assumed an independent uniform distribution for each cost input, and ran 150 simulations with Latin Hypercube Sampling.

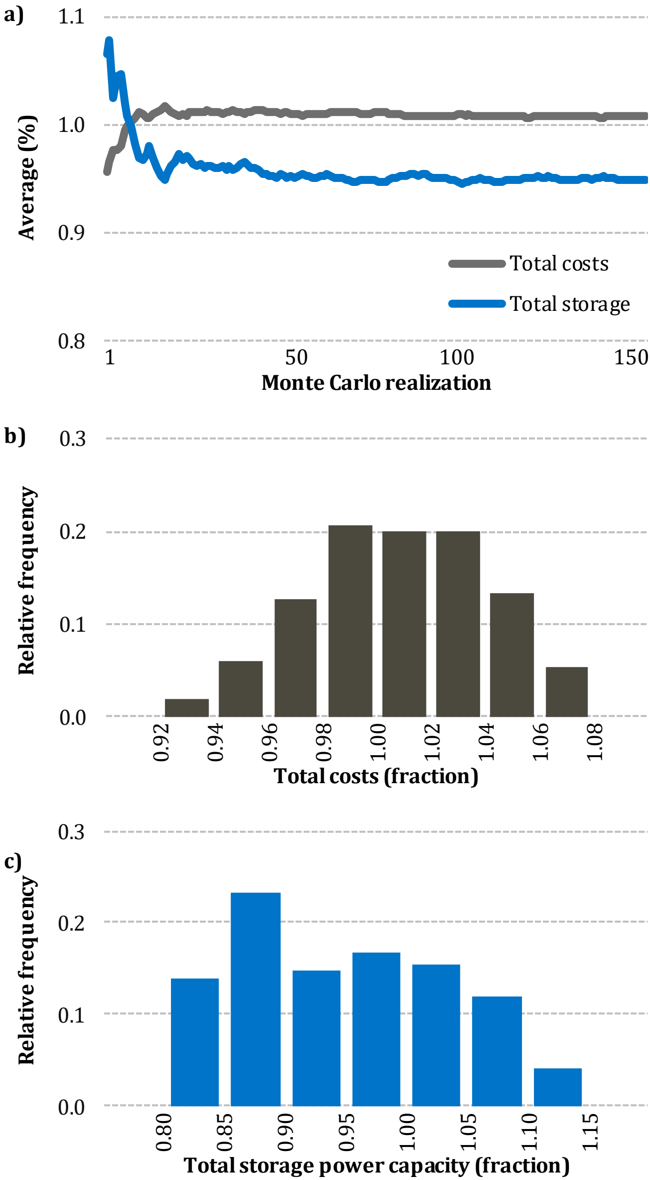

Fig. 25 Uncertainty quantification of results.

a) Convergence of Monte Carlo. b) Distribution of total energy costs.
c) Total storage power capacity.

5.4. Conclusions and policy implications

In this chapter, we developed a multi-objective framework for finding an optimal storage and renewable generation mix. We considered three criteria in the optimization, but more could be included. A first criterion considered was minimizing investment and operational costs of the power system. A second criterion referred to the environmentally friendly operation of hydropower reservoirs. Their extreme peaking was shown to be harmful to downstream ecosystems; thus, here we minimize the flashiness of the existing hydropower park. A third and final criterion aimed to minimize additional transmission systems as these are plagued by delays and cost overruns, frequently related to social opposition. In a case study that focuses on Chile in the year 2050, we illustrated the resulting tradeoffs between these three dimensions for a 100% renewable power supply.

From a traditional cost perspective only, the optimal storage mix is composed of PHS, BESS, and H_2 by shares of around 30%, 25%, and 45%, respectively, with a generation mix that has a solar-to-wind ratio of about 1.8. However, the system also relies on at least doubling the transmission lines and a severe ecological flashiness coming from hydropower plants. Once taking into account the other dimensions during the optimization, we could identify the following implications for the involved stakeholders of a power system.

