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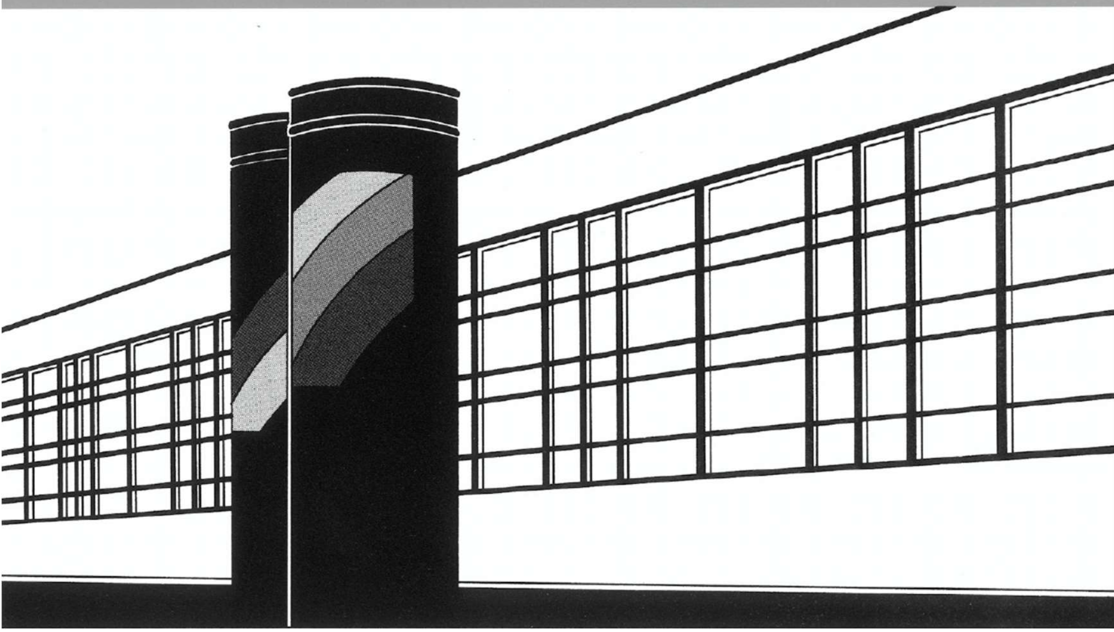

Heft 291 Simón Moreno Leiva

Optimal Planning of Water and Renewable Energy Systems for Copper Production Processes with Sector Coupling and Demand Flexibility

Optimal Planning of Water and Renewable Energy Systems for Copper Production Processes with Sector Coupling and Demand Flexibility

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Dedication and Acknowledgments

To my wife, Marce. Thank you for always being there for me.

A special thank you to the scientists who saw the scientist in me even before I did, Jannik Haas, Ludger Eltrop, Rodrigo Palma, and Willy Kracht. Also big thanks to the researchers who helped me find my way when the forest was getting hard to navigate, Wolfgang Nowak (the best supervisor one could wish for), and Christian Breyer. I also thank Felipe Valencia and Tobias Junne for the joint work and the effort invested in our research. Thank you to all my colleagues and friends who devoted time to discussing science. Working with you all has been amazing and you helped me improve and find my path as a scientist.

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List of acronyms

CAPEX	Capital expenditures
CSP	Concentrated Solar Power
DSM	Demand-Side Management
GWP	Global Warming Potential
IPHRO	Integrated Pumped Hydro Reverse Osmosis
LEELO	Long-term Energy Expansion Linear Optimization model
LCA	Life Cycle Assessment
MILP	Mixed-Integer Linear Programming
OPEX	Operational expenditures
PV	Photovoltaics
RE	Renewable Energy
RO	Reverse osmosis
tCu	Ton of copper

Variables in order of appearance

fC	Flow of converted vectors
η_c	Efficiency of the conversion technology
S	Storage level
lS	Losses in the storage
fT	Flow of transported vectors
d	Inelastic demand
fG	Electricity generation at fossil power plants
d^{wt}	Electricity demand for water transport
fR	Electricity generation from renewable sources
pR	Installed capacity of renewable energy technologies
eS	Energy capacity of the storage technology
pG	Installed capacity of fossil power plants
pC	Installed capacity of conversion technologies
pT	Installed capacity for inter-nodal transport
cC	Capital costs of technologies
oC	Fixed operational costs
vC	Variable operational costs

Nomenclature for scenarios in chapter 5

C100	Scenario considering reference process costs (Chapter 5)
C75	Scenario considering 25% reduced process costs (Chapter 5)
C50	Scenario considering 50% reduced process costs (Chapter 5)
T1	Technological scenario that does not consider seawater-PHES (Chapter 5)
T2	Technological scenario that considers seawater-PHES (Chapter 5)

Abstract

As the global energy transition advances, new tools are required that conceive a fully renewable future. This work is devoted to advancing methods for designing fully renewable energy systems that consider multiple forms of energy (multi-vector) and water for industrial processes. In particular, for the copper industry. This industry is intensive in the use of energy (with its subsequent emissions) and water, and it is often located in arid regions, where water is scarce but solar irradiation is abundant. Also, copper is especially relevant for the energy transition as renewables are more copper-intensive than conventional electricity generation technologies. Additionally, this metal is required for the electrification of other sectors, such as transport.

This thesis aims to elucidate the following question: *How should we plan the water and energy systems for the copper production of the future to be fully renewable and to use no freshwater?* Accordingly, it is structured around four contributions that offer insights into this question:

<u>First contribution</u> [1]: Current methodological approaches for renewable energy systems design in the copper industry are analyzed and complemented with learnings from applications in other fields. Six topics are identified where future research should focus:

- Energy demand modeling should be improved in terms of final uses and factors that determine it, among others.
- Mathematical models for systems design need to go beyond electricity to include other forms of energy.
- Water management should be integrated into planning models, especially when mines are in arid regions where desalination is required.
- Operational measures to implement demand-side management in existing operations should be further investigated.
- The potential for energy demand flexibility in the industry should be considered already at the design phase of future capacity for copper production.
- A comprehensive assessment of the environmental implications along the entire lifecycle of the proposed systems is recommended.

<u>Second contribution</u> [2]: The adoption of solar electricity at seven copper mines in different regions in the world is analyzed until 2050, and the tradeoff between increasing energy demand (due to the depletion of resources) and declining costs of solar electricity generation and storage is assessed. For this, the LEELO (long-term energy expansion linear optimization) model is employed. The results indicate that the cost-optimal electricity supply of mines located in sunny regions goes almost fully solar already by 2030. Moreover, low-cost solar electricity is expected to offset the effect of ore grade decline in the specific costs of electricity. This compensation effect is more favorable in copper-producing countries located in sunny regions, like Peru and Chile.

<u>Third contribution</u> [3]: Optimal water- and energy-systems designs are calculated for supplying desalinated water and the complete energy needs for a copper production process. For this, methods for planning water and energy systems are

advanced. In particular, a new version of the existing LEELO model is developed, to allow for planning multi-vector systems, including desalinated water, heat at different temperatures, and hydrogen. In addition, the model endogenously includes a concept for integrated pumped-hydro storage using seawater and reverse osmosis desalination (IPHROS). The results indicate that already at today's costs, fully renewable energy systems are economically attractive. When IPHROS is included, the tipping point when a fully renewable supply is the least-cost option happens ten years earlier, as soon as 2030.

Fourth contribution [4]: The potential for capacity-based energy demand flexibility in copper production (i.e. oversizing the processes) is assessed and projected until 2050. For this, the LEELO model is further developed again to consider the endogenous sizing of production processes (at single-stage resolution). This allows identifying the operations in a production process with the most potential for capacity-based demand flexibility. The results show that the operations of concentration and electrorefining offer demand flexibility in the cost-optimal setup. At current costs, implementing capacity-based demand flexibility results in a 5-12% reduction in the costs of a fully renewable energy supply. The economic benefits of capacity-based flexibility decrease over time is the costs of renewable energy generation and storage keep on lowering as expected.

Going back to the overarching research question, the design of renewable energy systems for copper production should:

- consider the multiple uses of energy, for example by endogenously integrating the different energy vectors in the planning model,
- include integrated systems for seawater pumped-hydro energy storage with reverse osmosis desalination,
- and include demand flexibility from the copper industry in the operation of the corresponding energy systems.

With these considerations in mind, the copper industry could be profiting from an energy supply that is cheap and fully renewable already in the next decade.

Rapid deployment of technologies that enable the use of renewable energy vectors (such as electro-trucks) is required for the copper industry to profit from this opportunity. Future research should search for other alternatives to implement operational flexibility (beyond the capacity-based options here considered) and investigate the role of the flexibility of the copper industry in larger regional energy systems. Also, regarding sector-coupled energy systems in general, IPHRO should be considered in the planning methods. At last, feeding copper (and other relevant materials for the energy transition) processes with renewable energy is not enough for a fully sustainable future. Indeed, many other social and environmental impacts of mining are fully independent of its energy supply. Relevant questions arise: whose needs are copper and the energy systems that it constitutes satisfying? How is the current prioritization of these needs consistent with a principle of reduced inequalities? This opens the door for an analysis in terms of economic and environmental justice.

Kurzfassung

Angesichts der fortschreitenden globalen Energiewende werden neue Modelle benötigt, die eine vollständig erneuerbare Zukunft vorsehen. Diese Arbeit befasst sich mit der Weiterentwicklung von Methoden für die Gestaltung vollständig erneuerbarer Energiesysteme, die mehrere Energieformen (Multivektor) und Wasser für industrielle Prozesse berücksichtigen. Insbesondere für die Kupferindustrie. Diese Industrie ist energie- (und damit emissionsintensiv) und wasserintensiv und befindet sich häufig in Trockengebieten, in denen Wasser knapp, Sonneneinstrahlung aber reichlich vorhanden ist. Kupfer ist für die Energiewende besonders relevant, da erneuerbare Energien kupferintensiver sind als konventionelle Stromerzeugungstechnologien. Darüber hinaus benötigen wir dieses Metall für die Elektrifizierung anderer Sektoren, wie z. B. des Verkehrs.

Ziel dieser Arbeit ist es, die folgende Frage zu klären: Wie sollten wir die Wasser- und Energiesysteme für die Kupferproduktion der Zukunft planen, damit sie vollständig erneuerbar sind und kein Süßwasser verbrauchen? Diese Arbeit gliedert sich in vier Beiträge, die Einblicke in diese Frage bieten:

Erster Beitrag [1]: Aktuelle methodische Ansätze für die Planung von Systemen zur Nutzung erneuerbarer Energien in der Kupferindustrie werden analysiert und mit Erkenntnissen aus Anwendungen in anderen Bereichen ergänzt. Es werden sechs Themen identifiziert, auf die sich die zukünftige Forschung konzentrieren sollte:

- Die Energienachfragemodellierung sollte u.a. im Hinblick auf die Endnutzung und die sie bestimmenden Faktoren verbessert werden.
- Die Modelle müssen über die Elektrizität hinausgehen und auch andere Energieformen einbeziehen.
- Das Wassermanagement sollte in die Planungsmodelle integriert werden, insbesondere wenn sich die Minen in Trockengebieten befinden, in denen eine Entsalzung erforderlich ist.
- Betriebliche Maßnahmen zur Umsetzung der Nachfragesteuerung in bestehenden Betrieben sollten weiter untersucht werden.
- Das Potenzial für eine flexible Energienachfrage sollte bereits in der Planungsphase künftiger Kapazitäten für die Kupferproduktion berücksichtigt werden.
- Eine umfassende Bewertung der Umweltauswirkungen während des gesamten Lebenszyklus der vorgeschlagenen Systeme wird empfohlen.

Zweiter Beitrag [2]: Der Einsatz von Solarstrom in sieben Kupferminen in verschiedenen Regionen der Welt wird bis zum Jahr 2050 betrachtet, und das Tradeoff zwischen steigendem Energiebedarf (aufgrund sinkender Erzqualitäten) und sinkenden Kosten der Solarstromerzeugung und -speicherung wird bewertet. Hierfür wird das LEELO-Modell (long-term energy expansion linear optimization) verwendet. Die Ergebnisse zeigen, dass die kostenoptimale Stromversorgung von Bergwerken in sonnenreichen Regionen bereits bis 2030 fast vollständig auf Solarstrom umgestellt wird. Darüber hinaus wird erwartet, dass kostengünstiger Solarstrom die

Auswirkungen des Rückgangs der Erzqualität auf die spezifischen Stromkosten ausgleicht. Dieser Kompensationseffekt ist in kupferproduzierenden Ländern, die in sonnenreichen Regionen liegen, wie Peru und Chile, am stärksten ausgeprägt.

Dritter Beitrag [3]: Es werden optimale Systemdesigns für die Versorgung von entsalztem Wasser und den gesamten Energiebedarf für einen Kupferproduktionsprozess berechnet. Hierfür werden Methoden zur Planung von Wasser- und Energiesystemen weiterentwickelt. Insbesondere wird eine neue Version des bestehenden LEELO-Modells entwickelt, um die Planung von Multivektorsystemen zu ermöglichen, die entsalztes Wasser, Wärme bei verschiedenen Temperaturen und Wasserstoff umfassen. Darüber hinaus beinhaltet das Modell endogen ein Konzept für integrierte Pumpspeicherkraftwerke mit Meerwasser und Umkehrosmose-Entsalzung (IPHROS). Die Ergebnisse zeigen, dass vollständig erneuerbare Energiesysteme bereits zu den heutigen Kosten wirtschaftlich attraktiv sind. Wenn IPHROS einbezogen wird, tritt der Wendepunkt, an dem eine vollständig erneuerbare Energieversorgung die kostengünstigste Option ist, zehn Jahre früher ein, nämlich bereits im Jahr 2030.

Vierter Beitrag [4]: Das Potenzial für kapazitätsbasierte Energienachfrageflexibilität in der Kupferproduktion (d.h. Überdimensionierung der Prozesse) wird abgeschätzt und bis 2050 projiziert. Hierfür wird das LEELO-Modell erneut weiterentwickelt, um die endogene Dimensionierung von Produktionsprozessen in einstufiger Auflösung zu berücksichtigen. Auf diese Weise können die Operationen in einem Produktionsprozess mit dem größten Potenzial für kapazitätsbasierte Nachfrageflexibilität identifiziert werden. Die Ergebnisse zeigen, dass die Vorgänge der Konzentration und der Elektroraffination im kostenoptimalen Setup Nachfrageflexibilität bieten. Bei den derzeitigen Kosten führt die Umsetzung kapazitätsbasierter Nachfrageflexibilität zu einer Senkung der Kosten für eine vollständig erneuerbare Energieversorgung um 5-12 %. Die wirtschaftlichen Vorteile der kapazitätsbasierten Flexibilität nehmen mit der Zeit ab, wenn die Kosten für die Erzeugung und Speicherung erneuerbarer Energien wie erwartet weiter sinken.

Um auf die übergreifende Forschungsfrage zurückzukommen, sollte die Gestaltung von Systemen zur Nutzung erneuerbarer Energien für die Kupferproduktion:

- die vielfältigen Verwendungsmöglichkeiten von Energie berücksichtigen, zum Beispiel durch endogene Integration der verschiedenen Energievektoren in das Planungsmodell,
- integrierte Systeme zur Speicherung von Meerwasser-Pumpenergie mit Umkehrosmose-Entsalzung einbeziehen,
- und Einbeziehung der Nachfrageflexibilität der Kupferindustrie in den Betrieb der entsprechenden Energiesysteme.
- Unter Berücksichtigung dieser Überlegungen könnte die Kupferindustrie bereits im nächsten Jahrzehnt von einer kostengünstigen und vollständig erneuerbaren Energieversorgung profitieren.

Damit die Kupferindustrie von dieser Chance profitieren kann, ist eine rasche Einführung von Technologien erforderlich, die die Nutzung erneuerbarer Energievektoren (wie z. B. Elektro-LKW) ermöglichen. Künftige Forschungsarbeiten sollten nach anderen Alternativen zur Umsetzung betrieblicher Flexibilität (über die hier betrachteten kapazitätsbasierten Optionen hinaus) suchen und die Rolle der Flexibilität der Kupferindustrie in größeren regionalen Energiesystemen untersuchen. Auch im Hinblick auf sektorgekoppelte Energiesysteme im Allgemeinen sollte IPHRO bei den Planungsmethoden berücksichtigt werden. Schließlich reicht es für eine vollständig nachhaltige Zukunft nicht aus, Kupfer (und andere für die Energiewende relevante Materialien) mit erneuerbarer Energie zu versorgen. In der Tat sind viele andere soziale und ökologische Auswirkungen des Rohstoffabbaus völlig unabhängig von seiner Energieversorgung. Es stellen sich wichtige Fragen: Wessen Bedürfnisse werden durch Kupfer und die damit verbundenen Energiesysteme befriedigt? Wie ist die derzeitige Priorisierung dieser Bedürfnisse mit dem Prinzip der Verringerung von Ungleichheiten vereinbar? Dies öffnet die Tür für eine Analyse unter dem Aspekt der wirtschaftlichen und ökologischen Gerechtigkeit.

Chapter 1. Introduction

This chapter contains text fragments of my previous publications:

"*Renewable energy in copper production: a review on systems design and methodological approaches*" by Simón Moreno-Leiva, Jannik Haas, Tobias Junne, Felipe Valencia, Hélène Godin, Willy Kracht, Wolfgang Nowak, and Ludger Eltrop, published in the *Journal of Cleaner Production* in 2020.

"*Copper mining: 100% solar electricity by 2030?*" by Jannik Haas, Simón Moreno-Leiva, Tobias Junne, Po-Jung Chen, Giovanni Pamparana, Wolfgang Nowak, Willy Kracht, Julián M. Ortiz, published in the *Applied Energy Journal* in 2020. My focus in this publication was the investigation of the tradeoff between ore grade decline and declining costs of solar energy generation and storage.

"*Integration of seawater pumped storage and desalination in multi-energy systems planning: the case of copper as a key material for the energy transition*" by Simón Moreno-Leiva, Jannik Haas, Wolfgang Nowak, Willy Kracht, Ludger Eltrop, Christian Breyer, published in the *Applied Energy Journal* in 2021.

"*Flexible copper: exploring capacity-based energy demand flexibility in the industry*" by Simón Moreno-Leiva, Jannik Haas, Wolfgang Nowak, Willy Kracht, Ludger Eltrop, Christian Breyer. To be submitted.

1.1. Motivation and relevance

Producing the materials and services that humanity requires has an impact on the environment. Energy needs are no exception, and its supply is indeed responsible for around three-quarters of global greenhouse gas emissions driving climate change [5,6]. To mitigate their climate impacts, energy systems are transitioning towards renewables-based generation [7]. Also, building this infrastructure will push the demand for certain raw materials, specifically that of copper [8]. The production of this metal is energy-intensive [9][10] —with the subsequent emission of greenhouse gases—and it often takes place in arid regions [11]. In this context, supplying copper production processes exclusively with renewable energy and desalinated seawater could be an alternative to reduce the environmental impact of the material supply for the global energy transition.

Renewables-based power systems are technically feasible and economically viable [12]. Also, there are different alternatives to balance out variable renewable generation from solar power and wind. These alternatives include energy transmission, demand and supply flexibility, storage, and sector coupling [13]. The latter means to integrate the planning of further energy-relevant sectors beyond electricity, such as transportation and heating. When considering different forms of energy, this is often referred to as multi-energy or multi-vector systems [14]. Moreover, the water sector (more specifically, the desalination sector) has also been considered in sector-coupled energy planning [15]. From an energy-systems modeling perspective, it is interesting to integrate different flexibility alternatives in the models so that an optimal combination can be found, as discussed in a recent review of the field of renewable energy systems planning [16]. This work aims at contributing to the existing body of knowledge in that direction, by combining the flexibility from the multi-vector approach, the water sector, and the demand-side into one optimization framework for energy systems planning applied to the copper industry. The smarter the systems designs our planning tools let us achieve, the closer we will be to a much-needed fast transition towards cleaner methods to satisfy humanity's needs for energy and materials.

1.2. Goals and research questions

The overarching goal of this work is to assist in the decision-making process for planning water and energy supply systems that operate within the ecological boundaries that guarantee a sustainable future. In particular, with attention to the water and energy needs in the copper industry and the exclusive use of renewable energy sources and desalinated water. With this, a global research question of this thesis can be formulated:

How should we plan the water and energy systems for the copper production of the future to be fully renewable and to use no freshwater?

To answer these questions, four specific goals -with their corresponding research questions- are considered in this work:

(1) Several methodological approaches for the design of renewable energy systems for copper production can be found in the literature. Moreover, relevant lessons can be learned when considering approaches from the broader and rich field of energy systems planning. Thus, the **first specific goal** is to understand the existing body of knowledge on renewable energy integration in copper mining and draw lessons from the literature on energy systems design for industrial, local, and regional energy systems. The corresponding research question is:

What are the existing approaches for energy system planning in copper production and what can we learn from energy planning in other fields?

(2) The performance of renewable energy systems depends on their location, as the availability of renewable resources like wind and solar irradiation varies across the geography. Additionally, the energy requirements of copper production increase with the depletion of resources in different regions. Thus, the **second specific** goal is to elucidate geographical tradeoffs between mineral depletion and climate in the design of solar power systems for some of the world's main copper mines. The corresponding research question is:

How does the location and age of copper mines around the world impact the timing and costs of solar power adoption?