5.4.1. Implications for storage companies

Compared to the pure minimum cost solution, the need for storage grows (up to 20%) when transmission and hydropower are more limited. This requirement is met by deploying more BESS, while PHS and H_2 remain quite constant in most scenarios. In short, storage companies celebrate if either (or both) transmission or hydropeaking are constrained.

5.4.2. Implications for transmission and generation companies

Additional transmission can be avoided for little economic effort; avoiding 30% of new transmission comes at almost no cost (<1%), and renouncing to all new transmission shows costs starting from 3% (depending on the level of hydropeaking). This is good news for planners and policymakers as they can concentrate on the development of transmission in less sensitive regions only. However, the upside for transmission companies is little. When additional transmission is constrained, the system relies more on local solar and storage. It is interesting that avoiding only 30% of transmission already creates a strong impulse towards solar generation. Possibly, both solar and storage companies will lobby against fully deploying transmission.

5.4.3. Implications for environmental organizations

Severe hydropeaking can be avoided for little extra cost (1%) if transmission helps in providing flexibility. If both transmission and hydropeaking are to be small, the cost increases are still limited (3%). The most extreme scenario is forbidding both;

costing up to 11% more. Affordable solar and battery systems appear to be the key enablers for achieving systems without hydropeaking nor new transmission facilities at such little extra costs. Environmental organizations cheer.

5.4.4. Overall policy implications

Altogether, the implications for policymakers are the following. Stronger rules for preserving sensitive freshwater systems below hydropower dams can be enforced at little additional cost. In parallel, new transmission projects can also be avoided for a small additional economic burden. This is enabled by the very affordable (projected) capital costs of solar and storage technologies, on which these solutions rely, for which a clear investment strategy is needed. Perceiving solar and storage systems as a mitigation measure to prevent hydropeaking and transmission could collaterally decrease the potential social opposition to storage technologies. The outlook for transmission companies might be cloudy, but solar generators, storage companies, and policymakers —and the fish— are looking forward to 2050.

5.4.5. Future work

In terms of future work, we identify the need for pathway planning (as opposed to static planning), as well as addressing the market feasibility of the recommended solutions. Furthermore, life-cycle emissions should be included, even for planning 100% renewable power systems, especially when needing to become carbon neutral or negative. In terms of externalities of hydropower, there are other aspects (e.g. social opposition) that may influence the deployment of new projects, and these should be looked at in the future. Also, the ecosystem impacts from hydropower could be detailed further.

5.5. Appendix

Table 14 Main investment decisions of extreme scenarios, per zone.
Numbers shown in GW (GWh in brackets).

Scn.	Component	Zone 1	Zone 2	Zone 3	Zone 4
Max. transmission Max. hydropeaking	BESS	-	-	0.4 (1)	6.5 (39)
	PHS	3 (60)	3 (60)	1.8 (40)	1.8 (40)
	H2	3.5 (2k)	2.4 (2.5k)	3.9 (0.8k)	3.2 (1.9k)
	Hydro (existing)	3.1 (9.8k)	3.1 (3.4k)	-	-
	Wind	9.4	0.0	13.4	4.1
	PV	0.0	22.4	7.8	19.4
	Transmission		L12: 2.3	L23: 3.2	L34: 0
Zero transmission Low. hydropeaking	BESS	-	4.8 (27)	-	6.7 (40)
	PHS	3 (60)	3 (60)	1.8 (40)	1.8 (40)
	H2	2.2 (1.3k)	5.2 (5.3k)	3 (0.7k)	2.4 (0.9k)
	Hydro (existing)	3.1 (9.8k)	3.1 (3.4k)	-	-
	Wind	6.0	7.5	9.5	3.6
	PV	2.5	30.0	3.4	20.0
	Transmission		L12: 0	L23: 0	L34: 0
Max. transmission Max. hydropeaking	BESS	-	-	1.2 (4)	6.7 (40)
	PHS	3 (60)	3 (60)	1.8 (40)	1.8 (40)
	H2	4.2 (3.2k)	1.9 (2.3k)	4 (0.9k)	3.1 (1.9k)
	Hydro (existing)	3.1 (9.8k)	3.1 (3.4k)	-	-
	Wind	10.2	0.0	16.7	4.1
	PV	0.0	18.8	10.9	19.8
	Transmission		L12: 1.8	L23: 5.2	L34: 0
Zero transmission Zero hydropeaking	BESS	-	6.1 (35)	-	6.7 (40)
	PHS	3 (60)	3 (60)	1.8 (40)	1.8 (40)
	H2	4.3 (3.1k)	4.6 (5.7k)	2.2 (0.6k)	2.2 (1.4k)
	Hydro (existing)	3.1 (9.8k)	3.1 (3.4k)	-	-
	Wind	8.4	9.3	9.1	3.6
	PV	2.9	30.0	4.2	20.1
	Transmission		L12: 0	L23: 0	L34: 0