(3) Existing approaches for industrial energy systems planning, in particular those in copper production processes, often neglect sectors other than electricity and focus on specific operations rather than considering the whole production process. Specifically, the integrated planning of a system for water and (multi-)energy supply for copper production is not observed in the literature. Thus, the **third specific goal** of this thesis is to develop a method for the integrated planning of cost-effective desalinated water and multi-vector industrial energy systems, applied to the case of copper. The corresponding research question is:

How to plan fully renewable and multi-vector energy-water systems and how would that system look like for a copper production process?

(4) Industrial processes can be flexible in their operation so that their energy demand better matches the availability of renewable energy sources. This way, highly renewable energy systems could complement other flexibility sources—such as storage and transmission—and achieve lower costs for 100% renewable configurations. Thus, the **fourth specific goal** is to analyze the potential of energy demand flexibility in the copper industry in a fully renewable multi-energy system. In particular, the flexibility from oversizing the capacity of the process (capacity-based). The corresponding research question is:

What is the effect of capacity-based energy demand flexibility of copper production processes on the cost-optimal design of a fully renewable energy supply for this industry?

Answering these questions is expected to shed light on strategies for a smarter and faster energy transition, especially in the copper industry. The four questions are addressed in independent chapters along this thesis. The structure and the approach of the analysis are explained in the next subsection.

1.3. Approach and outline

Addressing the research questions presented above will require different approaches. A detailed description of the implemented methods is available in corresponding chapters. This thesis is structured in 6 chapters. Chapters 2 to 5 address research questions one to four. The work is structured divided in parts regarding the methodological scope. In part I (chapters 2 and 3) a literature review is conducted, and an existing model is applied. In part II (chapters 4 and 5), the model is further developed to enable new capabilities. The aims and contents of the different chapters are explained in the following. Figure 1 summarizes the contents and structure of this work.

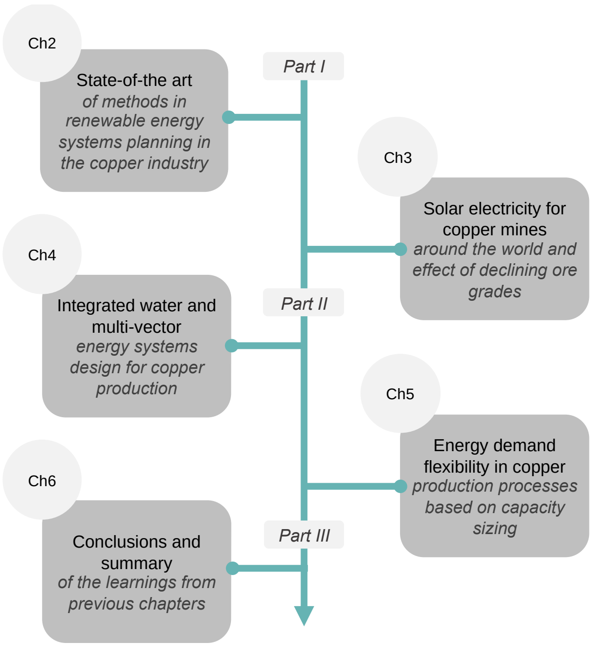

Figure 1: Overview of contents and structure of this work

- **Chapter 2: Understanding the state of the art and identifying challenges**
  In this chapter, I explore the existing methodological approaches towards the design of renewable energy systems in the copper industry. The analysis is complemented with learnings from the exploration of approaches in energy system designs with a broader scope: from local systems for industrial processes to large-scale interconnected systems. I propose a theoretical framework for the classification and analysis of methods to allow for a systematic review of the existing body of knowledge. The focus of the following chapters is based on the scientific gaps and challenges derived from this review.

- **Chapter 3: Solar power adoption for copper mines around the world**
  In this chapter, the cost-optimal adoption of a fully solar power supply over time is compared for copper mines around the world, based on regional differences in solar irradiance and using the LEELO[1] model [17]. Later, I compare this effect against the increase in energy demand for copper production as a result of resource depletion and decreasing concentration in the minerals. This way, I can shed light on the potential of the decreasing costs of solar energy to compensate for aging mines in different regions of the world.

- **Chapter 4: Integrated design of water and multi-energy systems applied to copper**
  In this chapter, a method for planning integrated energy and water systems is presented. This is an extension of LEELO where the supply of multiple energy vectors is considered, such as hydrogen, electricity, and heat. The first fully renewable designs for desalinated water and energy systems in copper production are proposed and the evolution of the cost-optimal configuration is projected up to 2050. I endogenously include in the optimal energy planning model an integrated concept for reverse osmosis desalination and energy storage using seawater pumping. This part of the work helps in understanding the technical feasibility and economic viability of fully renewable water and energy supply for copper production, as well as identifying relevant technologies and the expected evolution of systems.

- **Chapter 5: Exploring energy demand flexibility in the copper industry**
  In this chapter, the effects that different degrees of capacity-based energy demand flexibility in the copper industry have on the costs of fully renewable systems are assessed. I consider the endogenous sizing of components of the production processes at single-stage resolution within an optimization model for planning the required energy system, further extending LEELO.

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[1] Long-term Energy Expansion Linear Optimization

- **Chapter 6: What have we learned?**
  The last chapter of this dissertation summarizes the main learnings of the dissertation and it offers recommendations for further research on the field, as well as final reflections on the broader implications of the work presented in this thesis.

Part I – Analysis of the literature and exploration of solar electricity adoption

Chapter 2. Approaches and methods in energy systems planning for the copper industry

This chapter is based on the publication "*Renewable energy in copper production: a review on systems design and methodological approaches*" by Simón Moreno-Leiva, Jannik Haas, Tobias Junne, Felipe Valencia, Hélène Godin, Willy Kracht, Wolfgang Nowak, and Ludger Eltrop, published in the *Journal of Cleaner Production*. This chapter also contains fragments of my previous publication "Integration of seawater pumped storage and desalination in multi-energy systems planning: the case of copper as a key material for the energy transition" by Simón Moreno-Leiva, Jannik Haas, Wolfgang Nowak, Willy Kracht, Ludger Eltrop, Christian Breyer, published in the *Applied Energy Journal* in 2021.

Executive summary

Renewable energy systems are now accepted to be mandatory for climate change mitigation. These systems require a higher material supply than conventional ones. Particularly, they require more copper. The production of this metal, however, is intensive in energy consumption and emissions. Therefore, renewable energy systems must be used to improve the environmental performance of copper production.

We cover the current state of research and develop recommendations for the design of renewable energy systems for copper production. To complement our analysis, we also consider studies from other industries and regional energy systems.

We provide six recommendations for future modeling: (a) current energy demand models for copper production are overly simplistic and need to be enhanced for planning with high levels of renewable technologies; (b) multi-vector systems (electricity, heat, and fuels) need to be explicitly modeled to capture the readily available flexibility of the system; (c) copper production is done in arid regions, where water supply is energy-intensive, then, water management should be integrated in the overall design of the energy system; (d) there is operational flexibility in existing copper plants, which needs to be better understood and assessed; (e) the design of future copper mines should adapt to the dynamics of available renewable energy sources; and (f) life cycle impacts of the components of the system need to be explicitly minimized in the optimization models.

Researchers and decision-makers from the copper and energy sector will benefit from this comprehensive review and these recommendations. We hope it will accelerate the deployment of renewables, particularly in the copper industry.

2.1. Introduction

Keeping global warming under 1.5°C is required to limit the impact of climate change [18]. For this, global energy systems need to adopt increasingly high shares of renewables [16] and this transition will drive the demand for the required raw materials, like copper. On the one hand, this metal is required for expanding electrical power transmission and new generation technologies [8]. Indeed, inventories show that the specific copper requirement (per unit of energy generated) is higher for wind and photovoltaic (PV) power generation than for conventional technologies [19]. On the other hand, the production of this metal is energy-, water-, and emissions-intensive [10]. As resources are depleted (decreasing ore grades), the specific energy demand and subsequent emissions per produced unit of copper increase [20]. The most extreme scenario we found in the literature estimates the energy demand for copper production at 2.4% of the global energy demand by 2050 [21]. Consequently, to make the energy transition itself a cleaner process, copper production needs to improve its environmental footprint and integrating renewable energy is a means to do so.

The use of renewable energy (RE) in the copper industry is not new. For example, there are power purchase agreements (energy contracts) for renewable electricity supply (e.g. wind power for the *Los Pelambres* copper mine in Chile [22]). Solar heat plants are also in use, such as the *Pampa Elvira Solar* flat plate collector plant which supplies low-temperature heat for a *Codelco's* operation [23]. In spite of proven technical feasibility, the overall penetration of renewables in the copper sector remains low. For instance, the energy requirements for transport and heat are usually covered by fossil fuels and electricity generation is mostly based on conventional technologies. For example, in Chile (the world's leading copper producer), half of the energy consumed in the sector comes directly from fossil fuels [24]. The other half is electricity, half of which is produced with fossil fuels [25].

As the costs of renewable energy technologies continue to decrease, they gradually outperform conventional technologies. For example, [26] reports that the lower end of the levelized costs of electricity of photovoltaics (PV) and wind are down to 40 and 30 USD/MWh, while coal power sits at 60 USD/MWh. Moreover, the latest tenders reveal bid prices even lower than 20 USD/MWh for PV [27]. In a comprehensive review, [12] underline that fully RE-based systems are not only technically feasible but also economically viable.

In this context, this chapter aims at shedding light on the current modeling approaches for integrating renewable energy in copper production and identify the main gaps where future research should focus.

2.1.1. More copper will be needed for future energy systems

Fully renewable energy systems are required to mitigate climate change [7,28][29] and the copper industry would play a role in the transition to such systems. As RE technologies require more copper than conventional ones (as copper use per unit of energy produced) [19], transitioning towards highly renewable energy systems is a driver for copper demand [8]. Figure 2 shows the copper demand for selected technologies. More copper is required to produce electricity from PV and wind. In addition to RE generation technologies, transmission reinforcement (required to balance variable generation) and the deployment of electric mobility would also drive copper demand. [30] dismiss the possibility of a resource constraint on copper, estimating the use of copper for building 2050's world energy system at twice the current annual production. Nevertheless, with the depletion of copper deposits, the specific energy required for extraction increases. As a consequence, the energy return on investment of, for example, a wind turbine in the year 2050 would decrease by 15% as compared to 2012 [31]. Without a transition to renewable energy sources, greenhouse gas emissions will increase too.

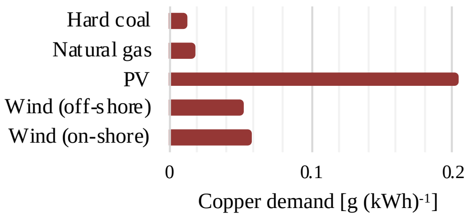

Figure 2: Copper demand for different generation technologies[2]

2.1.2. Renewable energy systems can improve the footprint of copper

Copper has an ecological footprint that is relevant to the technologies that will form the future energy system. To assess the impacts, Life Cycle Assessment (LCA) methods are usually employed. In LCA, all emissions at every stage of the life cycle of a product or process (including energy and materials supplies) and the resulting impacts on the environment are tallied. This allows for identification of the main impacts, relevant stages, and potential trade-offs when implementing changes. For example, [32] showed that copper is a relevant source of impact in wind turbine nacelle construction, where it is used in the generator and transformer. Nacelles, in turn, account for around 30% of the terrestrial ecotoxicity, petrochemical oxidation, and acidification along with over 40% of human toxicity associated with the life cycle impacts of wind turbines. In a review of LCA studies on different types of electric cars, [33] argue that copper supply is an important cause of human toxicity potential. The authors point out that reducing the use of coal in the energy supply of mining would reduce the impact of battery electric vehicles. [34] highlight that, in copper production, the main energy-related impact is the emission of greenhouse gases. Looking at ore grade decline, [35] argue that solar electricity would be the most effective (on-grid) alternative (as compared to wind and natural gas) to compensate for the corresponding increased Global Warming Potential (GWP). In a previous

[2]As reported in the Ecoinvent database version 3 [202] and retrieved through Gabi LCA software. The reference capacities of PV and wind technologies are 0.6 MWp and 1-3 MW. Germany is the reference for the inventories.

study, we estimated that, by replacing the total electricity demand of copper with solar power, GWP can be reduced by at least 60% and 75% for pyro- and hydrometallurgical copper production in Chile [36]. Other forms of energy would need to be addressed to achieve further reductions.

Finally, the water consumption of copper production can be a major environmental burden, especially in countries that concentrate major copper reserves and where water is scarce [37]. This means that the mines either compete with other local users for a (very) scarce resource or use seawater (crude or desalinated). The last option translates to an energy supply issue [11], which could be tackled with RE.

The use of renewables can thus be a means to lower the energy-related environmental footprint of copper production processes.

2.1.3. The impact of copper comes not only from energy

Copper production has other environmental impacts that are not related to energy. Although these issues are outside the scope of this study, they are summarized here for the sake of completeness. This should avoid giving the impression that RE technologies could solve all environmental problems in copper production.

Several studies have used LCA to analyze the overall impacts of copper production [35,38,39]. Non-energy-related environmental issues are: depletion of the metal, emission of heavy metals and sulfur dioxide to the air at smelters, emission of heavy metals and phosphorous to freshwater, and the land use of tailings storage facilities. Tailings management is an old concern that persists. [40] analyze the effects of copper mine tailings discharges in the coastal ecosystems of Chañaral in Northern Chile. They dived in an active landfill and found a reduction in light transmittance while simultaneously increasing the mortality of marine species compared to an unpolluted nearby site. Recently, [41] conducted an LCA to measure the environmental impact of tailings from copper production. They compared the impact of this part of the process to those of the rest of the operations. They concluded that when analyzing longer periods (tens of thousands of years) toxicity-related impacts arising from tailings management are higher than those of the stages in the main value chain of copper production. Moreover, risk of landslides exists when deploying tailings dams. These studies highlight that GWP is only one among many indicators needed to describe the environmental impact of copper production.

2.1.4. Research questions and contribution

The design of renewable energy systems for copper production is incipient and its systematic analysis can enhance the results in the field. The scientific literature is diverse and ranges from the evaluation of specific technologies to a few comprehensive system analyses. This study provides a comprehensive overview of the state of research on renewable energy systems for copper production and a number of recommendations for improving the design of these systems. Researchers and decision-makers in the energy sector and copper industry will benefit from this systematic review, which includes lessons learned from other fields where renewable energy systems are being deployed. Our recommendations serve as a guide for the design of the energy supply of existing and future copper production processes. This will, in turn, improve the environmental footprint of renewable technologies that require copper for their construction.

2.2. Methods and structure

This review is based on scientific literature published in peer-reviewed scientific journals, complemented with technical reports and official statistics when required.

The analysis is divided into the steps shown in Figure 3. Section 2.3.1 clarifies how copper is produced, the amount and type of energy required, how this demand is currently supplied and which factors influence energy consumption. Section 2.3.2 describes the current state of research on RE systems for copper production supplemented by a classification framework for the methods used in the studies. For a more comprehensive analysis, we consider studies that explicitly analyze the use of RE in copper production and studies that use copper production as a case study. Section 2.3.3 refers to the literature on renewable energy systems for other applications and sectors, aiming at finding lessons for copper production. Finally, in section 2.4, we present our recommendations for future research in the field.

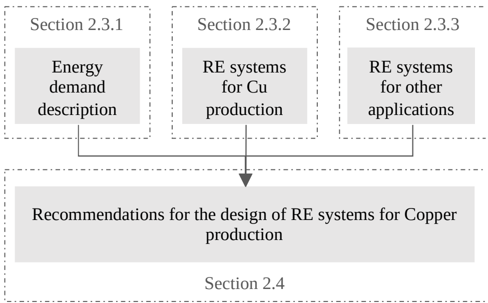

Figure 3: Structure of the analysis of the state of the art.

2.3. Design of renewable energy systems for copper production

2.3.1. Energy demand in copper production

To obtain the 24 million tons of refined copper produced worldwide [42], there are **two main processing routes** (see

Figure 4): **pyro- and hydrometallurgy**. These account for 67% and 16% of world production. The remaining 17% corresponds to secondary recycled production [43], which requires 85% less energy [44]. In the following, we briefly describe the first two –more energy-intensive– processes with a focus on energy consumption.

The description of the processes relies mostly on [45] and the figures on data from a comprehensive annual industry survey conducted by the Chilean Copper Commission [24]. Figure 5 shows energy consumption in copper production as reported in that survey. Because of greater copper demand and lower quality mineral resources, the total energy required to supply the copper that humanity consumes is expected to increase in the future. [21] project the energy demand for copper production to grow from around 150 and 100 to 200 and 160 GJ per ton of copper in 2050, for hydro- and pyro-metallurgical processes. The authors highlight that this would equal an impressive 2.4% of global annual energy demand.

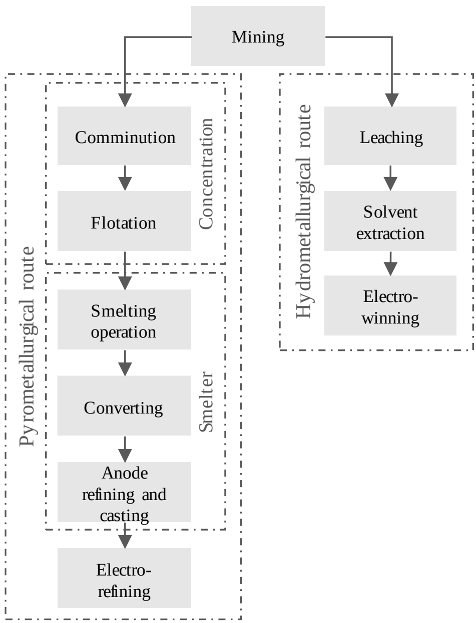

Figure 4: Simplified overview of copper production processes.
Based on [45].

Both processing routes (hydro- and pyrometallurgy) begin by mining the mineral from the ground. Usually, ores with a lower (around 0.5%) grade are mined in **open-pit operations**, while deposits with higher ore grades (around 1-2%) are accessed by **underground mining**. Open-pit mines dominate copper production [45]. The blasted rock is typically loaded and hauled by large trucks that run onboard diesel generators to power the electric motors that move the vehicle. One example is the Komatsu 930E truck, which is widely used in industry and whose engine has a gross power of 2.6 MW [46].

After transport, pyrometallurgical processes are usually used if sulfur and iron are present in the ore. For copper oxide ores, hydrometallurgical methods are used [45]. Both processing routes are described in the next two sub-sections.

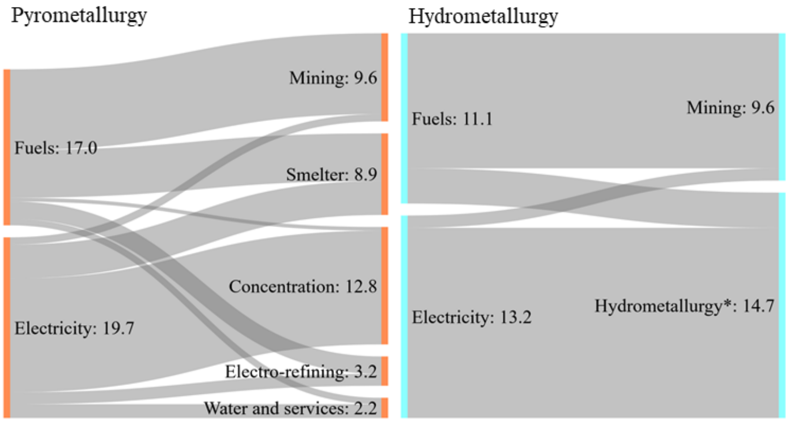

Figure 5: Energy flows in copper production in GJ per ton of copper.
*Left: Pyrometallurgical copper production. Right: Hydrometallurgical copper production. *Aggregates leaching, solvent extraction, and electro-winning. 2017 averages for the Chilean industry (Data from* [24]. *Mining is represented with the weighted average of open-pit and underground operations, and no distinction is made between (first-stage) mining for hydro- and pyro-metallurgy.*

The energy demand of pyrometallurgical methods

Pyrometallurgical copper production starts with fine milling (**comminution**) of the mineral. Standard equipment includes semi-autogenous mills, ball mills, and cyclonic separators. The milled mineral is then concentrated to around 30% of copper content in the froth flotation process. In this operation, the milled mineral is transferred into bubbled water tanks that collect copper-rich particles in the foam formed at the surface. This operation is called froth **flotation** and its main product is copper concentrate. This stage is intensive in the use of electricity (for the operation of the mills) and water (which may result in further electricity demand for water transport and/or desalination).

High-temperature processes are used to recover the copper from the concentrate by means of density differences. The concentrate is first smelted in the **smelting** operation (1,250°C) to produce copper matte (molten phase rich in copper) and slag (oxidized impurities). This operation uses fuels to achieve the required temperature. The matte is then oxidized to 99% pure copper in the **transformation process** (1,200°C) by injecting oxygen-enriched air. The converting operation is auto-thermal, meaning that the chemical reactions provide enough heat to maintain the required operating temperature. Electricity is required for the oxygen supply.

Electro-refining follows, refining the copper anodes cast in a previous stage (99% pure) through dissolution in an aqueous electrochemical reaction, where the copper ions plate on a 99.99% pure copper cathode. Electricity is required to drive the reaction and heat is needed to maintain the operating temperature of 60-65°C [47].

The energy demand of hydrometallurgical methods

The hydrometallurgical processing does not require milling the rocks down to sizes as fine as in the pyrometallurgical route. Instead, the crushed ore is disposed in heaps that are continuously irrigated with an aqueous solution of sulfuric acid, **leaching** the copper from the rock to the solution.

This solution is concentrated in the **solvent extraction** operation, where copper is transferred from the aqueous solution to an organic phase and then back to a more concentrated aqueous solution. Up to this point, energy is required for transporting solutions and minerals, and for comminution.