Part III – Epilogue

Chapter 6. Conclusions

This chapter contains text fragments of my previous publications "Challenges and trends of energy storage expansion planning for flexibility provision in low-carbon power systems – a review", "How much Electrical Energy Storage do we need? A synthesis for the U.S., Europe, and Germany", "A multi-service approach for planning the optimal mix of energy storage technologies in a fully-renewable power supply", "Multi-objective planning of energy storage technologies for a fully renewable system: implications for the main stakeholders in Chile", and "Energy storage and transmission systems to save the fish? Minimizing hydropeaking for little extra-cost".

6.1. Introduction

The main objective of this thesis is to assist the transition to a power supply based on renewable energy sources by enhancing the estimation of energy storage requirements. Focusing on tools for storage expansion optimization, following overarching question will be answered: *how to plan the optimal energy storage mix for fully renewable power systems with important shares of hydropower?*

More specifically, the thesis aims to (1) shed light on current storage expansion approaches, (2) systemize existing storage recommendations, (3) extend current planning models by adding multi-services (beyond the conventional energy balance), and (4) develop a multi-objective decision-making framework for including other dimensions beyond costs.

Towards meeting these objectives, four contributions were presented, distributed in Chapters 2 to 5. These will be shortly recalled below (Section 6.2). Their conclusions are condensed in Section 6.3, in order to then draw the general conclusions in Section 6.4. The final part will outline the future work (Section 6.5).

6.2. Summary of contributions

<u>The first contribution</u> (Chapter 2) [2] provided the fundamentals of expansion planning with energy storage systems. It also reviewed about 90 journal publications involving storage expansion planning and classified them according to their modeling approaches. From this classification, trends in storage planning were identified, and the outstanding challenges derived. The obtained insights are relevant for energy system modelers.

<u>The second contribution</u> (Chapter 3) [246] analyzed the energy storage system (ESS) requirements arising from 17 recent storage expansion studies for the U.S., Europe, and Germany. Their recommendations were systemized in terms of storage needs per share of variable renewable energy sources (VRE) and generation mix. Furthermore, strong assumptions and outliers were discussed. Altogether this synthesis helps to provide clarity for policymakers and energy system modelers.

<u>The third contribution</u> (Chapter 4) [254] developed a tool for storage planning, called LEELO. It finds the storage types, sizes, and locations that minimize the system-wide investment and operational costs. Generation technologies and transmission lines can also be planned. LEELO's novelties include the endogenous modeling of power system services (extending the classical approach of using energy balance only). Concretely, power reserves and energy autonomy are included as mechanisms of coping with short-term and long-term forecast errors, respectively. A case study (Chile for the year 2050 with a 100% renewable power supply) compared how this multi-service planning differs from the conventional energy-based planning, in terms of total costs, overall storage investments, and individual storage sizes.

<u>The fourth contribution</u> (Chapter 5) [323] proposed a multi-objective framework for storage planning (with the optimization being based on LEELO). It considered three objectives: (1) minimizing investment and operational costs of the power system, (2) minimizing the hydrologic alteration in the rivers downstream of the existing hydropower park to reduce the ecosystem-harm, and (3) minimize additional transmission systems as these are plagued by delays and cost overruns,

frequently related to social opposition. The resulting tradeoffs between these three dimensions were illustrated in a case study on Chile, and systemized from a multi-stakeholder perspective, including transmission and generation companies, storage companies, and environmental organizations.

6.3. Summary of conclusions

The first contribution suggested five items when planning storage expansion: (1) to acknowledge the technological diversity of the many available storage devices; (2) to capture their complex lifetime and efficiency curves; (3) to use a high spatial and temporal resolution; (4) to recognize the multiple services that storage systems can provide; and (5) to plan with multiple energy sectors (as storage and flexibilities might readily be present in other energy sectors) [2]. The corresponding chapter culminated with the following recommendation: "*The planning of future energy systems will be multi-sectoral and multi-objective, consider the multi-services of ESS, and will inherently require interdisciplinary efforts*" [2]. Indeed, for the design of the optimization tool LEELO, these recommendations were taken into account. More precisely, items (1), (2), and (3) were implemented following the state of the art, whereas items (4) and (5) led to a formulation that extended the current body of knowledge by integrating multiple services and by including some aspects of the water sector (hydropeaking) —although other energy sectors were not considered—.

The second contribution showed that, with growing shares of VRE, the ESS power capacity increases linearly, while the ESS energy capacity grows exponentially. What also became clear is that systems based on solar photovoltaic call for more ESS, while large shares of wind rely more on transmission capacity. Furthermore, by analyzing the outliers of the considered studies, the following assumptions showed to have a particularly strong impact on storage sizing: forbidding energy curtailment and limiting the energy exchange between regions (i.e. assuming island operation) overestimates the need for storage, and not modeling the transmission grid with its possible bottlenecks (i.e. copper plate) underestimates the storage requirements. These findings were considered in the design of LEELO and the scenarios under study. Concretely, LEELO includes the existing grid, allows transmission expansion, and tolerates a certain amount of curtailment. All scenarios deal with 100% renewable systems, which is where storage requirements peak.

The third contribution revealed that the considered multi-services have a significant impact on the storage requirements and confirms that the generation technologies also highly impact storage requirements. In the future, it only seems natural that storage systems will offer power reserves (leave an operational margin in their converters) as answer of not having dispatchable generation and energy autonomy (leave some energy stored) in response to absent (long-term) fossil fuel storage. Acknowledging these services in the planning tools strongly conditions both the total storage requirements as well as the individual storage technologies. Ignoring these services implies recommending suboptimal system configurations, which may be subject to additional unexpected costs, such as ex-post modifications for upgrades to meet the required service levels.

The fourth contribution found that the cost-optimal solution requires the existing transmission to be doubled and strongly relies on flexibility from the hydropower reservoirs, making them operate in such severe hydropeaking schemes that the downstream water bodies are far from the natural flow regime. After taking into account the other two dimensions during the optimization, the multi-objective framework provided evidence that sensitive freshwater systems downstream of hydropower dams can be protected at little extra economic burden. In parallel, new transmission projects can also be avoided for a low additional cost. Cheap (future) solar and storage technologies are the main enablers for achieving solutions with low hydropeaking and little new transmission lines at such low costs. For this to happen, a clear investment strategy is needed.

6.4. Overall discussion

To put the found storage sizes for Chile into the larger context of other studies and power systems, recall the reanalysis of storage requirements from Chapter 3; more precisely Fig. 14 about the storage capacities for the U.S. and Europe. For making a comprehensive comparison, the storage power capacities will now be normalized by the peak energy demand, and the storage energy capacities by the annual energy demand (of each power system). This results in Fig. 26, where subplot a and b show the storage power capacities and storage energy capacities, respectively. The triangles correspond to scenarios from the U.S. and Europe, where the color code from red to dark grey indicates systems going from solar-dominated to wind-dominated (following the definition presented in Chapter 3). In addition, a few selected scenarios for Chile are plotted with crosses[17], which will be detailed shortly after a few words on the general storage requirements.