Copper is recovered from the concentrated solution through **electro-winning**. In this process, copper ions are plated on a 99.99% pure cathode. This process operates at 45-50°C. Electricity is required to drive this electrochemical reaction and heat is needed to maintain the temperature.

Factors that determine the energy demand for copper production

The main factors that determine the energy consumption in copper production are (1) the **process route** (pyro- or hydro-metallurgy); (2) ore **grade**; (3) mineral **hardness** and **liberation size**; (4) **mine age** and type (**surface or underground**); (5) **location** of the mine and **access to water**; and (6) **process design** and **equipment selection**. These factors are addressed in the following:

(1) Mineral **processing** by the pyrometallurgical **route** (for sulfide ores) or hydrometallurgical **route** (for oxide ores) involves different operations and equipment, and results in different energy requirements, as explained in the previous section.

(2) The unit energy demand (energy per mass of copper produced) increases with lower ore **grades** [20]. There has been a downward trend in copper ore over the last decade so that more mineral needs to be processed to extract the same amount of metal. For example, in Chile, the average concentration plant copper grade was 1.0% in 2008, while in 2017 it was 0.8% [48]. In the same period, the energy demand for concentration increased by around 50% [24].

(3) Grinding is the most energy-intensive process in mineral processing [49]. **Rock hardness** and **liberation size** are especially relevant in comminution processes since harder rocks require more energy to be milled to the required liberation size (the particle size at which the metal is exposed enough so that it can be recovered in the concentrate). Both rock hardness and liberation size usually vary spatially in the mine. This could be seen as providing demand-side flexibility when considering the integration of solar energy, as shown in [50–52]. This would require miners to be open to modifying both the design and operation of the concentrator. The latter, in turn,

could affect operational paradigms such as maximizing the throughput being the only operational goal.

(4) Energy consumption also varies between **surface** and **underground mining**. For instance, in Chile, the average energy consumption was 10.2 and 4.3 GJ/t of copper produced at open-pit and underground mines in 2017 [24]. While open-pit mining uses almost exclusively fossil fuels, half of the energy for underground mining is electric. As **mines age**, trucks must cover longer distances in the pit, which increases their energy demand [53]. The cost of further deepening the mine will rise until it is no longer economically viable to continue open-pit mining. Then, the operation has to transition to underground mining, as it is happening with *Chuquicamata* and *Grasbersg* [54].

(5) Depending on the **mine location**, **access to water** can be an issue. As pointed out by [11], the issue of water supply in the use of seawater becomes an energy supply problem, as water has to be pumped and desalinated from the coast. For the Chilean mining industry, it is estimated that the electricity demand for seawater desalination and transport will increase a fourfold over the next decade [55]. The composition of the minerals, which in turn depends on the location of the mine, can exacerbate the water problem. For example, when the ore has relevant amounts of molybdenum, the use of non-desalinated seawater in the flotation process is discouraged as it undermines its recovery [56]. This would add desalination costs (to the seawater transport costs). **The location** also plays a role as it determines transport distances. Altitude, in particular, affects the head for water pumping systems and the efficiency of combustion processes.

(6) But not every factor is exogenous. **Process design and equipment selection** determine the quantity and form of energy demand. For example, at the smelter, the choice of equipment determines how much energy is needed overall and how the proportions of fuel and electricity are distributed. For instance, if flash smelting, flash converting, and slag flotation are used, 3.5 GJ and 1.5 GJ of electricity and fuels per ton of copper would be required. If Noranda smelting, Pierce-Smith converters, and slag flotation are used, 4.4 GJ and 4.1 GJ of electricity and fuels per ton of copper would be required [57].

To summarize, the energy demand for copper production is distributed between different operations, and the quantity, form, and dynamics depend on multiple factors, both endo- and exogenous to the process design. Therefore, representing it as an aggregated consumption or neglecting its thorough characterization would considerably limit the design and analysis of renewable energy systems.

2.3.2. Studies on designing renewable energy systems for copper production

In the studies on renewable energy systems for copper production, the approaches vary widely. Aiming for a well-structured analysis, we first define a classification for these different methodological approaches and then provide a review of the literature.

Classification of models

Three defining aspects were identified among the approaches to energy system design: 1) the treatment of demand, 2) the consideration of energy vectors or forms of energy, and 3) the operational resolution of the copper processes. These aspects will be described in the following. We selected them as they determine the freedom that the corresponding decision making (optimization problems) would have.

(1) The energy demand of production processes can either be treated as *exogenous* to the model, meaning that it is an input parameter that must be satisfied and cannot be modified (Figure 6-a) or as *endogenous*, meaning that the modification of the demand is allowed (Figure 6-b).

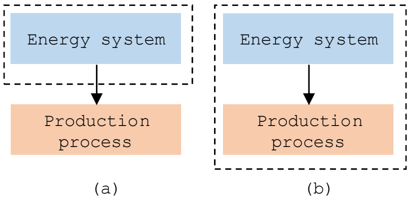

Figure 6: Methodological classification for energy system design models depending on how the energy demand of the productive processes is treated.

The dashed lines represent the components of the system where the model can make decisions. (a) Demand is exogenous (b) Demand is endogenous.

(2) Energy can be considered in three ways: as a *single-vector* (e.g. only electricity) (Figure 7-a); as *non-exchangeable multi-vectors*, i.e. consider more than one form of energy without allowing for transformations between them (Figure 7-b); or *exchangeable multi-vector*, i.e. consider more than one vector and allow for transformations between them (Figure 7-c). The latter gives the most degrees flexibility in the design.

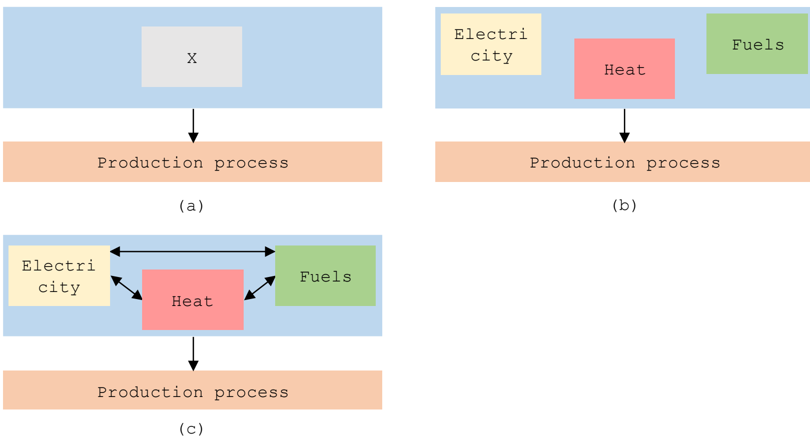

Figure 7: Methodological classification for energy system design models according to energy vectors.
(a) Single-vector (b) Nonexchangeable multi-vector (c) Exchangeable multi-vector

(3) The aggregation and the scope of the description of the energy demand of the production processes vary. We observed three options. First, the demand for the entire process is considered as one aggregated node (*full-process aggregated demand*, Figure 8-a). Second, a single operation within a production chain is considered while the rest of the operations are neglected (*single-operation*, Figure 8-b). Third, the entire process with an operation-sharp resolution is considered (*full-process, single-operation resolution*) (Figure 8-c).

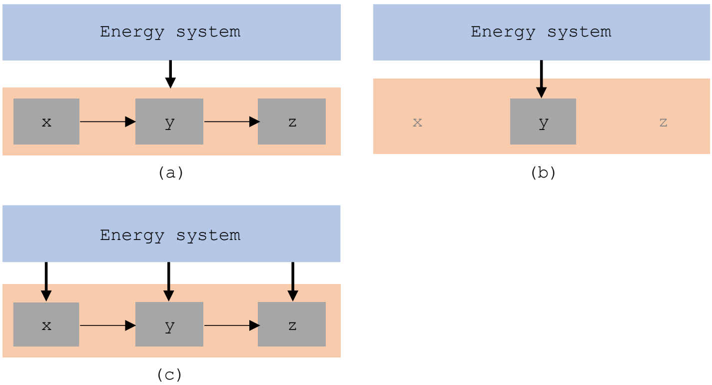

Figure 8: Methodological classification for energy system design models according to energy demand representation.
(a) full-process aggregated demand, (b) single-operation, (c) full-process, single-operation resolution.

Relevant studies

Eleven studies on the design of renewable systems for copper processes are considered. An overview of these, based on the aforementioned classification, is presented in Table 1. The discussion is divided into two parts. First, studies are reviewed and discussed that consider demand as an exogenous parameter that cannot be changed (studies 1-7). Later, the analysis is performed for the studies that take into account changes in the energy demand of the processes (studies 8-11).

Table 1: Summary of approaches of studies on renewable energy use in copper production, following the above-explained framework.

		Treatment of demand		Energy vectors			Representation of demand		
	Study	(1a)	(1b)	(2a)	(2b)	(2c)	(3a)	(3b)	(3c)
(1)	[58]	x		x				x	
(2)	[59]	x				x	x		
(3)	[60]	x				x	x		
(4)	[61]	x				x	x		
(5)	[62]	x		x			x		
(6)	[63]	x		x			x		
(7)	[64]	x		x			x		
(8)	[50]		x	x				x	
(9)	[51]		x	x				x	
(10)	[65]		x	x				x	
(11)	[66]		x		x			x	

(1a) Demand-exogenous treatment;(1b) Demand-endogenous treatment;(2a) Single vector;(2b) Non-exchangeable multi-vector;(2c) Exchangeable multi-vector;(3a) full-process aggregated demand;(3b) single-operation;(3c) full-process with single operation resolution.

Seven studies with demand-exogenous approaches are identified. (1) [58] present a single-vector, and single-operation energy system design. It is a novel design that supplies a copper **electro-refining** plant directly with **direct current** from a **PV** plant. Since PV technology generates direct current and electro-refining requires electricity in this form, the losses and capital costs of conversion can be avoided. In this case, distributed energy generation avoids not only transmission losses but also those of (electricity) conversion processes. This study shows by way of example the relevance of understanding the end-use of energy in production processes so that the full potential of RE can be exploited.

Next, a series of papers from Amusat's group is introduced. They deal with the design of an interchangeable, multi-vector energy system for copper production, using a full-process aggregation of the energy demand. (2) [59] present a method for the minimum capital cost **design of RE systems for continuous processes** and apply it to a case study of copper production in Chile. They consider two RE generation technologies (PV and concentrated solar heat) and three energy storage technologies (molten salts, pumped hydro, and compressed air) in a set of performance models. The RE system supplies both electricity and heat (as a constant share of electricity), but it does not consider fuels demand (e.g. for trucks). The optimal solution defines hourly time profiles for energy generation, storage, and supply, as well as the sizes for the components. (3) [60] extend the method to consider the uncertainty of RE generation profiles in the design of the off-grid RE system. They also add a synthetic case study in Canada. The authors propose modified versions of standard energy systems reliability indexes (expected energy not supplied and energy index of reliability) to develop a probability-based model that minimizes costs and unsupplied energy. (4) In [61], the authors further extended the method to integrate the optimization of capital costs and system reliability into one multi-objective optimization problem. They solve this problem with an evolutionary algorithm and produce the corresponding Pareto fronts.

(5) [62] analyze the **economic feasibility** of providing electricity for mining operations with a **CSP** plant using a probabilistic model for the energy price. The approach of this study is single-vector and full-process with aggregated demand. They assessed the feasibility of the plant considering standard financial contracts (power purchase agreements) within the industry. Furthermore, they propose economic incentives to improve the competitiveness of CSP. Current market prices are lower than those considered by the authors. In spite of that, the potential for technology learning and the effect of sector coupling should still be considered when assessing the integration of CSP technologies.

(6) [63] address the **cost-optimal design** of a renewable **electricity supply system** based on photovoltaics and a novel floating wind-power technology. They design the system to supply 10% of the electricity demand of the mining industry in Antofagasta, Chile. The approach is single-vector and full-process aggregated. Despite the authors argument that the electricity costs of the proposed system (250-270 USD $(MWh)^{-1}$) are only slightly higher than the average prices in the region, this alternative is more than double the average costs of current contracts of large clients (80 USD $(MWh)^{-1}$ (Consejo Minero, 2016)). Such high costs, however, can be explained by conservative cost assumptions and the use of immature technologies in their study. This fact, however, should not discourage the implementation of mature renewable energy systems, which are proven to be techno-economically viable with their cost decreasing every year [12] and already outperforming conventional technologies (as explained in section 2.1). Moreover, since a 100% renewable electricity supply is feasible, we see no reason to limit the share of renewables in future systems.

(7) In the last study with an exogenous-demand approach, [64] present an **energy management system** (EMS). An EMS is a control system that coordinates the operation of an energy system under a certain optimality criterion. In this case, the EMS aims at promoting self-consumption of distributed (local) renewable energy in industrial processes. They apply the method to a wind-power system for a copper production process. In this study, the goal was to minimize costs and the energy exports under the assumption that these would not be paid by the national grid operator. We classify this work as single-vector and full-process aggregated demand. The authors proposed a stochastic EMS to account for renewables variability. This results in increased imports from the grid and the use of a local co-generation system, which translates into 15% higher costs over a non-stochastic EMS. This study shows that control systems have an influence on the economic performance of distributed energy generation for industrial processes. It should be noted that the services provided by the co-generation system could also be provided with renewable or storage technologies.

We identified four studies with demand-endogenous approaches. (8) [50] present the design of an on-grid combined **PV** and **battery energy storage system** to supply electricity for milling. The authors use this system for a **semi-autogenous grinding** mill and implement **demand-side management** (DSM) based on the classification of rocks by hardness. This approach of this study is single-vector and single-operation. The authors showed that PV can be more cost-effective when DSM is adopted. (9) In a later study, [52][51] further analyze this DSM alternative by soft-coupling the energy system design model with a geometallurgical model of a mine. The authors analyze the effect of variability and uncertainty of rock hardness. They also propose a scenario where the mineral is classified into hard and soft stockpiles to illustrate a realistic implementation of this DSM alternative and they report cost reductions.

The previous example is one of many possibilities for shifting loads in mining for **energy system flexibility**. However, to the best of our knowledge, a comprehensive inventory of flexibility alternatives within copper production processes is still missing in the literature. We foresee further flexibility alternatives in the production of oxygen for smelting, which has a relevant electricity demand [68] and can be stored in tanks, and in the systems for water desalination and pumping, among others. All of these alternatives require a proper economic analysis that compares the cost of their implementation to the value of the flexibility they could provide to power systems. In power grids, the structure of the market would determine the ways the different participants of the system can benefit from the implementation of flexibility alternatives.

(10) [65] discuss the use of **concentrated solar heat** in copper **smelting**. The authors propose a central tower solar-thermal plant to supply the heat needs of this operation. They also consider **modifying the energy demand** of the process by changing the energy contributions from fossil fuels, pre-heating, and oxygen injection. They argue that the smelting operation could be carried out without direct use of fossil fuels and using only pre-heating and oxygen supply. This could allow for complete electrification. They do not size or design any specific system. Still, this approach would be demand-endogenous, single-vector, and single-operation. An integrated concept for heat and electricity supply using concentrated solar technologies is still to be modeled and analyzed, as well as its combination with other RE technologies. The fact that some smelters already have turbines to generate electricity using recovered heat could foster the adoption of the concentrated solar power (CSP). This, since part of the equipment required for a CSP plant, the turbines, is already familiar to the operation. In addition, the use of microwave or electric arc furnaces could be considered.

(11) In the last study considering modifications in the energy demand, [66] present an application of solar-thermal technologies. They propose using concentrated solar heat to produce gas from the waste tires of large mining trucks via pyrolysis. They evaluate the GWP of this alternative and compare it to pulverizing the tires or performing pyrolysis with conventional energy. Considering waste management as part of the operations involved in copper production, this study can be classified as demand-endogenous (since different configurations for the process, which would impact its energy demand, are assessed), non-exchangeable multi-vector (considers electricity and heat), and single-operation. This study does not size components of an

energy supply system but compares the environmental performance of different technologies.

We observe a completely different approach in the scientific trend aiming at directly extract copper using solar heat and alternative chemistry, emerging as a third alternative to pyro- and hydrometallurgical methods. Experimental concepts have been proposed for copper sulfides [69] and oxides [70]; [71].

We observe interesting results in the ongoing studies that suggest there is space for **smarter integration of renewables** in copper production. Barriers to do this, however, exist. Current models are not able to capture the **complexity of energy demand** in copper production. This is required to assess distributed **multi-vector energy systems** and **energy demand flexibility** in the copper industry. We expect that multi-vector systems and demand flexibility would allow cheaper designs. The modeling of the energy demand for **water supply** is untouched in the design of RE systems for copper supply. We expect this factor to be even more relevant in the future, as seawater use is increasing and water reservoirs can be used for energy storage. In the modeling of energy technologies for copper production, there are mature technologies that still need to be included (e.g. heat pumps, electric heat, and hydrogen fuel cells). Analysis of these could also enable cheaper designs. In section 2.4 we elaborate on the recommendations for the design of RE systems for copper production, based on the analysis presented in this section and the learnings from other fields of application that we present in section 2.3.3

2.3.3. Studies on designing renewable energy systems in general

In this section, we explore the scientific advances in designing energy systems for other distributed systems, national or regional grids, and the inclusion of environmental issues. We do this with the aim of identifying opportunities and drawing lessons that assist in designing cleaner energy systems for copper production.

Distributed renewable energy systems

Our examination of the literature on distributed renewable energy systems, with a focus on industrial applications, revealed two main approaches. Both methods combine different technologies to form exchangeable multi-vector systems, but they approach the design from different perspectives. On the one hand, we see approaches for **distributed energy systems** in the field of power systems optimization or system expansion models. This translates to cost optimization models (usually mixed-integer linear programming, MILP) to define the capacities of components in the energy system (energy generation, transport, and storage technologies) and its operation (energy flows in time). On the other hand, we see approaches for **locally integrated energy sectors**, in the field of **process integration**. These extend models intended to reduce the overall heat demand of a group of processes by recovering excess heat. In more general terms, as defined by [72], *a family of methodologies for combining several parts of processes […] for reducing the consumption of resources or harmful emissions*. Therefore, these latter models would require a demand representation for the full process with a single-operation resolution (see Figure 8).

About **distributed energy systems optimization**, [14] reviewed the design and analysis of energy systems that incorporate different forms of energy (multi-vector or **multi-energy systems**), with a focus on distributed systems (**distributed multi-generation**). The author highlights that multi-vector systems improve the environmental and economic performance, as compared to supply systems designed for each vector (e.g. electricity, heat, or fuels) independently. This effect is more relevant in distributed systems. The components of distributed systems are often smaller, and with only a few units, the outage of one component can threaten reliability. Smaller scales also stress the effects that non-linear efficiencies could have on the optimal system configuration. With distributed systems confined in smaller geographic areas, the variations of renewable resources are harder to smooth out, as compared to larger systems. The local conditions of the energy market (e.g. fuel prices, on-grid electricity price, etc.) will have further influence on the optimal design and operation of distributed systems.

In terms of **distributed multi-vector systems for industrial processes**, [73] developed a MILP model for designing exchangeable multi-vector energy systems for industrial processes at minimum cost. This model, called *ficus*, is open-source available online. It allows for dynamic prices, the import and export of energy from and to the grid, and considers transient behaviors and scale economies for different components. *Ficus* was originally applied to case studies for steel, aluminum, iron, carbon-based products, and car production processes. These case studies showed that the energy demand profiles of each industry strongly determine the cost-optimal capacities of the components in the energy system. This stresses the need for a thorough understanding of energy requirements for the industrial process one wants to analyze (**how much** energy, **when**, and for **which use**). Similarly, [74] present a MILP model for designing a heat and electricity on-grid distributed supply system at minimum cost. The model considers combined heat and power, PV, wind, central heating, electricity, and heat storage technologies. The approach of the study is demand-exogenous, non-exchangeable multi-vector, and full-process with aggregated demand. Case studies with the model show considerable savings in the total energy costs as compared to current conventional energy systems (internal rates of return for the projects of up to 34%, depending on the industry and its energy demand profiles). These results depend on the characteristics of the market. Such a model could similarly be useful in evaluating the effects of market conditions and public policies on the **optimal amount of distributed renewable energy generation** at industrial sites. In turn, these conclusions could support **planning in the regional and national energy systems** where these industries participate.

[75] present a **multi-objective optimization** model for designing distributed energy supply systems and apply it to a group of industrial processes. This model allows for analyzing **trade-offs between the costs and CO_2 emissions** of the energy system. The authors considered combined heat and power, solar heat, and a heat distribution network (as a binary option) to provide electricity and heat. Following our classification, this approach is demand-exogenous, non-exchangeable multi-vector, and full-process with aggregated demand. [76] include the possibility of implementing energy demand schedules in industrial processes. They implement an optimization model that includes operational scheduling as a decision variable. Such

approaches can be especially interesting when analyzing how energy markets should be designed (signals and incentives for the players) to aid in the balancing of systems through **industrial energy demand flexibility**. This study is demand-endogenous, non-exchangeable multi-vector (heat and electricity), and full-process with single operation resolution. The results suggest **benefits** for both the **industrial** and **power grid operators** from the implementation of such systems. MIND is one more model for the analysis of energy systems in industrial applications, focusing on the analysis of the management of energy demand dynamics or the implementation of efficiency measures [77]. An application of this method to an iron foundry is presented by [78]. The authors analyze the impacts of changing the smelting equipment on the total energy costs of the process, highlighting the suitability of energy system optimization models for assisting the **design of industrial processes**.

In terms of the second main approach, **locally integrated energy sectors** (or, more generally, **process integration**), [79] adapt the MIND model to analyze process integration for steel production. They quantify the effects of different modifications to the process operation and equipment on the energy demand of the process. This type of model requires detailed modeling of every operation in each process, to identify and assess energy recovery and energy efficiency measures. This type of model does not focus on identifying optimal mixes for energy generation and storage, which distinguishes it from optimization models for distributed energy systems. In spite of this, there are efforts to use process integration-based models to design RE systems [80]. These techniques are more than 40 years old [72], but have been evolving continuously. [81] argue that more recent developments (e.g. the entire field of total site heat integration [82]) should be considered to enhance the performance of processes.

A further degree of complexity is added when considering the **very low future costs for PV** electricity generation. We anticipate that it could happen that the configuration that minimizes energy demand may not be the same as the one that minimizes costs. Shifting load profiles to daylight could yield cheaper solutions, even when resulting in increased total energy consumption.

There are several fully renewable island energy systems in the world [83–85]. The operation of these systems is based on control systems that differ from the current techniques in power systems [86,87], where conventional technologies dominate. The main difference is the use of more **frequent real-time measurements** to determine the amount of power to be delivered by each generation unit (dispatch). This is done so that despite the variability of the renewables, the electricity demand is always satisfied [88,89]. To smooth out this variability, complementary systems (like water supply) can be coordinated to increase the hosting capacity for renewables in the energy system [90–92]. **The excess of electric energy** is used to **fulfill additional demands** and/or is **transformed** into other energy vectors (e.g., heat). From this perspective, large industrial processes pose an attractive context for moving towards fully renewable energy systems [88]. Since they are multi-vector energy systems, the variability of renewables can be smoothed-out by taking advantage of the synergies between the different individual industrial processes [93–95]. Consequently, going towards a fully renewable energy system for copper production raises the following question: how the individual operations should be scheduled to **adapt the energy**

demand to the availability of renewable energy resources. This requires a re-think of copper production processes.

Renewable energy systems for regional grids

This section examines the design of renewable energy systems at the regional level (states, countries, or even continents) in order to draw relevant conclusions for designing a fully renewable energy supply for the copper industry. In recent years, many studies on the planning of large-scale energy grids have emerged. The majority focuses on integrating high shares of renewable technologies. [96] analyzed 500 scenarios arising from almost 20 studies to derive the storage requirements for the U.S. and Europe for increasing shares of renewables. Beyond the explicit numbers, they underline that, when designing highly renewable systems, attention needs to be paid to the generation mix and the transmission system. When the penetration of renewables grows greater than 50% (of annual demand), **storage technologies** are needed, especially if the grid relies more on **solar** than on **wind** power. This is consistent with the findings from [97], who reviewed 60 studies.

Continuing the analysis of the challenges in renewable systems planning, another recent review is provided by [13]. They systematize the planning approaches of about 90 journal publications and derive challenges and trends for large energy grids. The authors recommended **acknowledging technological diversity** (including efficiency-, lifetime-, and cost-curves) to understand better how technologies can complement each other; improve the spatial and temporal resolution to better capture the variability of renewables; represent the diverse services (beyond energy balancing) that are needed in the operation of power systems, such as reserve capacity; and include the different energy sectors, as these can support each other and may have **flexibility readily available**. [97] also see **sector-coupling** (like multi-vector systems, but for large-scale systems) as particularly critical when reaching very high levels of renewables. In addition, they recommend capturing the **full spectrum of flexibility options**; besides energy storage and sector-coupling, this includes demand-side management and transmission reinforcement and expansion. The interaction of future regional energy systems with the industrial sector, particularly copper production, would be defined by the **flexibility that the energy demand of the industry can provide**.

In terms of **temporal resolution**, the current standard for models is an hourly time-resolution, for renewable system design on a regional level [12]. Coarser resolutions would underestimate the variability of renewable generation and risk under-sizing the storage capacity [98]. In more precise resolutions the resources are quite uncorrelated; in other words, their variability tends to cancel out, which is why a more refined time resolution does not add much value in large systems. This stands in contrast to planning the infrastructure for **distributed renewable energy systems**, where the **area is smaller** and the **time resolution** needs to be **higher** to achieve the same effect. For example, for wind turbines, turbines separated by around 10 km would require a time-resolution of about 5 minutes to exhibit an effect equivalent to that of those separated by 200 km with a time resolution of 1 hour [99].

Another relevant issue in energy systems modeling is the **consideration of uncertainty**. One of the main sources of uncertainty is **the future costs** of technologies. To project these costs, **learning curves** are commonly used, as in [100].

When using these curves, one should pay attention to the effects of cost increases in early commercialization, the phenomena of forgetting, and economic and socio-political factors [101]. An additional source of uncertainty arises when the planned system has a reliance on fossil fuels, whose prices are extremely hard to predict. Fortunately, the relevance of this source of uncertainty will decrease for growing shares of renewables. Uncertainty in energy systems planning can be dealt with methods that differ in complexity. These range from scenario analysis to Monte Carlo simulation and other stochastic approaches. The selection of the adequate method depends on the nature of the source of uncertainty and the goals of the study [13].

In summary, three aspects relevant to the energy systems of copper production are identified. First, **distributed generation** is more exposed to the **variability** of the (local) resources and thus the **value of flexibility**, in any of the presented forms. Second, grid-connected mines have a **bidirectional relationship with the power system**: they can profit from the flexibility of the grid and offer demand flexibility to the grid. We expect that energy planning tools that consider this alternative will achieve cheaper solutions. Third, there are several approaches to **deal with uncertainty** when designing energy systems, which can be easily applied to copper production.

Environmental impacts in energy systems modeling

This section analyses the integration of environmental impact indicators into the design of energy systems. All the models listed for the design of copper production systems focus on costs, direct emission of CO_2, and/or use of energy as a further objective to be minimized. In view of the significant impacts that energy supply has globally on **human health**, **ecosystems** and **resource availability**, future research should include environmental sustainability in the design of future copper production. Here we can learn from current studies in energy system analysis, which incorporate **LCA-based indicators** into the design of large-scale energy systems. For example, [102] show that pricing indirect CO_2 emissions reduces the global electricity production from gas, hydropower, and bioenergy, and increases the shares of CSP, wind and nuclear energy. [103] consider the whole LCA perspective by including the single-score *ReCiPe* indicator **in the objective function**. They show that environmentally sustainable systems drastically reduce fossil fuel-based power generation, with a shift towards high shares of wind and PV technologies. Research can present trade-offs such as those between costs and environmental impacts; it is up to stakeholders to decide what set of tradeoffs to accept.

Transferring LCA to the modeling of energy systems for copper production seems to be straightforward. For each technology, an LCA coefficient can simply be considered as model input. Limitations exist, however, from **data availability** and the granularity of **life cycle inventories**. In addition, assumptions about the **technological progress** of specific technologies in copper production (foreground database) and the evolution of the global energy supply are required as inputs for the LCAs (background database).

2.4. Recommendations

Drawing from the literature review and analysis from section 2.3, the following section aims at identifying specific recommendations for the modeling and design of future RE systems in copper production. Figure 9 provides an overview of the recommendations and the parts of a generic energy model that they cover (resources, energy conversion, flexibility, and/or demand).

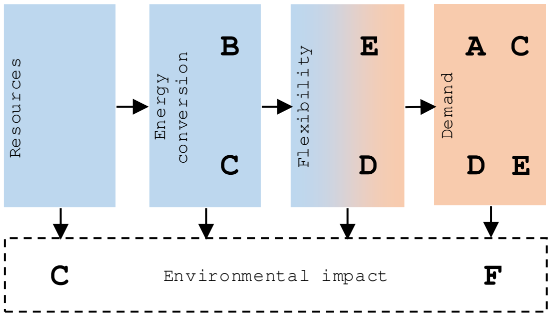

Figure 9: The recommendations and the component of a generic energy system model that they cover.

Each letter represents a recommendation.

2.4.1. Recommendation A: Improve energy demand models

In section 2.3.2, we saw that the detail of the energy demand of copper mines in literature is rather poor for both for the operations within the production processes and in the characterization of the final forms of use. In the current paradigm, where dispatchable (mostly fossil) technologies are used, rough characterizations of energy requirements could suffice. In highly renewable systems, an improved understanding of the energy demand for copper production processes is crucial for accurate system design. This means to describe better *when*, *where*, *in which form*, and *for which purpose* the energy is needed. Each of these characteristics is explained below.

Description of *when* means having demand profiles in a high time-resolution. This includes all cycles involved in the production processes throughout the year (seasonality), as well as the constraints and flexibilities in their maintenances.

Representation of *where* the energy is demanded is relevant since the location of the different stages in the production process determines the energy demand for transport (distances) and heat (ambient temperatures). Also, altitude impacts pipeline transport and the performance of combustion processes (given the change in the partial pressure of oxygen). The location also determines the availability of renewable resources and the quality of the mineral resource.

Description of the *form in which* and the *purpose for which* energy is demanded means the identification of heat (and temperature), electricity, fuels, and final use requirements. This allows for the identification of all potential solutions and the selection of the optimal technically feasible designs for integrated multi-vector systems.

2.4.2. Recommendation B: Include multiple energy vectors in the analysis

In addition to the overly simplified temporal and spatial treatment of energy demand, the literature also treats copper production poorly with regard to the energy vector. For example, it is common practice to limit the analysis to electricity or to identify the primary energy demand of fossil fuels as an aggregate of the demand for transport and heating processes (which take place at different temperatures). Basing the energy system design on such data biases the result towards solutions that simply replace the current energy vectors. Explicitly considering the different energy vectors (electricity, heat at different temperatures, and fuels, all convertible from one form to another) in the design of the energy supply system can enable solutions with lower environmental or economic costs. From a modeling perspective, this can be addressed by (i) representing the energy demand by the final use or service it provides, (ii) integrating technologies for energy conversion, and (iii) defining a node for each form of energy.

A comprehensive range of technologies should be considered to find the optimal solution. We observed that there are mature energy conversion technologies that have not yet been considered in copper energy modeling (e.g. heat pumps or electric heat technologies). Broadening the range of technologies could reduce the total costs.

2.4.3. Recommendation C: Integrate water management in the energy model

As explained in section 2.3.1, water supply results in an energy issue for copper production in arid regions. In these regions, large quantities of energy are required for water transport (e.g. in Chile, 100 km long and 3000 m high [104]) and desalination. The energy demand for desalination is one and two orders of magnitude greater than those of groundwater and surface water extraction, respectively [105].

Sizing the water supply system within the energy system optimization model (endogenization) could enable more economical designs. The option for water dams as energy storage technology can also be considered. Modelers should consider presenting this dual nature of the water supply system in a model for optimizing the energy system: (1) as a source of flexible energy demand for its transport and desalination and (2) as an energy storage alternative. In large scale systems, this idea has been addressed recently. For example, desalination has been considered in a study for the renewable energy transition of Europe [106]. For local systems, having a detailed water infrastructure co-design is of even greater advantage, given the higher value of flexibility.

2.4.4. Recommendation D: Explore demand-side management of current operations

The fluctuations of renewable energy resources need to be balanced through a flexible system. This can be done by means of transmission expansion, storage, or demand flexibility, as illustrated for large systems in section 2.3.3. In highly renewable systems, more demand can be allotted in times when more RE is available. This can occur at different timescales and the profitability of implementing such measures would strongly depend on the characteristics of the local energy markets. In any case, from a systems perspective, considering this alternative provides further degrees of freedom to the optimization model, allowing it to find cheaper solutions.

Demand-side management is a very common flexibility option in general energy system design. However, in section 2.3.2 we observed that in the copper world the only example found was the management of rock feed to the mills. Undoubtedly, the copper sector has many other potential sources for operational flexibility, along different time horizons. In the following we list some of the examples we foresee: (1) The maintenance of plants could provide seasonal flexibility for highly solar energy systems by scheduling them in winter, thus reducing investment in long-term energy storage; (2) The smelter could provide short-term flexibility using its thermal inertia; (3) the oxygen production system at the smelter could provide flexibility by storing oxygen instead of energy; and (4) the upcoming truck-fleet electrification can implement smart charging strategies for demand-side management. However, the list of alternatives still needs to be completed and its value, possible compromises, and the impact on the optimal system design understood.

2.4.5. Recommendation E: Design future mines and processes to adapt to renewables availability and consider copper flexibility in energy planning

In the past, when fossil fuels were the cheapest alternative, the energy was available on demand. As variable renewable technologies emerge as the cheapest alternative, we may benefit by adapting the production design to the availability of RE sources. Since the magnitude of many structural investment decisions in the mining industry makes them quasi-irreversible from an economic perspective, it is key that the options for matching the energy demand with renewable energy resources are considered in the early stages of project design. This means selecting and sizing equipment in consideration of the renewable energy variables. For example, when designing a new smelter, the selection of the smelting furnace will determine the form (electricity or fuels) and the amount of energy that will be required. In turn, this will affect the flexibility and costs of the overall energy system.

Acting on the demand is not a new idea in large-scale systems. A direct example would be planning a power system with electric vehicles. The copper industry can also play a role in regional energy systems by providing additional flexibility to the system. We expect this role to be particularly relevant in countries where the energy demand of the industry is comparatively high, as in Chile (30% of national electricity demand [107]). Consequently, we should consider the flexibility from the copper industry when planning energy systems for regions where this industry demands a relevant share of energy. In addition, the potential for energy flexibility should be considered when planning mining operations.

2.4.6. Recommendation F: Include environmental impacts in the assessment

As the impacts of energy systems are not limited to greenhouse gases, a wider consideration of impacts is needed. Moreover, the environmental impacts of copper production go beyond its energy supply, as anticipated in section 2.1.3. Despite several studies having assessed individual environmental impacts of copper production, addressing them thoroughly when designing energy supply systems for copper has not been observed. Such an analysis should consider life cycle emissions so that tradeoffs can be identified. To this end, life cycle impact indicators can be integrated into energy systems optimization models as further objectives. Also, if modifications in the process-equipment are considered, its impacts should be considered. However, this kind of analysis is currently limited by data availability and its granularity (regions, technologies, and stages of the lifecycle).

2.5. Conclusions

A comprehensive review of the design of renewable energy systems for copper production was conducted. To identify paths for further improvement, we explored the design of distributed renewable energy systems for other industrial processes and the design of regional systems.

Based on our review, we draw six recommendations for future research that would enable the design of more economical clean energy systems for copper production. The recommendations are: (a) improve energy demand models, (b) consider multiple energy vectors, (c) integrate water supply in energy system optimization, (d) assess energy flexibility of current production processes, (e) design future mines for flexible operation and consider copper flexibility in energy systems planning, and (f) include environmental impacts comprehensively in the design of energy systems for copper production.

The research gaps corresponding to some of these recommendations will be addressed in the remaining of this dissertation. In section 6.3, the contributions of each chapter are matched with this list.

The deployment of renewable energy systems, crucial to climate change mitigation, will demand more copper. Its production will continue to suffer from declining ore grades and the resulting increase in energy demand. Intensive use of renewable energy in copper production will help to mitigate the associated costs and environmental effects. This is happening naturally as renewables outperform conventional technologies on cost. We expect that designing systems based on our recommendations enables more cost-effective solutions and speeds up the transition to a 100% renewable energy supply.

Chapter 3. Exploring the integration of solar electricity: fully solar by 2030?

This chapter is based on the publication “Copper mining: 100% solar electricity by 2030?” by Jannik Haas, Simón Moreno-Leiva, Tobias Junne, Po-Jung Chen, Giovanni Pamparana, Wolfgang Nowak, Willy Kracht, Julián M. Ortiz. My focus in this publication was the investigation of the tradeoff between ore grade decline and declining costs of solar energy generation and storage.

Executive summary

This chapter addresses the adoption of solar electricity in the copper industry. It focuses on designing the future electricity supply of the main copper mines around the world, from 2020 to 2050, using distributed solar photovoltaic energy, storage, and a grid connection. We also analyze the effect of increasing energy demand due to ore grade decline.

For the design, we use an optimization model called LEELO. Its main inputs are an hourly annual demand profile, power-contract prices for each mine, cost projections for energy technologies, and an hourly annual solar irradiation profile for each mine.

Our findings show that it is attractive for the mines to have, today, a solar generation from 25% to 50% of the yearly electricity demand. By 2030, the least-cost solution for mines in sunny regions will be near fully renewable, while those in other regions will take until 2040. The expected electricity costs range between 60-100 €/MWh for 2020 and 30-55 €/MWh for 2050, with the lower bound in sunny regions such as Chile and Peru. In most assessed locations, the very low solar energy costs will compensate for the increased demand due to declining ore grades. In the upcomming chapters the analysis is extended to multi-energy and water supply systems.

3.1. Introduction

In this chapter, we focus on the recommendation (a) provided in chapter one, by exploring the effects on the costs and design of the electricity supply of two defining factors. Specifically, location—and thus climate—and the increasing specific energy demand due to declining ore grades (concentration of metal in the mineral resources). So far, the literature on renewable energy systems for copper operations has focused on process-specific solutions, a limited geographical scope, and off-grid schemes. However, these technologies are also economically competitive when connected to national grids. For example, the world's largest copper producer [108], Chile, has been deploying these technologies without subsidies for many years [104,109]. This country's favorable conditions for the deployment of solar technologies [110] have fostered rapid growth in solar power contributions to the national electricity market. But this is far from being a local phenomenon. The prices of solar electricity and storage technologies are expected to continue dropping in the coming years, worldwide [111], making them even more economically attractive for the mining companies to opt for these cleaner technologies over conventional energy sources. In this context, regions with good climate conditions for solar energy would have an edge in the transition towards cleaner power systems. Geography also determines the amount of energy demand and costs for copper production. For example, lower ore grades and harder rocks require more energy, as higher flows of mineral must be processed to recover the same quantity of copper, and more energy is required for its grinding [31]. Or, if freshwater is scarce, seawater must be desalinated and transported, thereby increasing electricity demand [112]. The location of the mines is an important factor when assessing the performance of their energy systems.

In terms of designing renewable energy systems (i.e. not specific to copper mining), there are numerous studies available. The review in [96], for example, systematized the energy storage needs for power systems with increasing shares of renewable generation; or references [13] and [113] that reviewed the modeling approaches for system planning. Together, these three reviews looked at over 300 publications, which further highlights the relevance of the topic. However, what also comes clear is that none of these publications deals with copper operations, although supplying them with solar energy could be particularly promising given their location in sunny areas.

As can be seen from the reviewed studies above, scientific research has not yet offered an analysis of how the location of mines worldwide determine the pace at which this energy-intensive industry can transition to a cleaner energy supply. But solar-based copper production has the potential to reduce the impact of every industry where this metal plays a role, particularly of the energy industry of the future. To explore this potential, we ask: How, where, and when? We offer valuable insights to answer these questions. Concretely, the goals of this chapter are:

- Elucidate **when** fully solar photovoltaic electricity supply is the cost-optimal alternative for copper production in different locations worldwide and how **the optimal sizes of the components** of the system evolve in time;
- Assess the resulting electricity price of the copper mines when strongly relying on solar power;
- Explore if decreasing costs of photovoltaic (PV) systems can compensate for the increasing **energy demand from lower ore grades** and how this effect varies among regions.

We analyze case studies on the main copper-producing countries in the world. As these are mostly sunny regions, we limit our analysis to solar electricity to ease the description of the tradeoffs that could arise between power generation and mining conditions in different locations. To the best of our knowledge, this is the first study analyzing the effects of geography on the energy costs of mining operations transitioning to renewable systems. Moreover, it is the first time the combined effect of the mineral and the solar resource on energy costs for mining are analyzed for a wide global sample of locations. Our investigation is then useful for decision-makers in the field of mining aiming at cleaner production and those in the field of energy policy who want to identify paths towards cleaner systems. Also, given that copper is a key material for the infrastructure of power grids, scientists trying to understand the lifecycle impact of future energy systems can also profit from this study.

In the next section, we describe the methods, mainly based on an optimization model for generation expansion planning. In section 3.3, we explain and discuss results about the optimal system configuration in the different mines, the resulting electricity costs (per unit of energy), and resulting specific electricity costs (per unit of copper mass). In section 3.4, we present the conclusions.

3.2. Methods

Our hypothesis is that fully solar-powered systems are soon to become more cost-effective than current grid mixes for supplying copper mines around the world. To evaluate this hypothesis, we plan the optimal generation system for seven of the world's largest copper mines. In this case study, we size the PV systems as well as the energy storage capacities (battery and hydrogen systems) for different milestone years from 2020 until 2050. We focus on supplying the current *electricity demand* profile of these mines, i.e. the provision of heat and fuels and the energy re-design of mining processes are out of our scope.

First, the optimization tool used for planning the electricity supply of the mines is explained (subsection 3.2.1), followed by the inputs and assumptions (subsection 3.2.2), the scenarios assessed for our case study (subsection 3.2.3), and the methods to project the future specific energy costs for the different mines (subsection 3.2.4). Figure 10 depicts a general summary of the methods.