What becomes clear for the U.S. and Europe, for renewable shares close to 100%, is that the recommended storage power capacity culminates in solar-based scenarios around 40–75% of the peak demand. Most found scenarios for Chile exceed this range (with the exception of the minimum cost solution that, as mentioned earlier, relies on doubling transmission, strong hydropeaking, and provides no services). These larger storage requirements for Chile can be explained by its rather small power system (peak demand in the year 2050 around 30 GW) without interconnections to neighboring countries, whereas Europe and the U.S. are massive systems (peaks around 700 and 600 GW) with meshed grids spanning over wide territories. Furthermore, Chile is a slim country, meaning that generation resources are highly correlated (e.g. the sun rises at very similar times throughout the country). The case of the demand is similar (e.g. most of the people wake up at the same time, contrasted with the four time zones of the U.S.).

[17] Note that, with exception of the two marked scenarios, we chose to plot results from Model B (i.e. without the multiple services) to make a fair comparison with other existing studies that do not account for such services.

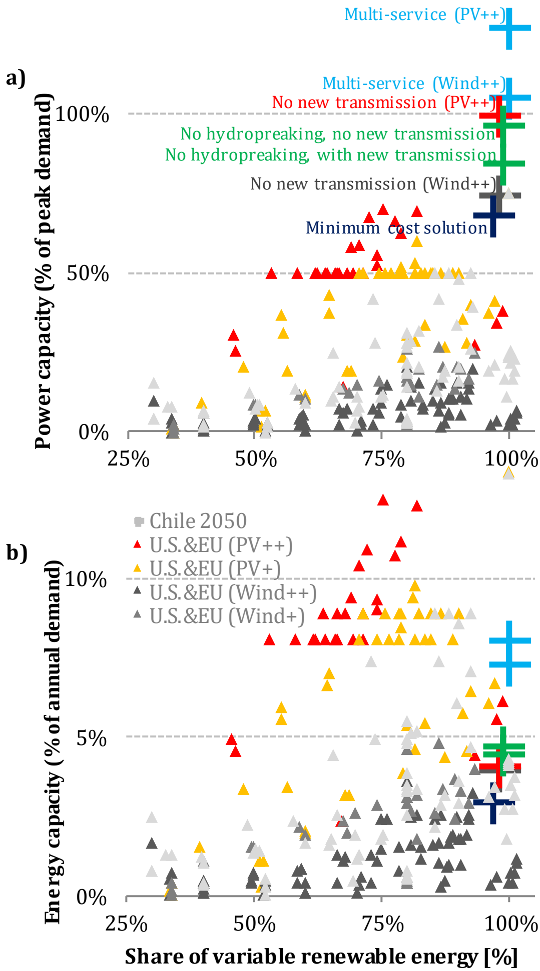

Fig. 26 Comparison of recommended ESS sizes (U.S., E.U., and Chile)

a) Power capacity (normalized by peak demand), b) Energy capacity (normalized by annual demand). Note that for Chile (crosses), only selected scenarios were chosen and that these are all 100% renewable scenarios but plotted with a slight displacement on the x-axis for the ease of display.

As what refers to energy capacities, for the U.S. and Europe storing between 5 and 13% of the annual demand is recommended for solar-based grids, while these requirements could be much lower for wind-based mixes. The attained numbers for Chile, 3–7%, seem to be lower than the other studies considered here. However, Chile's existing hydropower reservoir already provides a buffer of 6%, which situates the total need for energy capacity between 9 and 13%.

In terms of the more specific scenarios for Chile, the lowest storage (power and energy) capacities are obtained when cost is the only optimization target while transmission is expanded (dark blue cross). Without transmission expansion, the power capacities increase slightly if wind generation is preferred (grey cross) and strongly if solar is the main energy source (red-cross). For these two cases, the energy capacities also grow but are more similar to each other. The power capacities of the scenarios when hydropeaking is minimized (green crosses) are clearly above the minimum storage solution but located between the two former (red and grey crosses). In other words, avoiding hydropeaking does increase the need for power capacities, but not beyond the uncertainty coming from the generation mix. In terms of energy, mitigating hydropeaking calls for slightly larger capacities, related to the loss of flexibility in the water use. Finally, the multi-service planning approach (light blue crosses) shows an extreme demand for both power and energy capacities. Values above the peak demand might seem odd at first sight but have two explanations. First, it might simply be the cost (and the necessary infrastructure) for being energy autonomous and secure. In fact, a share of that capacity corresponds to gas turbines (power-to-gas-to-power), which already today serve as a backup and exceed peak demand. And second, this overcapacity can also be interpreted as new infrastructure that (while idle) is potentially serving other energy sectors (e.g. solar fuel production). What becomes crystal-clear for Chile, as long as no interconnections with neighboring countries exist, is that all considered futures strongly rely on storage.