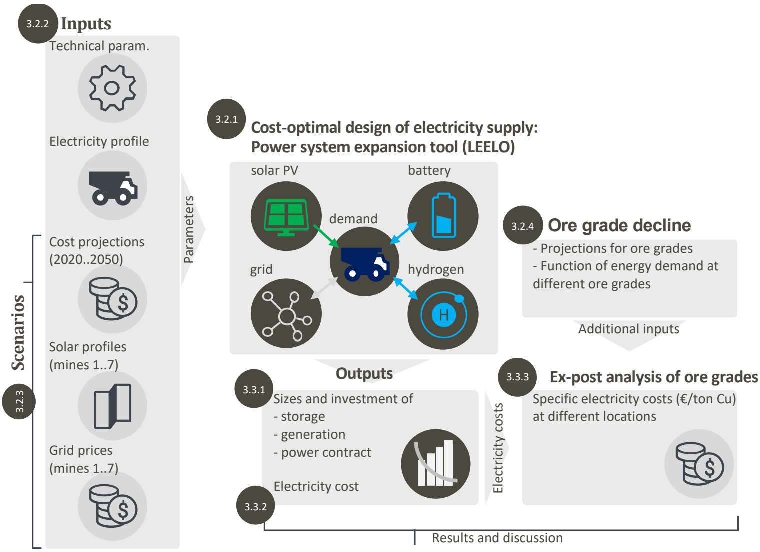

Figure 10: Overview of methods in chapter 3.
Black circles indicate the corresponding section in the document.

3.2.1. Power system expansion tool (LEELO)

For the design of the electricity supply, we use LEELO (long-term energy expansion linear optimization), a tool to find the cost-optimal combination of energy storage and generation technologies. This tool is explained in depth in reference [17] and has been validated in multiple other publications [114,115]. In short, this tool:

- Minimizes the investment (treated as annuities) and operating costs of the whole system.
- Decides the sizes of energy storage (power capacity, energy capacity) and generation technologies in which to invest.
- Considers a one-year modeling horizon with full hourly resolution (i.e. 8760 timesteps) for which the optimal operation of each technology is determined. The main equations (or constraints) include the energy balance of each storage device, the energy balance in each node of the system, and transmission constraints, among others.

In contrast to the full version of LEELO, here we consider a single node system (and not a national grid). The technologies used for generation and storage are solar PV, and battery and hydrogen storage. The maximum import and export capacities are limited by a power contract, which is sized as a part of the optimization, as explained in [50]. The full model also allows for modeling multiple power system services; for simplicity, here we considered the classical energy balance equation only (power reserves and energy autonomy are not used).

The main inputs to the model will be explained in the next subsection.

3.2.2. Inputs

The most relevant inputs to the model refer to the profiles of renewables, electricity demand, costs projections of technologies, and grid prices, as will be explained now. The full dataset is published as supplementary material in reference [116].

Mines considered

We focus on the major copper-producing countries of the world [117], considering the largest copper mines of each country. Included are Chile (Escondida), Peru (Cerro Verde II), China (Dexing), United States (Morenci), and Australia (Olympic Dam). To increase the geographic range, two other mines are included, given their significance in the global copper market (although their respective countries do not produce as much copper): Grasberg (Indonesia) and Buenavista Del Cobre (Mexico). Together, the countries and mines considered account for over 60% and 18% of the world’s copper production, respectively.

In terms of inputs to the model, the difference between each mine is the solar irradiance and the grid energy cost. The shape of the profile of electricity demand is assumed to be the same for all mines.

Electricity demand

We will use a yearlong hourly electricity demand profile for all mines. We decided to use the same profile for all mines because of their similarity (steady operation) and because of data availability.

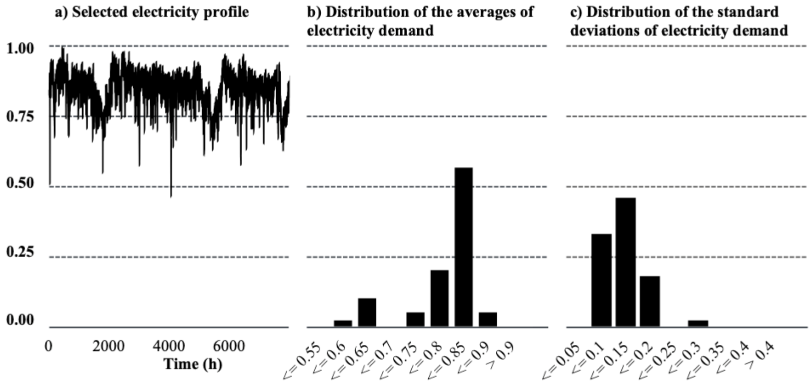

Figure 11: Electricity demand profiles for a generic copper mining operation.
In a) the y-axis represents the power demand normalized by its maximum value. In b) and c) the y-axis represents relative frequency. a) Selected representative profile for the simulations b) histogram of the average of the available demand profiles for the different mines (normalized) c) histogram of the standard deviations of each profile

To create this profile, hourly energy demand profiles of mining companies are gathered from the databases of multiple power system operators. The data include six different mines from Chile [118] and Peru [119] over the years 2013-2017, resulting in 21 profiles (not all mines had complete series of data for the time span). From these data sets, we defined a representative demand profile. For this, we first normalized the profile datasets by dividing them by their respective maximum values. Data points close to zero (below 40%) are filtered out (because the demand does not reach zero in normal operation, we assumed that those are measurement errors or exceptional contingencies) and replaced by a moving average of 48 hours. By using this approach, persistent periods of low demand (e.g. planned maintenances) are still captured. The normalized profiles for the different mines have mean values between 0.62 and 0.88, and a median of 0.82. The standard deviation ranges from 0.06 to 0.16, with a median of 0.10. To serve as a LEELO model input, a single profile (Figure 11**a**) was selected that represents all mining operations (the one that minimizes the variance to the other profiles). **Figure 11c** shows a histogram for the normalized averages of the electricity demand profiles, while in **Figure 11d**, we show the distribution of their standard deviations.

Solar profiles

For each mine, we use a different hourly resolved solar profile. These profiles are produced by renewables.ninja [120], based on NASA's ERRA and MERRA-2 global meteorological reanalysis and Meteosat-based CM-SAF SARAH satellite dataset [121]. This tool converts the irradiance data into power time series using a technical power plant model in which parameters, such as the general energy losses and type of tracking, can be set. The authors validated these simulations against more than a thousand national PV systems datasets from transmission network operators [120].

For our study, local solar profile data, based on the corresponding mine site latitude and longitude, were downloaded for each year between 2007 and 2016 by using the corresponding region's latitude and longitude coordinates (Table 2). Keeping in mind that the variability in meteorological conditions beyond simple yearly energy averages may affect the optimal sizing of the system (such as sequences of cloudy days), a representative year was chosen from the data. We used the same criteria as for the demand profiles. Using historical data implies that potential changes in future irradiation, resulting from climate change, are neglected, which is a minor limitation [122].

In terms of the chosen type of PV power plant, we decided to use a single-axis tracking system. This kind of system is today the most widely deployed one in arid zones and is projected to remain more cost-efficient than fixed installations [123]. As inputs to renewables.ninja (to generate the PV output power profile), we specified a 15% system loss, 1-axis tracking, a tilt of 0º, and an azimuth angle of 180º, values which are frequently observed in real projects.

Table 2 Long-term average of global horizontal solar irradiation for each region

Country, Mine	Latitude (º)	Longitude (º)	Yearly irradiation (kWh m^{-2} $year^{-1}$)
Chile, Escondida	-24.28	-69.04	3000
Indonesia, Grasberg	-4.05	137.11	1090
United States, Morenci	33.10	-109.36	2080
Mexico, Buenavista del Cobre	30.97	-110.30	2050
Peru, Cerro Verde	-16.53	-71.57	2580
Australia, Olympic Dam	-30.43	136.84	2050
China, Dexing	28.90	117.75	1300

Cost projections for energy technologies

The investment and operational costs, lifetime, and efficiency of PV and the storage technologies are taken from Breyer's team [124]. This database uses learning curves to project costs to the year 2050 and has been validated in numerous journal publications [111,124–128]. We assumed a capital cost of 5%.

PV system prices have been dropping in the last few years, with this trend expected to continue in the next decades. Technological improvements and widespread use are the drivers of this trend. In 2020, PV plants (for single-axis tracking) are expected to have a lifetime of 30 years, capital costs of 750 thousand euros per MW of installed capacity (k€ MW^{-1}) and operational costs of 11 k€ MW^{-1}.

By 2050, capital costs are forecast to have decreased to 330 k€ MW^{-1}, operational costs to 5 k€ MW^{-1}, and the plant lifetime increased to 40 years [124].

We consider two storage systems: Li-ion battery systems (BESS) and hydrogen systems (H_2 systems). Battery storage systems are mainly composed of the batteries (which determine the energy capacity) and the inverters/chargers to convert between direct and alternating current (which determine the power capacity). The H_2 system is composed of an electrolyzer (to convert power to H_2), a methanizer (to generate CH_4 from CO_2 and H_2), a gas tank (to store methane), and a gas turbine (to convert methane to power). The gas turbine has a scrubber to recover CO_2 for use in methanization, thereby closing the carbon loop. A valid alternative to the methanizer-gas turbine-scrubber setup would be fuel cells. However, the copper industry is more familiar with gas turbines, and many mines have them already as a backup. Such a configuration was seen to likely provide an easier transition over fuel cells. Nevertheless, for the sake of completeness, we explore the use of fuel cells in one case (Chile in 2050) to understand the scale of the impact of this assumption.

In terms of investment costs for these storage devices, we considered the following. For batteries, the used investment cost of power capacity is 99 €/kW in 2020, falling to 25 €/kW by 2050. The energy capacity cost is expected to drop from 283 €/kWh to 71 €/kWh for these years. For the H_2 system, the investment costs are 2220 €/kW in 2020 and 1120 €/kW in 2050. The cost for installed energy capacity is expected to drop from 69 €/kWh to 40 €/kWh in the same period. These assumptions are aligned with reference [129].

Grid prices

The assumed grid prices (i.e. the price of electricity purchased from the grid) are based on reports from regulating agencies of each region [107,130–135], as summarized in Table 3. Future grid price projections are not part of our work. This is a limitation given that grid prices can strongly dictate the profitability of alternative generation solutions.

Table 3 Assumptions for grid electricity price

Country, Mine	Grid Price (€/MWh)
United States, Morenci	59
Australia, Olympic Dam	102
Mexico, Buenavista del Cobre	74
China, Dexing	100
Peru, Cerro Verde	77
Chile, Escondida	87
Indonesia, Grasberg	81

For selling the surplus of electricity, we assumed an energy export price of 50% of the import price, which is a common ratio in the absence of subsidies. The maximum exported power and the maximum imported power must respect the contracted power level.

3.2.3. Scenarios

In summary, we defined the following set of scenarios comprehending different mines and target years:

- Mines: we look at seven mines to represent the main copper-producing countries and other internationally significant copper operations. Each mine is characterized by i) a different solar profile and ii) the (current) grid price.
- Target years: we define a set of 5 target years (2020, 2025, 2030, 2040, and 2050). The differences between these years are the (projected) capital costs, operational costs, and the lifetime of the PV and storage technologies.
- Grid price: To account for the uncertain evolution of grid prices, we consider scenarios with prices that are 20% higher and 20% lower than the current prices at each assessed location for each target year.

The combination of these scenarios (mines and target years) results in a total of 35 cases. These scenarios allow us to answer our first research question (when, where, and how to become fully solar) and our second research question (energy costs when strongly relying on a solar generation). For our third research question, the competitiveness of the different mines in terms of their specific-energy demand, we will further consider their ore-grades. These ore-grades are not inputs to our optimization tool but used only in a post-processing evaluation, as detailed next.

3.2.4. Effect of declining ore grades

To analyze how the energy costs from declining ore grades could be compensated with falling costs of solar electricity, we need three elements: future energy costs, projections of the ore grades, and the relation between the ore grade and the electricity demand (which is nonlinear). The first element corresponds to outputs from our energy systems optimization model, while the other two will be explained now.

The forecasts for the ore grade in the different countries are based on reported yearly data for 2005-2017 [136] and then extrapolated for future years using an exponential fitting. China was not considered in this part of the analysis due to a lack of data for historical ore grades. To calculate the relationship between the ore grade and the electricity demand, we resort to reported ratios in the literature [20]. Note that this source [20] shows values in terms of primary energy, which we transformed into electrical demand following their assumptions and using statistical data from Chile [137]. The resulting values of the two latter elements are shown in subsection 3.3.3.

3.3. Results and discussion

This section has four components. First, we show the solar system design (PV, batteries, H_2 systems) for the different copper mines around the world, from 2020 to 2050. Second, we focus on the resulting energy costs. Third, we analyze the competitiveness of copper production, given the different ore grade projections in the mines. And fourth, we discuss the limitations of our study and motivate future work.

3.3.1. When should copper go solar?

Here, we first present a general overview of the results and then look deeper into each targeted year for different system outcomes.

Figure 12 shows the cost-optimal source of electricity (pie charts) and investment decisions (bar charts) for the selected mines in the target years. The pie charts show the share of electricity imported from the grid and the solar share (self-supply). The bar charts show the size (in % of peak demand, i.e. $MW_{installed}/MW_{peak\ demand}$) of the power contract, the battery system power capacity (the energy storage capacity is indicated with text in hours), the H_2 system power capacity (the energy storage capacity is indicated with text in weeks), and the size of the solar PV system. For example, the investments of Chile 2020 (left-hand side set of bars) show the power contract to be around one (i.e. similar to the peak demand), the PV system to be close to 1.5 (i.e. 1.5 times the peak demand), the battery system to be very small, and the H_2 system to be non-existent.

The general trend seen is a decreasing reliance on imports from the grid to satisfy demand. This is expected; as the price of solar technologies continues to decrease, eventually, they become cheaper than the current grid price. These growing solar shares are achieved with support from storage technologies. For sunnier regions, the simulation results suggest an earlier turn to a fully renewable energy supply. Consider now each target year:

2020: Optimization results show the potential for high solar shares in the near future, from 25% to 50%. Shares around 25-35% are quite inexpensive because of the low integration costs. In other words, the installed PV power plant is sized to match the energy demand during sunlight hours. During night time, mine operations rely on a grid backup, foregoing the need for storage. In fact, both energy storage technologies (BESS and H_2 systems) are almost non-existent at this point for every region. If not yet available, the construction of the PV plants should start immediately to achieve such systems in a timely matter.

2025: Chile, Peru, and Australia have 80% of their supply covered with solar electricity. Indonesia is on the other extreme with only a quarter of the electricity coming from PV, due to its lower solar resource and low grid prices, relative to the other locations. The rest of the locations approach half solar electricity supply in their cost-optimal solutions. Larger shares of PV are mainly enabled by deploying affordable battery storage. H_2 systems are still irrelevant because the grid provides a cheaper back up during winter.

2030: Chile may have the first fully renewable mine in the world. But also Peru, Australia, Mexico, and China are now largely based on solar generation (80-

90%), with only a few weeks per year relying on the grid. Battery investments are very strong, equalling peak demand, and the first H_2 systems are deployed, offering long-term storage given its larger storage capacity. The U.S. and Indonesia exhibit a slower rate of local solar deployment due to their lower grid prices.

2040: Chile, Peru, and Australia are fully renewable. The rest of the countries are above 80%. Additionally, energy storage system investments are strongly increasing, and their power capacity is 1.5 to 2.0 times the peak demand. Both China and Indonesia require larger power capacities of batteries compared to the other regions, mainly because of a need to balance intra-day fluctuations from variable weather.

2050: All regions are practically fully renewable. That is, if the current grid costs stay constant, it will be cheaper to be fully solar by 2050, leading to sustainable power production in copper mines and dramatically decreasing the corresponding carbon footprint. Such a scenario favors meeting environmental laws and regulations and garners a positive image for the mining industry, both locally and for international trading partners.

In short, shifting to solar is an attractive investment. Mines in all regions should target a solar share of at least 25% by 2020, with the first locations reaching almost 100% by 2030. By 2040 all mines should be nearly fully solar. Such a transition is possible due to rapidly falling PV and storage prices. These findings are helpful for all decision-makers related to the energy supply of mines and reveal a quick need for action.

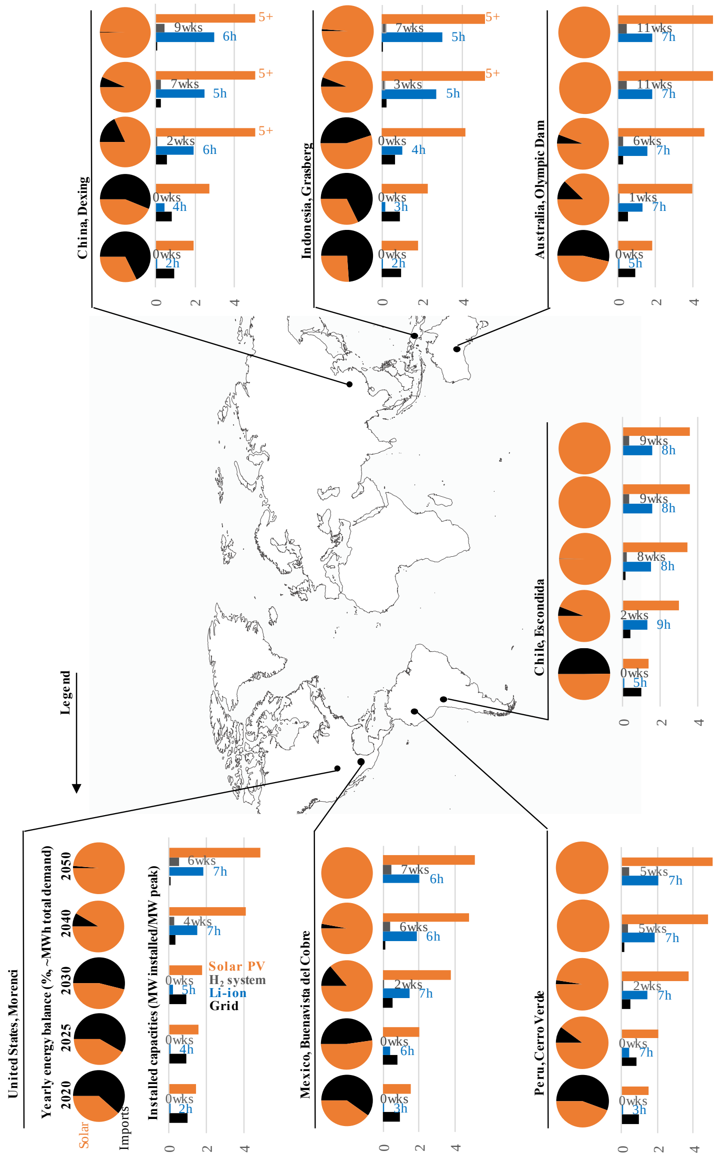

Figure 12 Solar share and investment decisions (grid contract, and battery, hydrogen, and solar system) at each mine for the years 2020 to 2050

3.3.2. How much cheaper can solar PV make the electricity costs for mines?

In this section, we show how the average electricity costs will develop over time in each region if the optimally designed system (solar, storage, grid) is deployed (Figure 13). These costs consider all investment and operational costs from local solar and storage systems and the grid imports/exports

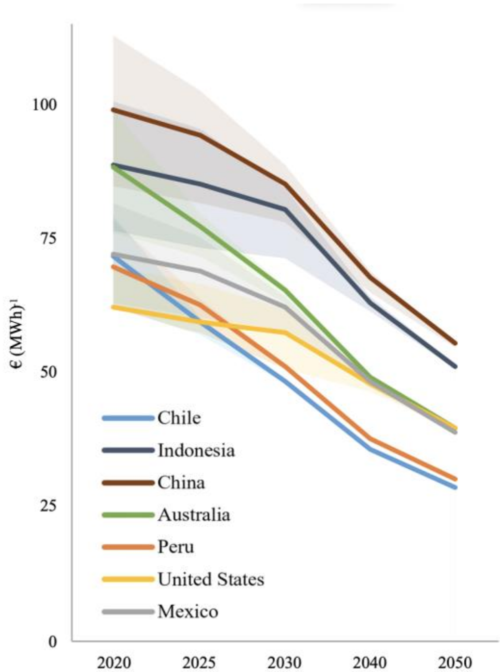

Figure 13 Average costs of electricity (solar, storage, grid) in each region. *The shaded areas represent the spread resulting from the grid price scenarios.*

Figure 13 shows how deploying solar systems will reduce the electricity costs for copper mines around the globe, even in those countries with lower solar resources. Current prices range between 60 and 100 €/MWh and are expected to be between 30 and 55 €/MWh in 2050. The spread of these ranges is based on differences in climatic conditions and grid prices of each location. Solar generation gives Peru and Chile the opportunity to, very rapidly, achieve the most competitive electricity costs, worldwide. Notwithstanding the competitive advantage that such costs could provide, other mine characteristics, such as ore grade, also play a role in determining the final competitiveness of copper extraction at a particular site. Overall, our results are consistent with cost projections for the evolution of global power systems found in the literature. In [129], the authors calculate a global levelized cost of electricity of 52 [€/MWh] by 2050. Moreover, in the regionally disaggregated results of the same study, the cost of electricity is at 39 [€/MWh] in South America by 2050. In our results, the local systems in that region are also at the lower end of the costs. More precisely, our results indicate even lower costs for the mines. This would be explained by the exceptionally favorable climatic conditions for solar energy that can be found in the specific locations of the mines.

The shaded areas presented in Figure 13 show the spread of the resulting electricity costs for the grid price scenarios. The impact of grid prices decreases over time as the share of local generation in the optimal electricity supply increases. This is, of course, conditioned by the assumptions for the cost evolution of the generation technologies. Further discussion about this limitation is offered in section 3.3.4.

Grid prices might be affected, among others, by the on-grid deployment of larger solar capacity. This would decrease the grid cost, offsetting the attractiveness of *local* solar solutions and, at the same time, improving average electricity costs. This logic also applies if grid prices are lowered by other factors (e.g. fossil fuel costs). The opposite is true if grid prices increase relative to the levelized costs of solar energy (plus the required integration costs, e.g. from storage systems): local solar electricity could become attractive even in locations with a low solar resource. In general, there are pros and cons of deploying local energy generation systems. On the one hand, mines could not profit from scale economies in the investment costs that very large-scale plants have. On the other hand, it would allow mines to profit from enhanced flexibility if multi-energy systems are deployed and could save transmission costs. In spite of these remarks, the message for the mine operators is clear: it is cost-effective to go solar, especially if the grid stays as it is now, that is carbon-intense and comparatively expensive.

Regarding our hydrogen technology selection, we observed that including fuel cells instead of gas turbines would result in a 5% reduction in the specific electricity costs for the mine in Chile in 2050. This cost reduction is due to the lower costs and higher efficiency of the fuel cells. The installed capacities of the respective storage technologies are not affected.

In conclusion, all mines can significantly reduce their energy costs with solar energy. Moreover, miners can profit from this opportunity regardless of the evolution of their respective regional power grids. Chile and Peru have particularly advantageous positions with the potential of reaching a cost of around 30 €/MWh. This information is relevant to mine planners that are looking to secure supplies with low electricity costs.

3.3.3. Can solar systems make the copper processing more competitive?

In this section, we analyze how the energy required per ton of copper produced can affect the competitiveness of mining operations in the global copper market.

Copper mines around the world are exposed to decreasing ore grades (Figure 14a). This, in turn, results in increased specific energy demand (MWh/ton Cu, Figure 14b). When this information is crossed with the energy costs from the previous subsection, we obtain the projections of specific electricity costs (€/ton Cu), as shown in Figure 14c. There, we observe how most countries can compensate for the electricity costs from lowering ore grades with cheap solar energy. For example, Chile in 2040, despite having its specific electricity demand doubled, would have specific electricity costs 8% cheaper as compared to the situation in 2020. It is also remarkable that in that case, the cost-optimal electricity supply would be full-solar, so the lower costs of PV and lithium batteries, along with the excellent solar resource of this country, explain this effect. Peru, where the solar resource is also high, would also benefit from this effect. Mexico and the U.S. are especially effective in offsetting their declining ore grades, with expected specific energy costs being at least 30% lower by 2050 than today. Nevertheless, their ore grades are among the lowest worldwide, which is why they still have comparatively high specific costs. In Australia, cheap solar energy would not be enough to compensate for a steep decline in the ore grade. At last, in Indonesia, the specific electricity costs are expected to decrease in the long-term. This country has the worst solar resource among the countries assessed in this study, but the forecast for its ore grade is the most favorable one.

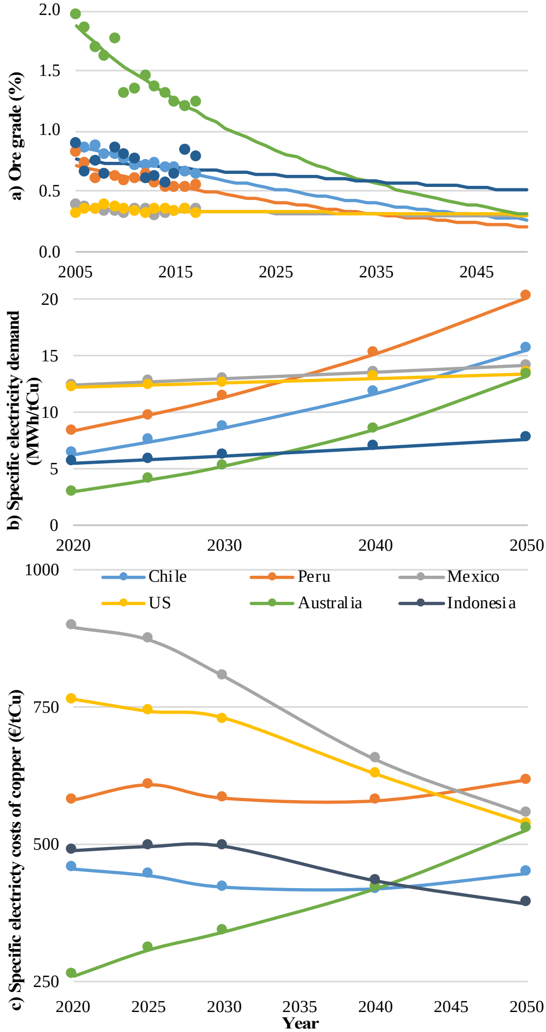

Figure 14: Combined effect of decreasing ore grades and solar electricity costs

a) Reported and forecasted (from 2018) ore grade by country. b) Forecasted specific electricity demand for copper production, by country.c) Obtained electricity costs per ton of copper for the different countries over the next decades, considering declining ore grades and the adoption of the optimal shares of solar electricity

We now address how do the specific electricity costs per ton of copper processed in 2050 of our scenarios compare to a stubborn scenario. Our scenarios imply that the mines adopt the optimal solar systems that we have discussed earlier; the stubborn scenario assumes that no changes are done in the technology mix of the power systems of each country and, thus, the grid prices remain constant (as in Table 3). Both scenarios follow the projections in ore grades decline and the resulting increase in the specific electricity demand for copper production. From Figure 15, it becomes clear that the stubborn scenario results in higher production costs for every country. The competitiveness of the mines in Chile, Peru, and Australia would be particularly compromised if they were to decide not to transition towards highly solar systems. This points again to the improvement in competitiveness that solar systems can offer.

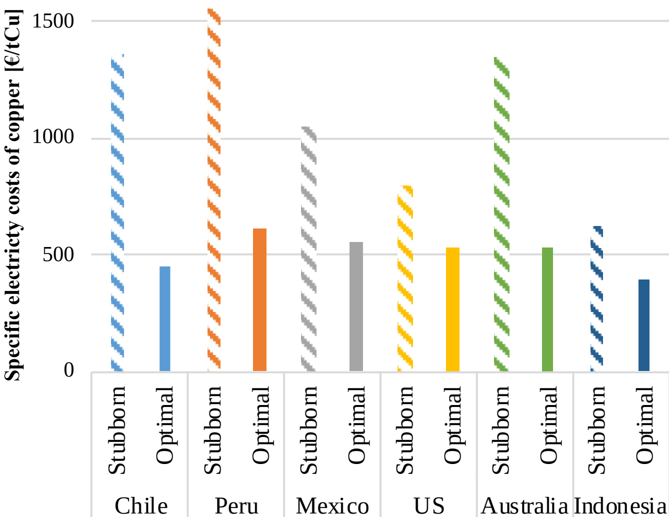

Figure 15: Electricity costs per ton of copper for 2050 by country.
Optimal solar mixes versus a stubborn scenario (current grid mix and costs remain constant)

In summary, all copper mines are exposed to decreasing ore grades, which translates into a higher specific electricity demand. Most locations can counteract this by deploying cost-effective solar and storage solutions. Chile can be particularly successful in this challenge given its high solar resource, while in Indonesia, solar technologies can be successful given the (currently) high grid price.

3.3.4. Limitations and outlook

Cost assumptions

Planning the future is inherently plagued with uncertainty, so as the cost projections considered in this study. They rely on learning curves that relate the deployed capacity of a technology (e.g. amount of sold solar PV modules) with its costs. This capacity is extrapolated to forecast future costs, which for more mature technologies has a reasonable precision, but for incipient technologies might be burdened with larger errors. While solar PV belongs to the mature technologies, batteries and, especially H_2 systems, are rather new. Hence, the costs and success of a highly solar strategy depend on how close the actual deployments of these storage devices are to the forecasts used in the learning curves. This economic data becomes the main driver of the results in our techno-economic model, but additional flexibility can be achieved in these systems by, for example, demand-side management strategies [51,52], which could help further reduce total costs.

Another factor that impacts the recommendations obtained is the on-grid electricity cost. We addressed this source of uncertainty by defining low and high grid price scenarios for each country, as a proportion of their current grid prices. Nevertheless, a more refined analysis would require considering region-specific models for energy system expansion planning that forecast time series for on-grid prices. This could be addressed in future work.

In terms of the specific energy costs of copper, these depend on the grade of the ore. Their future value relates to the projections of grades in new mines and the market conditions [138], which is yet another challenge that we propose as next step. Minding these considerations, it must be stressed that our forecast for the ore grades should not be used for purposes other than the comparison of the effects analyzed in this work.

Despite these considerations, our model and results do allow us to shed light on the trends of supplying solar energy to copper operations, as well as the combined effect of declining ore grades and decreasing costs of solar technologies. Furthermore, the inputs and outputs of the many scenarios are openly available.

Dimensions beyond costs

The integration of renewable energies into energy-intensive processes and the resulting de-fossilization of electricity supply are clearly beneficial for the sustainability of the energy system. As shown in this work, higher shares of fluctuating renewables require auxiliary technologies like BESS and H_2 systems. Thereby, environmental burdens associated with the increasing deployment of renewable energy technologies and flexibility options will be shifted to the upstream supply chain, increasing requirements for raw materials and triggering questions of land-use change. While the literature of ex-post environmental assessments in energy scenarios (see e.g. [139] [140]), as well as supply risks due to material bottlenecks (see e.g. [44],[45]), continues to grow, the integration of such factors in our models has largely failed to materialize so far. Thus, future studies should establish holistic assessments of energy technologies and scenarios beyond the sole consideration of system costs and direct emission constraints, which may be pivotal for the structure of model-based generation portfolios. As highlighted in [141], the linkage of energy system planning to methods in ‘Industrial Ecology’ allows for exploring new mitigation options, which may lead to more relevant mitigation scenarios as robust foundations for policy advice.

It is not only about electricity supply

Copper production requires not only electricity but also heat and fuels. For example, in Chile, the direct consumption of fossil fuels in the copper industry is as high as the electricity demand [137]. Some processes, such as haulage, have been transitioning to hybrid or fully electrical motors [142]. Therefore, every energy vector should be considered when aiming at fully decarbonizing the energy supply of the industry. Moreover, considering multiple energy vectors in the design of distributed energy systems adds further degrees of flexibility for integrating high shares of renewable technologies. Considering multi-energy systems, where energy can be transformed from one vector to another, is expected to yield solutions that are more cost-effective than those achieved when designing the supply of the different vectors independently [14]. While there is already experience in the industry on the use of solar thermal technologies for low-temperature applications [104] and several other solar technologies have been proposed for supplying the entire energy needs of the copper industry [143], a research gap remains in the integrated design of multi-energy systems for copper production.

3.4. Conclusions

We explored the future electricity supply of copper mines with an optimization model, called LEELO. In a case study, we looked at seven of the largest copper mines around the world and designed their electricity sourcing based on solar and storage technologies until the year 2050. We considered the specific energy cost (€/ton Cu), and the ore grade decline of these mines. Other inputs to the model include a generic yearly demand profile (hourly), a power-contract price for each mine, and an annual solar irradiation profile (hourly) for each mine.

Our findings show that mines need to start today with solar investments. All regions studied should already have by 2020, solar generation matching between 25 and 50% of the yearly electricity demand. By 2030, sunny regions should have near fully renewable supply, while regions with a lower solar resource will become predominantly solar by 2040.

Depending on the mine, the early costs (2020) of electricity range between 60 and 100 €/MWh. By 2050, this decreases to a range of 30 to 55 €/MWh, a result of the technological maturation of solar and storage technologies. Sunny regions will clearly benefit from lower electricity prices, enabled by solar technologies. Solar systems will allow all regions to have lower electricity prices than current grid prices.

Another relevant factor in copper extraction is the specific cost of electricity, strongly driven by the ore grade (lower grades mean higher energy demand). We observe that the effect of decreasing ore grades on specific energy costs can be offset by deploying highly solar power systems. This compensation is stronger in countries with good solar resources, such as Chile and Peru.

Solar copper mines showed to be economically attractive, given that many operations are within sunny regions. The above recommendations only hold if the technology-cost projections that were used in the analysis materialize. In terms of solar PV, the inherent uncertainty is low, as opposed to H_2 storage that is in an earlier stage of development. In the next chapter, we explore the integration of further energy demands, in a multi-vector setup that also considers heat, fuels, and the water and transport sector.

Data availability

The sources of the main inputs are all referenced throughout the manuscript, and compiled into one file that is openly available on an online repository [116].

Part II – Multi-vector water and energy system model with capacity-based energy demand flexibility

Chapter 4. Multi-vector water and renewable energy system including integrated desalination and pumped-hydro storage with seawater

This chapter is based on the publication “Integration of seawater pumped storage and desalination in multi-energy systems planning: the case of copper as a key material for the energy transition” by Simón Moreno-Leiva, Jannik Haas, Wolfgang Nowak, Willy Kracht, Ludger Eltrop, Christian Breyer, published in the Applied Energy Journal in 2021.

Executive summary

In this chapter, we present the first integrated design for desalinated water and energy supply that considers all forms of energy required in the copper production process.

For this, we develop an optimization model for planning integrated multi-vector energy and water systems. The model includes -for the first time in an energy system planning model- a concept for integrated pumped-hydro storage using sweater and reverse osmosis desalination.

Our results show that water-energy systems for copper production based exclusively on renewables can today achieve costs as low as those of conventional fossil-based systems, when integrating multi-vector planning and seawater pumped-hydro storage. For a case study in Chile and in fully renewable scenarios, the specific cost of supplying energy and desalinated water decreases from 520-670 € per ton of copper at current costs to 330-360 by 2050. By 2030, using seawater pumped-hydro storage makes a fully renewable, multi-energy scenario the least-cost alternative. Such an integrated system is an enabler for reducing the environmental footprint that copper brings into the global energy transition.

4.1. Introduction

In the previous chapter, we assessed the adoption of PV and two storage technologies for the main copper-producing regions in the world. We showed that, by 2030, copper mines located in sunny regions go fully solar and that the very low PV costs can compensate for the increased energy demand from lower ore grades. However, energy vectors other than electricity were not considered (such as heat and fuels). Going beyond electricity into the field of multi-energy (or multi-vector) systems, in [144], cost-optimal designs for supplying the electricity and heat demand of a mine using wind power were presented, with a focus on the use of hydrogen. The authors concluded, for a case study in the North West Territories in Canada, that going fully renewable is technically feasible but economically unattractive. Finally, in [145], a method to optimally design the water supply of mining operations was developed, considering the energy demand for this process.

In Chapter 1 a series of challenges were identified regarding the design of renewable energy systems for copper production. First, energy demand representation needs to be improved so that the final uses are understood, and so that alternative supply routes can be proposed. The integration of transport and fuels demand along with electricity and different-temperature heat demands has not been observed in the literature. Also, the integration of water management systems in the energy system design process should be considered. This point is especially relevant when mines are located in arid regions, where water supply ultimately translates into an energy supply problem [11]. We address these challenges in this chapter.

Several studies have addressed the interaction between water and energy systems. First, from a water sector perspective, models that minimize the energy consumption for pumping in water supply systems have been presented [146]. In addition, there have been scientific efforts in exploring the potential for demand-side management of water supply systems at small scale (supply for one building) [147], large scale (transport from catchment to demand centers) [148], and its overall integration in smart grids [149]. While the approaches used for minimizing energy use and costs vary, the energy sector is usually considered exogenously, either with constant electricity prices or with static time-series obtained from existing power systems. Studies on the integrated planning of seawater desalination and multi-energy supply systems have been conducted for countries in arid regions, as Saudi Arabia [150], Chile [151], and Kazakhstan [15]. An idea to integrate seawater pumped hydro storage and seawater desalination with reverse osmosis (Integrated Pumped Hydro Reverse Osmosis, IPHRO) is presented in [152], where the feasibility of this concept is tested for different locations around the world.

In this chapter, we address the following research gaps, regarding methods and applications. First, the endogenous integration of the IPHRO concept in optimal planning models for multi-energy systems remains unaddressed in the literature. This could open the door for a new source of flexibility in the systems, which would speed up the integration of variable renewable generation. Second, the integrated design of water and multi-energy systems for copper production is not observed in the literature.

Such designs could help improve the environmental footprint of this key industry for the energy transition.

The goal in this chapter is to design water and multi-energy supply systems for copper production processes that use 100% renewable energy and have zero freshwater consumption, at hopefully little-to-no additional costs. This way, we expect to contribute to a faster and cleaner energy transition. We hypothesize that this goal can be achieved by simultaneously planning the energy (including multi-vectors) and water supply systems for copper mines. We contribute to the body of knowledge by:

- Developing a new method for integrated water and multi-energy systems planning, including for the first time an integrated concept for seawater desalination with pumped-hydro storage (IPHRO, as presented in [152]) endogenously in such planning models.
- Finding the optimal design (capacities and operation) of a desalinated water and multi-energy supply system, under different technological scenarios. This is the first design of such systems for the copper industry, which is a key material for the global energy transition.
- Analyzing the differences in costs and direct carbon dioxide emissions for different technological scenarios and their evolution until 2050, considering transparent cost-projections for the components of water and energy systems.
- Assessing the uncertainty of the proposed solutions. Uncertainties from emerging technologies are considered.

The proposed methods are demonstrated with a case study in Chile that is representative of the copper industry in the world's main copper-producing region. In the next section, we explain the methods. In section 4.3, results are presented and discussed, analyzing its limitations too, and offering insights for further research. Finally, in section 4.4, conclusions are presented.

4.2. Methods

Costs and carbon dioxide emissions are compared for four different technological scenarios that supply the energy and water needs of a generic copper mining operation in seven milestone years until 2050. For that, an optimization model is used that calculates the cost-optimal installed capacities of the different technologies in the system and its operation. This model is based on mass and energy balances. Its inputs include technology cost projections, performance parameters (including generation profiles for variable renewables), and demand curves for different energy vectors. An ex-post analysis of costs and CO_2 emissions is performed that allows us to compare the different scenarios. Finally, the robustness of our results against selected sources of uncertainty is tested using Monte Carlo simulations. Figure 16 offers an overview of the methods. In the following, they are explained in detail.

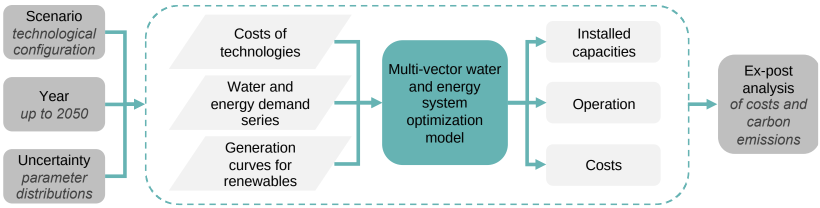

Figure 16: Overview of the methods in chapter 4

In section 3.2.1, the optimization model is presented. In section 3.2.2, the inputs for the case study are explained. Section 3.2.3 presents the considered scenarios. Section 3.2.4 covers the ex-post analysis of costs and carbon emissions. In section 3.2.5, the approach for assessing uncertainty is presented and, in section 3.2.6, data availability is detailed.

4.2.1. Optimization model

A linear optimization model is used to calculate the cost-optimal size of the components of the system and its operation. The model is an extension of the Long-term Energy Expansion Linear Optimization model (LEELO). which is detailed in reference [17] and has been validated in multiple publications [2,115,153,154]. The new formulation integrates buses and demand nodes for multiple energy vectors, desalinated water supply, and an integrated concept for seawater pumped-hydro storage and reverse osmosis. Final energy demand consists of electricity, heat, and fuels. A wide selection of technologies is considered for energy generation, transformation, and storage, along with the technologies for water desalination and transport.

Figure 17 represents the configuration of the system components for one node in the proposed optimization model. At each node, there can be installed capacity of every technology for energy generation (represented with circles in the figure), conversion (arrows), and storage (boxes). Technologies that require seawater are only allowed when the node is at the sea. In this study, we consider the demand for electricity, hydrogen, low-temperature heat, and desalinated water. Demands are represented with triangles connected to the respective buses (horizontal lines) in the figure. Transport of electricity and desalinated water is considered, and it is characterized using the distance between nodes and the altitude difference, in the case of water transport. Desalinated water can be produced either with an independent RO plant or with one that is part of an integrated concept for energy storage and seawater desalination, which is explained in the following.

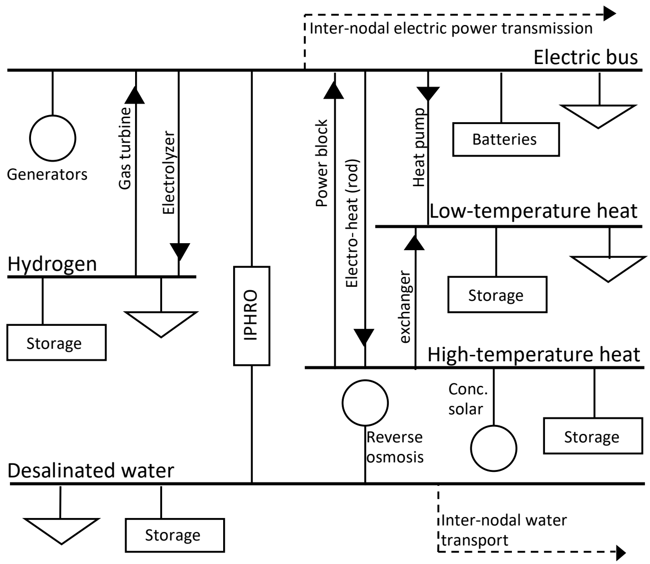

Figure 17: Topology of the multi-vector system for a single node.
Horizontal lines represent the buses for each vector and the corresponding demand (triangles), generation technologies (circles), and storage (boxes).