Back to the main question, "*how to plan the optimal energy storage mix for fully renewable power systems with important shares of hydropower?*", it became evident that multi-services, multi-sectors, and multi-objective approaches are needed and that they have a strong impact on the final investment recommendations. This thesis took a first step in that direction. Two detailed extensions (multi-service, multi-objective) when planning storage determined a higher need for these technologies. For storage companies, the future looks bright.

6.5. Outlook

In this final section of the thesis, six future lines of research are identified to overcome the current limitations:

- Environmental aspects: The scenarios (in Chapters 4 and 5) all revealed a large demand for storage. Manufacturing such amounts of storage might, however, generate considerable environmental impacts. There are diverse emissions, which, from a lifecycle perspective, are not negligible (but smaller than those from fossil fuels), as well as toxic components that arise after the end-of-life of storage facilities. Additionally, material availability is a concern for some technologies, for example Molybdenum in Li-ion batteries.

Including these aspects in a broader multi-objective decision-making process will be addressed soon.

- Hydropeaking: The multi-objective optimization (in Chapter 5), aiming to (also) mitigate hydropeaking, used one system-wide hydrological flashiness index as a proxy for measuring the ecological health of all rivers. This is a clear simplification and calls for more precise metrics in the future. Moreover, the found system costs are sensitive when this index approaches zero, which underlines the relevance of better understanding a meaningful threshold.
- Multi-energy sectors: This thesis focused on the electricity sector. However, recognizing the flexibility (sometimes readily available) in the heat, transport, and water sector is becoming ever more relevant in the transition to fully renewable power systems. Evidently, multi-energy planning is a necessary improvement to which international research has caught on during the last two years. But only considering the *advantages* of the different energy sectors does not paint the whole picture. There are social and environmental externalities which need to be tackled (see the above environmental aspects and hydropeaking).
- Multi-services: The developed optimization tool (in Chapter 4) included power reserves and energy autonomy as two new services to storage planning. The definition of the *level* of these services is both a technical decision (i.e. how much errors do or will our forecast tools have?) as well as a political one (i.e. how many days, weeks, or months does each region strive to be energy independent to affront situations of crisis —no matter if natural or geopolitical ones—). As a first step, different service-levels were assessed in scenarios. Furthermore, different types of services, beyond the ones considered here, could arise in the future (e.g. environmental services or resilience). Refining the service level, types, and alternative formulations are left as future work.
- Regional scope: While international research puts strong efforts on assessing the energy transition for developed countries, studies for emerging regions are scarce. In fact, this thesis provided the first 100% renewable scenario for Chile. An evident future direction is to provide such assessments for all countries that have not been evaluated yet. In parallel, energy systems around the globe are continuously becoming more interconnected (e.g. transmission lines and fuel markets), which calls for models with a wider regional scope, for example Latin America, the Americas, and, and —why not? — the globe.
- Uncertainties: Beyond the above-outlined limitations (which all inherently reflect uncertainty), there are other sources of uncertainties that remain unresolved. The forecast errors of renewables have been (indirectly) addressed in this thesis via the multiple-services (in Chapter 4) but could also be addressed directly with formal stochastic formulations. Furthermore, there are well-known issues inherent to planning future systems, among which the most important are the projections of investment costs and projections of energy demand. Especially the costs for hydrogen systems, which today are on a very incipient level of deployment, seem to be particularly uncertain. And the future electricity demand strongly depends on the success of electromobility, including deployment, charging strategies, and car-sharing.

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