The option of building integrated infrastructure for seawater desalination with reverse osmosis (RO) and seawater pumped-hydro storage is considered. This concept offers further operational flexibility by taking advantage of the fact that turbines and RO plants operate at similar head heights: using a single pump-turbine, seawater is pumped to a reservoir that can let water flow to the pump-turbine and the RO plant. This sub-system is represented in Figure 18. We consider it as presented by Slocum et al. [152]. They call this concept *Integrated Pumped Hydro Reverse Osmosis* (IPHRO); we stick to that name and integrate it within our optimization model. This is the first time this concept is integrated endogenously into a multi-vector energy system planning model.

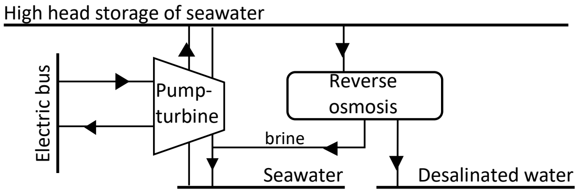

Figure 18: Schematic representation of the IPHRO concept

The IPHRO concept also considers mixing the stream of concentrated brine from the RO plant with the stream of seawater from the turbine. This aims at reducing the environmental impact of RO in the ocean.

The decision variables of the optimization model are the energy and power (or volume and flow) capacity of the different components of the system, as well as their operation at an hourly resolution over a year. The objective function is the sum of the annualized capital costs and the operational costs (fixed and variable) over a year. The main restrictions are the balances for the different vectors and the generation profiles for the variable renewables. In the following, the formulation of these restrictions is explained.

The balances for the heat, water, and hydrogen buses have the formulation presented in **equation 4.1**, where the index v enumerates the different vectors except electricity. In **equation 4.1**, $fC_{n,c,t}$ are the flows converted into vector v ($x \rightarrow v$) and converted from vector v to another vector ($v \rightarrow x$) by conversion technology c during t at node n; η_c is the conversion efficiency; $S_{n,s,t}$ is the level of storage technology s at t and at node n; $lS_{n,s,t}$ are the losses in storage s during t; and $fT_{n,T,t}$ is the flow transported by transport technology T to node n. Finally, $d_{v,n,t}$ is the inelastic demand for vector v. In the heat bus, primary solar heat generation is represented as a conversion technology that converts a solar irradiation profile into usable heat. For this study, inter-nodal transport is considered only for water and electricity.

$$\sum_{c:\,x\rightarrow v} fC_{n,c,t}\eta_c - \sum_{c:v\rightarrow x} fC_{n,c,t}\eta_c - \sum_{s:stores\;v} (S_{n,s,t+1} - S_{n,s,t}) - \sum_{s:stores\;v} lS_{n,s,t} + \sum_{T:transports\;v} fT_{n,T,t} = d_{v,n,t}\;, \forall v, n, t \tag{4.1}$$

The balance of the electricity bus is represented in **equation 4.2**. Here, $fR_{n,r,t}$ is the electricity generated by variable renewable energy plant r; $fG_{n,g,t}$ is the electricity generated by conventional generator g; $fC_{n,c,t}$ is the energy converted into electricity ($x \rightarrow e$) or from electricity ($e \rightarrow x$) by conversion technology c; $d_{n,t}^{wt}$ is the electric power demand for water transport; $fT_{n,T,t}$ is the electric power transported to node n; and $d_{n,t}$ is the inelastic electricity demand at node n at timestep t. Note that storage technologies follow Equation 1.

$$\sum_{r} fR_{n,r,t} + \sum_{g} fG_{n,g,t} + \sum_{c:\,x\rightarrow e} fC_{n,c,t}\eta_c - \sum_{c:\,e\rightarrow x} fC_{n,c,t}\eta_c - d_{n,t}^{wt} + \sum_{T} fT_{n,T,t} = d_{n,t}\ ,\forall n,t \quad (4.2)$$

Besides, power generation from variable renewable sources $fR_{n,r,t}$ is bounded by the availability of the corresponding resource ($profile_{n,r,t}$ in **equation 4.3**). Also, the flows generated, converted, and transported by each technology are limited by the installed capacity. For simplicity, we exemplify this with the restriction for renewable generators (**equation 4.4**), where $pR_{n,r}$ is the installed power-capacity of technology r at node n. The restrictions for the rest of the technologies are analog. For storage technologies, the stored energy must be below the installed capacity $eS_{n,s}$ (**equation 4.5**).

$$fR_{n,r,t} \leq profile_{n,r,t}\ ,\forall n,r,t \quad (4.3)$$

$$fR_{n,r,t} \leq pR_{n,r}\ ,\forall n,r,t \quad (4.4)$$

$$S_{n,s,t} \leq eS_{n,s}\ ,\forall n,s,t \quad (4.5)$$

Finally, the objective function is formulated in **equation 4.6**, where pG are the installed capacities of fossil generators; pC are the installed capacities of the conversion technologies; pT are the capacities for inter-nodal water and energy transport; cC are the capital costs of technologies; oC are the fixed operational costs; and vC are the variable operational costs. Then, $z_{opt} = arg\ min(z)$ represents the design and operation of the system. Note that the power demand arising from a vector's transport are accounted for in the corresponding buses and therefore the resulting variable operating costs are not explicitly written in the objective function, but they are implicitly considered.

$$z = \sum_n \sum_r pR_{n,r}(cC_r + oC_r) + \sum_n \sum_g pG_{n,g}(cC_g + oC_g) + \sum_n \sum_c pC_{n,c}(cC_c + oC_c) + \sum_n \sum_T pT_{n,T}(cC_T + oC_T) + \sum_n \sum_s eS_{n,s}(cC_s + oC_s) + \sum_t \sum_n \sum_r fR_{n,r,t} vC_r + \sum_t \sum_n \sum_g fG_{n,g,t} vC_g + \sum_t \sum_n \sum_c fC_{n,c,t} vC_c \quad (4.6)$$

4.2.2. Inputs

In the following, the inputs to the optimization model are explained. These can be reviewed in detail in the permanent repository [155].

Case study

Our methods are demonstrated with a fictional case study that is representative of a generic copper mining operation. The case study is located in the Atacama Desert in Chile (the world's main copper-producing country [156]), where several copper mines are located. More than 3 GW of PV generation capacity is installed in northern Chile [157]. Also, a project exists for building the first seawater pumped-hydro storage of the region (the Valhalla's Espejo de Tarapacá project) [152].

Two spatial nodes model the system. One node is located at the seashore and is where the desalination plant and the pumped-hydro seawater energy storage will be located. Desalinated water must be transported to the second node, which corresponds to the mining operation where the final water and energy demand takes place. The nodes are 140 km apart and node 2 is at 2700 meters above sea level. The production process is considered from mineral extraction to copper refining, via pyrometallurgical methods. The production flow is set at 1000 tons of refined copper (tCu) per day. This is used as a reference to scale energy and water demand. However, the results for total costs and emissions are later normalized (per ton of copper) to ease the comparison.

Selected technologies

PV, wind power, and geothermal energy are considered for primary electricity generation. In the reference scenarios, where fossil fuels are allowed, combined-cycle gas-fired power plants are also considered. For heat generation, concentrated solar heat with parabolic trough technology is considered (which can be converted to electric power if the model sees this as cost-effective). The selection of parabolic trough against other solar concentration technologies is based on data availability and the widespread use of this technology. Considering other alternatives, such as a central receiver, is discussed in section 3.3.4.

For energy storage, we consider lithium-ion batteries, hydrogen storage in salt caverns, high-temperature heat storage, seawater storage with height difference (as part of IPHRO concept), desalinated water storage, and low-temperature heat storage.

Finally, for energy conversion technologies, we consider electrolyzers for power-to-gas conversion, combined-cycle hydrogen turbines for gas-to-power, electrical rods and heat pumps for power-to-heat, power blocks for generating electricity from high-temperature heat (eventually completing a concentrated solar power -CSP- plant), heat exchangers to produce low-temperature heat, and a pump-turbine that generates electricity from high-pressure water and vice-versa. Because hydrogen-fueled gas turbines already exist for large experimental installations and based on [158], we assume that they are commercially available as of 2030. The chargers/dischargers of batteries are also modeled as conversion technologies. A RO desalination plant is also considered, which produces desalinated water from high-pressure seawater.

The selection of technologies is based on trends in renewable energy systems planning [13] and recent applied studies in the field [159]. Proven technologies are favored. From an energy planning perspective, the most novel alternative that we consider is the IPHRO concept, which does not report existing installed capacity to date. However, a seawater pumped-hydro energy storage plant exists in Okinawa, Japan [160].

Costs of technologies

The costs of the system are calculated per annum. Capital costs (CAPEX) are expressed as annuities using the corresponding lifetime of technologies and a discount rate at 5%, based on [161]. Fixed operational costs (OPEX) are indexed to the corresponding installed capacities and variable OPEX to the corresponding flows.

Cost and lifetime assumptions are taken from [162] and [159] and complemented with the following sources and assumptions. Detailed cost assumptions can be found in Appendix 1. The costs of PV and Li-ion batteries are taken from [163]. The assumptions on hydrogen-related components are taken from on [158]. The assumptions on water transport and desalination components are complemented with [150]. The variable OPEX of fossil-based power generation is adapted to the region of the case study. For this, a combined cycle efficiency of 60% and a natural gas buying cost of 25 €/MWh are assumed, based on reported industrial prices of natural gas in the local market [164]. Diesel costs are assumed at 0.3 €/l, based on [165]. Fuel price assumptions serve merely as a reference since fuel prices are highly variable. We consider the costs of protecting against seawater corrosion by increasing the capital costs of the interface for the seawater pumped hydro storage by a factor of 1.8, which would be rather conservative [166].

Performance of technologies

Three parameters characterize the performance of the technologies in the system: their lifetime, their efficiencies, and -for variable renewables- their generation profiles. The assumed lifetime and efficiency of technologies are static parameters that can be reviewed in detail in the appended file. The same source as for the costs is used [162]. This is intended to provide consistency in the input data.

Generation profiles of variable renewable sources depend on the weather. We use existing models to calculate hourly generation profiles for a set of different locations in the sea and mine nodes. As explained in section 4.2.2, these profiles then constrain the energy generation of the corresponding plants in the optimization model. PV profiles are obtained from *Explorador Solar* for single-axis horizontal tracking modules [110]. For wind power generation profiles, we use *renewables.ninja* [167] for a turbine model Vestas V90 2000 with a hub height of 80 meters. Heat generation profiles for CSP are obtained using *SAM software* [168]. Only the heat generation profile of the solar field is used because the other components that complete a standard CSP plant are sized independently within our optimization problem.

The configuration and performance of the RO desalination plant are based on [152]. We assume a water recovery efficiency of 50% at the RO plant. Concentrated brine leaves the RO modules at high pressure and some energy can be recovered. The efficiency of that process is set at 30% of the energy content of the input flow at the modules. The efficiency of vertical water pumping is set at 76%, based on [150].

Water and energy demand modeling

Water and energy demand profiles are aimed at representing a generic operation of copper mining and refining. For this, we use data from a survey covering all the main copper mines in Chile [137]. From that database, the specific demand for electricity and fuels is retrieved, expressed as energy per unit of copper content in the output, for the different stages of the production process. We use the specific energy demand factors to calculate the total demand for a given production level. We model the dynamics of electricity demand using generic power load curves for copper mining [2]. We also represent the seasonality of low-temperature heat demand based on local weather series. We assume a constant demand for fuels. In the following, we explain the use of the different energy vectors along the copper production process. This characterization is based on [169].

First, copper ore is extracted and hauled on trucks. Depending on the scenario (see section 4.2.4), the energy demand for mineral hauling is covered with diesel or electricity. The mineral is then milled and concentrated; these operations are powered with electricity. Later, copper concentrate is smelted and converted to produce copper anodes, demanding electricity for the oxygen supply and fuels to start the reactions (natural gas or hydrogen depending on the scenario). The anodes are then electro-refined, demanding both electricity to drive the electrochemical reaction and low-temperature heat to maintain the required temperature.

To model water demand, we use data on specific water use in the Chilean mining industry for 2019 [170]. This value is adjusted to the production levels and a specific water demand of 119 m^3 per ton of refined copper is obtained. This is consistent with the blue water footprint reported by [171] for the same region in 2014 (96 m^3/tCu). The difference with that value can be explained by the decline in the copper content of the mineral during that period: more mineral must be processed to recover the same amount of copper. The specific water demand is then adjusted by production. We assume that the water demand is covered exclusively with desalinated seawater. Water desalination and its transport over long distances and with high pumping heads are common praxis for mines in arid locations [11].

4.2.3. Ex-post analysis of costs and emissions

Once the cost-optimal capacities and flows in the system are found by the optimization model, additional fossil fuel flows are added if fossil fuels are allowed in the scenario (e.g. forcing the use of diesel in trucks). The corresponding costs are also added to the total costs of the system. Finally, the direct emission of carbon dioxide from the combustion of fossil fuels is calculated using emissions factors from [172], as shown in Table 4.

Table 4: Carbon dioxide direct emission factors.

Fuel	Emission factor $kgCO_2/MWh_{gross}$
Diesel	267
Natural gas	202

From [172].

4.2.4. Scenarios

Four scenarios are compared (summarized in Table 5). These are implemented by activating/deactivating the corresponding technologies and demands in the optimization model. The first two scenarios include fossil fuels for energy supply and serve as a reference. Scenario one (S1) does not consider the IPHRO concept, while scenario two (S2) does. The last two scenarios represent the fully renewable multi-vector approach. Similarly, scenario three (S3) does not include the IPHRO concept and scenario four (S4) does. All scenarios use exclusively desalinated seawater. These four scenarios are calculated for the milestone years 2020, 2025, 2030, 2035, 2040, 2045, and 2050.

Table 5: Comparison of the four scenarios considered in chapter 4

Scenario	Energy supply	Water supply	Pumped-hydro seawater storage (IPHRO)	Heat and fuels
S1	Fossil sources allowed	Desalinated with RO	No	exogenous
S2	Fossil sources allowed	Desalinated with RO	Yes	exogenous
S3	Fully renewable	Desalinated with RO	No	integrated
S4	Fully renewable	Desalinated with RO	Yes	integrated

The scope of the optimization problem is the water and energy supply system. Water and energy are supplied in forms that can be directly used in the production processes without further transformations, except the electricity supply for the drivetrains of trucks when these use an on-board diesel generation. In that case, the electricity for the electric motors is generated onboard using diesel. We discuss this assumption in section 4.3.4. To ease the comparison among scenarios, a greenfield approach will be followed, starting from scratch for each milestone year. This makes sense for mining operations as they can have shorter planning horizons for infrastructure, as opposed to more gradually evolving national grids (e.g., 30 years for planning a national energy transition versus 5 years for building the energy system for a new mine or renewing an existing one).

In all scenarios, the demands for energy in the form of electricity, heat, and fuels are considered. However, only the fully renewable scenarios (S3 and S4) are modeled with a sector-coupled (or multi-energy) approach. In the conventional scenarios (S1 and S2), the flows of fossil fuels for heat and transport are added ex-post. This is explained in further detail next. Details on the demand levels for the case study can be found in the appendix.

Conventional fossil-allowing energy supply (without and with IPHRO, S1, and S2)

These first two scenarios will serve as a reference to represent the current energy supply in copper mining based on fossil fuels. In other words, the energy demand for heat and transport is prescribed to be supplied with fossil fuels. With this, we aim at representing the current standard de-coupled way of designing and managing energy supply in the industry.

This is implemented by removing the demand for heat and fuels from the respective buses in the optimization model and including the use of fossil fuels ex-post. These demands are covered by natural gas for heat supply (for copper smelting and refining) and diesel for transport. For electricity generation, gas-fired power plants are enabled in the optimization model. In S1, building pumped-hydro seawater storage is not allowed. However, the RO plant is still considered. For S2, the option of storing seawater (at the high reservoir) is activated.

Fully renewable (without and with IPHRO, S3, and S4)

Two fully renewable scenarios are defined, where fossil fuel-based energy supply is *not* allowed. Here, the demands for the final forms of energy that are required in the process (electricity, heat, and hydrogen) are defined as an input to the optimization model. Consequently, their supply can result from transformations among different vectors stemming from different sources. We refer to this as a multi-vector (or sector-coupled or integrated) configuration. Using the final *service* that energy provides in the process as the input in the optimization model is discussed in section 4.3.4.

In these scenarios, transport is assumed to be electric, and its demand is then added to the electricity demand profiles. Also, in both scenarios, hydrogen is considered for initiating the smelting process. At last, while S4 considers the option of building the IPHRO concept, S3 does not.

4.2.5. Internal consistency against selected sources of uncertainty

The process of planning future energy and water systems involves dealing with uncertainties of various kinds. Although in this study we rely on consistent data, results are tested against the uncertainty of specific components: seawater storage, the seawater pumping system, and the inter-nodal pipeline for desalinated water. Uncertainty in the cost of fossil fuels is also considered. We select those components based on their importance for the topological differences among scenarios and the relative novelty of their inclusion in energy systems design. Monte Carlo simulations are performed for the year 2030. We use triangular probability distribution functions to avoid infeasible extremes. Figure 19 shows the histograms for the input data. The selection of the distribution parameters is based on the following criteria. The peak of the distributions is at the original assumptions based on the literature. The minimum and maximum are arbitrarily set at plus-minus fifty percent, except for the lifetime of the seawater pump-turbine. For this technology, which has only one reported application, the distribution is left-skewed to represent the potential negative effect of seawater-induced corrosion on the lifetime of the technology. In particular, the minimum is set at 20 years, the peak at 50, and the maximum at 60. 50 runs are performed, based on reported experience with similar setups in energy systems planning for the number of runs required for convergence [114].

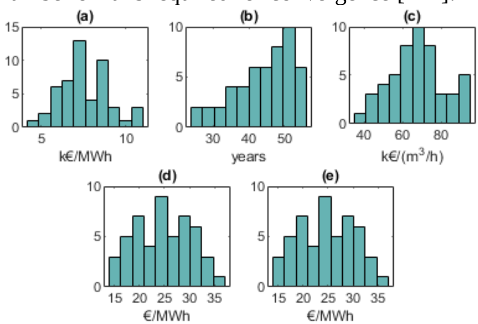

Figure 19: Histograms of the input data for the Monte Carlo runs to test internal robustness of results against selected sources of uncertainty.

(a) Specific CAPEX of seawater storage. (b) Lifetime of the seawater pump-turbine. (c) Specific CAPEX of inter-nodal water pipeline. (d) Cost of natural gas. (e) Cost of diesel.

Software and access to data and code

The optimization model is implemented in GAMS [173], reading data from MS Excel, with some tasks automatized with VBA. Matlab is used for generating the random inputs and for analyzing and plotting the results. All the input data described in the previous subsections can be found in a permanent repository in reference [155].

4.3. Results and discussion

The description of the results is organized as follows. First, the installed capacities and the operation of the systems are analyzed, to understand the cost-optimal designs under the different scenarios (section 4.3.1). Next, the resulting costs and emissions are explored to compare the economic and environmental performance of the proposed solutions (section 4.3.2). In section 4.3.3, the results for the Monte Carlo runs are presented that describe the effects of the selected sources of uncertainty. Limitations of this study and new research paths are discussed in section 4.3.4.

4.3.1. Infrastructure and operation

Infrastructure

The infrastructure plan resulting from the optimization is presented in Figure 20, which shows the cost-optimal installed capacities for generation and conversion technologies until 2050 for the four scenarios (S1 to S4). Figure 21 shows the energy-capacity of the storage technologies. Recall that these are calculated for a greenfield approach and that the capacities correspond to the desalinated water and energy supply systems required for the production level of the case study (1,000tCu/day). This production capacity puts our case study in the middle of the world's top 20 copper-producing mines. As a reference, Las Bambas in Peru has a production capacity of 430,000tCu/year, Chuquicamata in Chile 370,000, and Kansanshi in Zambia 340,000 [174]. After describing the general trends, we will analyze the scenarios individually and conclude the section with a remark on the flexibility of inter-nodal water transport.

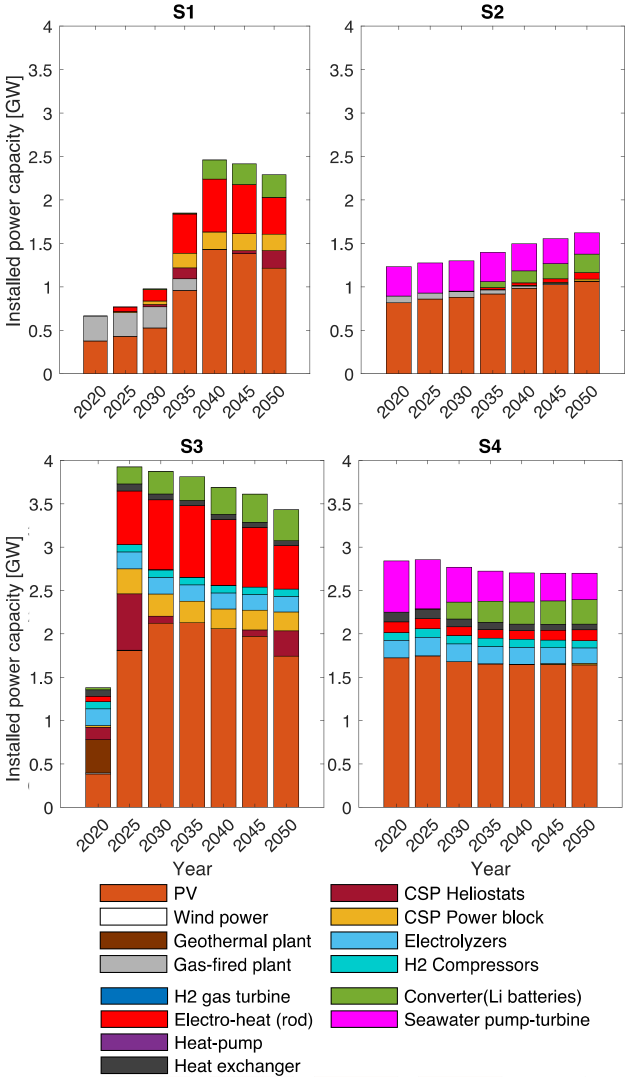

Figure 20: Installed power capacities of generation and conversion technologies until 2050 for the four technological scenarios.

Capacities correspond to the production level of the case study (1000 tCu/day).

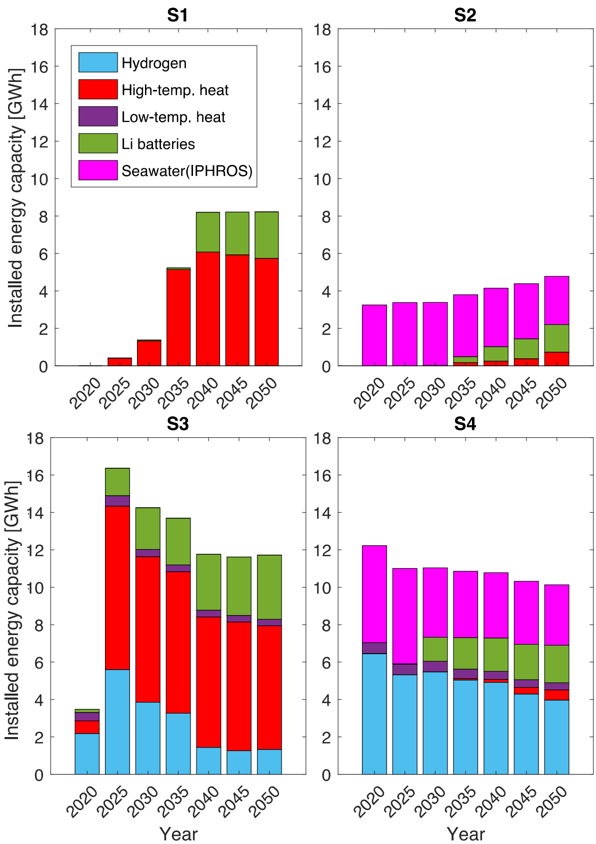

Figure 21: Energy capacity of storage technologies for the four scenarios until 2050. *Capacities correspond to the production level of the case study.*

Figure 20 shows that all scenarios rely strongly on PV, complemented with energy storage technologies and/or fossil-based power generation. This is consistent with the excellent climate conditions that the region of the case study offers for solar energy [104]. PV dominates solar generation (over CSP) because it has lower costs when combined with pumped-hydro storage. If that storage option is not available (S1 and S3), CSP becomes more relevant but the solar fields are complemented with electro-heat. Note that, for CSP, the capacity of the solar field, the thermal energy storage, and the power block are sized independently. S1 and S2 exhibit the lowest total installed capacities for energy generation, conversion, and storage since those capacities cover only the electricity and desalinated water demand. Recall that here diesel (for hauling) and gas (for low-temperature heat at the refining and smelting operations) directly supply the other demands. If the IPHRO system (integrated seawater desalination and energy storage) is allowed (S2 and S4), then the model always recommends its deployment. Heat pumps and hydrogen turbines do not play a relevant role in any of the considered scenarios.

In S1, gas-based power generation is complemented with PV in the initial years and the cost-optimal electricity supply goes 100% renewable in 2040, as a result of declining costs of PV generation and storage. The total nominal capacity of the system increases over time as more PV capacity is installed in later years. The system uses electro-heat and high-temperature heat storage with steam turbines (power block) to balance increasing shares of variable primary energy generation. From 2040, batteries are installed as a result of declining costs, and a slight decline in total capacity is observed as CSP is deployed again.

In S2, the IPHRO concept acts as a low-cost source of flexibility for the system, which is now able to balance out more variable generation from PV using seawater pumped-hydro storage. This allows dispensing with 70% of the gas-powered generation capacity needed in S1, already at current costs. From 2035 on, lithium batteries and high-temperature heat storage are also installed, resulting in an upwards trend in total installed capacity.

Recall that in S3 and S4, fossil fuels are not allowed. In S3, geothermal power is installed for current cost conditions, offsetting storage capacity and resulting in an exceptionally low total installed capacity. However, already by 2025 the technology is no longer installed, when a larger share of solar energy combined with storage offers lower costs. High-temperature heat generation with concentrated solar energy only shows relevant capacities if installed by 2025 but not later. By 2050, it becomes again relevant in the cost-optimal mix, as a result of the projected decline in the costs of CSP. However, from 2025 on, high-temperature heat storage becomes relevant, be it fed from concentrated solar or electro-heat (with the corresponding power block for reconversion to electricity). Some capacity for low-temperature heat storage is also installed. Electrolyzers for hydrogen generation are always installed, but no gas-to-power capacity is observed. Hydrogen is used directly in the production processes. The installed capacity for generating this gas is around three times its demand, which suggests that this component is operated flexibly. Lithium batteries are installed as soon as 2025 and their share increases as their costs decline, displacing hydrogen storage capacity.

In S4, the model recommends deploying relevant capacities of seawater pump-turbines (as a part of the IPHRO concept), allowing the integration of a high share of PV already at current costs. The recommended capacity of PV is practically constant until 2050. The flexibility from the IPHRO configuration is complemented with hydrogen storage and lithium batteries from 2030 on. In both 100% RE scenarios (S3 and S4), hydrogen is more convenient around 2025 and is later offset by Li-ion batteries, given their better round-trip efficiency.

Regarding inter-nodal water transport and seawater desalination, the installed capacities are close to the final water demand (4944m^3/h in the case study), being oversized at most by 1.5%. This implies that the water supply system does not offer significant flexibility to the system. This is consistent with respective findings in literature for the flexibility of seawater RO plants [175][15].

In summary, the solutions are solar-dominated for all scenarios -which is consistent with the location of the case study-, hydrogen systems are only considered in renewable scenarios, and lithium batteries become increasingly relevant over time. In addition, IPHRO is a relevant component of the cost-optimal systems. This component is new in energy systems planning and the effect of some of its uncertainty sources is analyzed in section 4.3.3.

Operation

In this subsection, we explore the operation of selected components of the cost-optimal systems presented in the subsection above. The components that offer the most storage capacity are selected for the discussion. For the sake of space, selected scenarios are plotted that are representative of the 100% renewable configurations. In particular, the technological scenarios S3 and S4 are explored for the year 2030, because after this year the technological configuration of the system does not change significantly.

Figure 22 and Figure 23 represent the operation of the system over one year, at hourly resolution. For each plot, the x-axis represents the days of the year and the y-axis represents the hours in each day. Figure 22 shows the operation (charging/discharging and state-of-charge) of the buses for high-temperature heat and hydrogen, and lithium batteries for S3 in 2030. Figure 23 does it for IPHRO, hydrogen, and batteries for S4, also in 2030 (high-temperature heat storage is not installed in this scenario). In both figures, the first row of plots represents the state-of-charge of storage technologies, and the second row represents the operation of the bus. The operation corresponds to the difference between inputs and outputs to the bus of the corresponding vector. For example, for the batteries, it corresponds to the operation of the inverters. The difference is normalized by the power capacity of the input technology; the inverter, in the case of batteries.

The operation is consistent with the generation profiles of solar energy, which dominates the installed capacities in the system. This can be observed at the centered horizontal green stripes in the operation plots, indicating charging during daylight. In S3, high-temperature heat storage empties before sunrise and reaches a maximum state of charge by sunset. This pattern holds across seasons. In S4, the high-head seawater storage (from the IPHRO systems) behaves the same way. Seawater storage is peculiar in that it can discharge to two different devices that produce two different vectors: a turbine that generates electricity and a RO plant that produces desalinated water. This results in the storage being charged (with the pump-turbine) and discharged (to the RO plant) at the same time during daylight.

The hydrogen bus and batteries operate similarly in S3 and S4. Intra-day variations can be clearly observed in the operation of the hydrogen bus. However, the variations in the state-of-charge are starker at a seasonal level, as the storage reaches its maximum during a series of days in the winter ahead of days where the hydrogen production is cut off (the operation is planned with perfect foresight). Note that hydrogen is directly used to supply the final demand for the gas at the copper production processes. As exposed in the previous subsection, there is no gas-to-power capacity installed in these scenarios. From the perspective of the electric power bus - and considering the absence of gas-to-power capacity- the hydrogen system does not operate as an energy storage technology but it does operate as a flexible demand helping to balance out variable generation.

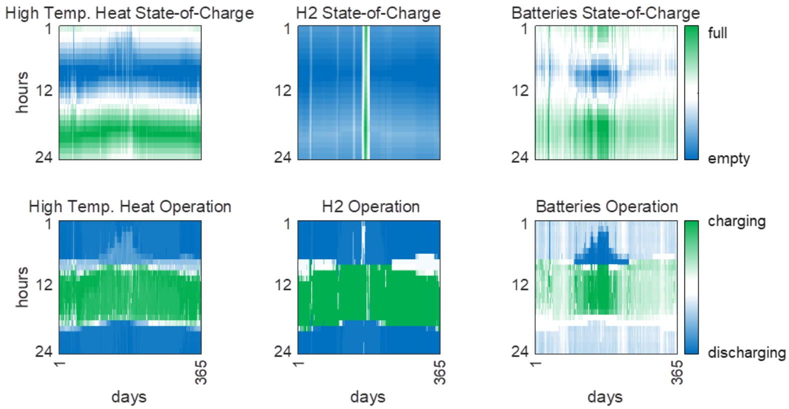

Figure 22: Operation of selected components of the system for S3 in 2030.
The operation corresponds to the difference between inflows and outflows of the respective bus, normalized by the power capacity of the input technology.

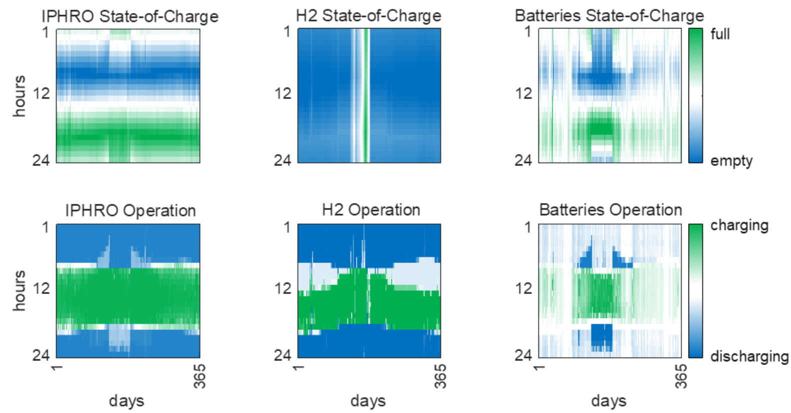

Figure 23: Operation of selected components of the system for S4 in 2030.
The operation corresponds to the difference between inflows and outflows of the respective bus, normalized by the power capacity of the input technology.

In the configuration of the case study, the final demand for desalinated water takes place at a node that is necessarily at a higher altitude than the seawater reservoir. This fact cancels one of the benefits of IPHRO: not having to pump again for distribution. However, the following co-benefits remain: larger pump-turbines can be employed, with the subsequent benefits in efficiency and economies of scale, and the concentrated brine that leaves the RO plant can be diluted with the seawater coming from the turbine, helping to mitigate the impact on marine ecosystems [152]. For example, for S4 in 2030, the total volume of water leaving the turbine is over fourteen times the total volume of brine produced at the RO plant. This would allow for a significant dilution before the brine goes back to the sea. To understand the environmental effects of the proposed systems thoroughly, further research is required (see section 4.3.4).

In summary, the storage technologies behave consistently with a solar-dominated system. Hydrogen production is flexible, and this gas is used for supplying final demand. High-temperature heat storage and IPHRO exhibit the clearest match with PV electricity generation.

4.3.2. Costs and emissions

In the following, the evolution of costs and emissions is analyzed for the four technological scenarios until 2050. Later, our results are compared against estimations for the energy costs of the copper industry in the region of the case study.

Figure 24 presents the total specific costs of the water and energy supply system for the four technological scenarios over time until 2050 (euros per ton of refined copper produced). All scenarios have decreasing costs over time, due to the lowering costs of energy technologies. The cost decrease is starker for S3 and S4, where the energy supply is 100% renewable, given the forecasted decrease in the costs of renewable generation and storage technologies (see Appendix 1). In S1 and S2, energy demand for heat and transport is always supplied with fossil fuels, thus limiting the effect of decreasing renewable energy and storage costs. This explains the lower rates at which the costs of the fossil scenarios decrease in Figure 24, which ultimately results in the renewable scenarios achieving lower costs in the future.

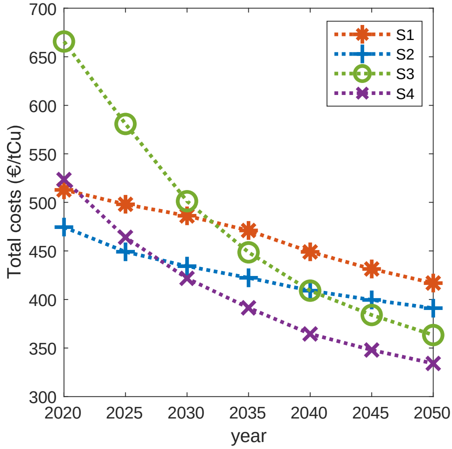

Figure 24: Cost comparison of the four technological scenarios over time.
Specific costs per ton of fine copper produced. S1 and S2 consider heat and fuel demand exogenously. S3 and S4 use exclusively renewable energy. S2 and S4 use integrated seawater pumped-hydro storage and desalination (IPHRO)

The technological configuration in S4 allows reaching competitive costs for a 100% renewable-based water and energy supply already in the year 2020 (on the plot: the 2020 costs of S4 and S1 are practically the same). At current costs, the larger installed capacities in S4 do not translate into dramatically increased total system costs. As of 2040, both renewable-based scenarios (S1 and S4) offer lower costs than fossil-based ones (S1 and S2). Even sooner, by 2030, S4 becomes the least-cost option, and that trend remains over the entire time horizon considered here. In other words, the IPHRO concept allows having a low-cost fully renewable energy supply sooner. The cost gap between S4 and S3 (no IPHRO) decreases over time, as the cost of other technologies (such as Li batteries and CSP) decreases. We observe that these results confirm our working hypothesis and suggest that IPHRO is a concept worthwhile exploring rather sooner than later.

Note that we do not consider a scenario where fossil fuels are allowed and the energy demand for heat and transport is endogenously integrated into the optimization model (sector coupling). Such a scenario could only lower the overall costs of the system as it would have further degrees of freedom. However, it is out of the scope of this work. The fossil-based scenarios that are considered here are intended as a reference that represents current approaches in planning the energy and water supply in the industry.

Regarding direct emissions of carbon dioxide (Figure 25), S2 performs better than S1. In S2, already today IPHRO displaces a major share of the natural gas-based generation used to balance out PV generation. The emissions in S1 and S2 level out in 2040, as electricity generation becomes renewable-based, and the remaining emissions come from the use of fossil fuels for heat and transport. This explains the flattening of the curve for S1 after 2040 that can be observed in Figure 25. S3 and S4 are emission-free since only direct carbon dioxide emissions from the combustion of fossil fuels are considered.

The scenarios presented here do not consider a carbon tax. Its implementation could further accelerate the tipping point where a sector-coupled and fully-renewable water and energy supply system becomes the cheapest option. For the industry to profit from these lower costs, quickly deploying the enabling technologies for integrating renewable fuels and electricity within the copper production is needed.

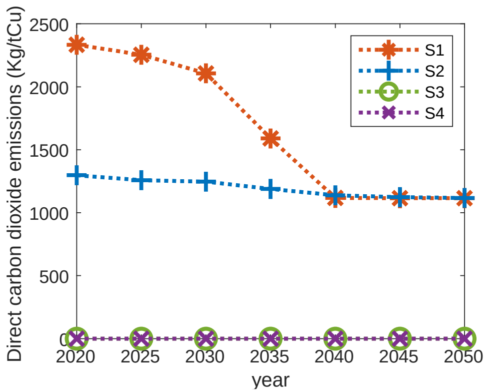

Figure 25: Evolution of direct carbon emissions from fossil fuel combustion for the four technological scenarios.

Specific emissions are expressed as kg per ton of fine copper produced.

As a reference, we estimate the current energy costs in the copper industry for the region of interest at around 614 €/tCu. This bottom-up estimation is based on an electricity cost of 89 €/MWh [176], diesel cost of 0.3 € per liter, and the average specific energy consumption for the industry in the region as reported in [137]. The estimation of diesel cost is based on values reported by operators in the copper industry. However, we deem this estimation low and it might be biased by direct or indirect subsidies. Therefore, it must be considered when interpreting the results that the costs of the fossil-based system could be higher and so we would be in the conservative side of costs for conventional systems. Although the resulting estimation for the overall costs is compatible with our results (ranging between 460 and 660 €/tCu in 2020), it cannot be directly compared, since many case-specific factors determine the water and energy demand of the process (copper concentration in the mineral, location, and age of the mine, among others) [1]. Regarding emissions, previous studies have found the carbon footprint of copper to be around 2.5-8.5 tCO_{2eq}/tCu for mines in Australia [177] and 4 tCO_{2eq}/tCu for a case study in Chile [178], which is higher than what we present. However, the direct CO_2 emissions we present in this study should not be interpreted as the full global warming potential of the proposed systems, as lifecycle emissions and other greenhouse gases were not considered.

At last, the total costs of the system could be even lower if we consider a connection to the grid, which would provide further flexibility to the operation. This would also open the door to explore the potential of the mining industry to provide flexibility to the grid through demand-side management.

In summary, a fully renewable supply of desalinated water and energy is economically feasible already at current costs and will become cheaper over time. This is achieved by integrating the design and operation of the different vectors. Also, the tipping point when renewable-based systems are the cheapest option is sooner when using IPHRO.

4.3.3. Uncertainty in the selected components

Next, we analyze the effect of uncertainties from the IPHRO system, water transport, and fossil fuel prices on the total costs of the system for the four technological scenarios in the year 2030. Recall that this is the first year where a fully renewable scenario is the cheapest option and that this trend continues towards 2050.

Figure 26 shows the results of the Monte Carlo runs for the total costs of the desalinated water and energy supply system for the different technological scenarios in 2030. It is the statistical version of Figure 24, presented for the year 2030. The costs in scenarios S1 and S2 are more disperse because of the uncertainty in fossil fuel prices. S2 is consistently cheaper than S1: the worst-case cost of S2 is below the median cost for S1. S4 dominates S3 for every realization, which stresses the value of IPHRO. The difference in costs is explained by the low costs of seawater energy storage in 2030 relative to those of batteries and hydrogen systems. Also, apart from having the lowest median cost, S4 offers less dispersion since it avoids fossil fuels and their volatile prices. The results show that a fully renewable-based desalinated water and energy supply is an economically viable option, more so when implementing IPHRO, even when uncertainties in the cost and lifetime of critical components are considered. For extreme cases, the lowest and the highest costs are attained when using fossil fuels. There is still room for more detailed quantification of the uncertainty in the system.

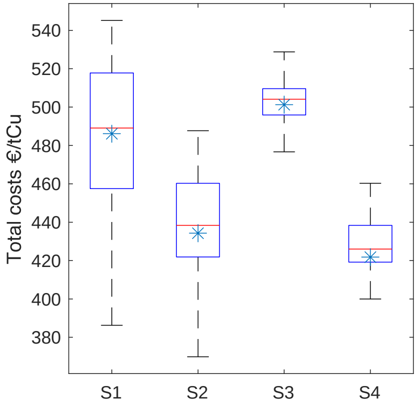

Figure 26: Total system costs for the Monte Carlo runs of the different technological scenarios for the year 2030.

Red horizontal bars show the median and the blue boxes represent the interval between the 25th and 75th percentile. The stars represent the results for the deterministic formulation as presented in Figure 24.

In summary, the deterministic cost comparisons between scenarios show internal consistency when tested against selected sources of uncertainty.

4.3.4. Limitations and future work

In this subsection, the modeling of the water technologies is discussed first, followed by cost assumptions, modeling of energy vectors, and the re-design of the mining operations.

Nonlinear phenomena in water transport and seawater pumped-hydro energy storage are neglected such as variable pumping efficiencies and head height-dependent power generation efficiency (as the filling level varies). Given the high head of the considered pumped storage in the case study, this approximation is considered acceptable. Some characteristics of the design of the high-head seawater reservoir could be further analyzed when moving to an engineering phase, including the geometry and its effect on losses by evaporation and infiltration and the CAPEX of the reservoir.

For concentrated solar heat, parabolic trough technology was considered, as explained in section 4.2. Considering also solar tower plants is recommended as, compared to parabolic trough, this technology offers a higher efficiency and currently has lower installed capacities, resulting in more potential for future cost decreases.

The internal consistency of our results against the uncertainty coming from relevant assumptions is analyzed (CAPEX of seawater storage and water pipelines, the lifetime of the seawater pump-turbine, and prices of natural gas and diesel).

However, a comprehensive uncertainty analysis of the system is still missing. Different costs for the main generation technologies (solar PV and wind) were not evaluated for a given year because the corresponding forecasts are increasingly becoming more precise, as solar and wind are now the most widely deployed technologies worldwide. If anything, the market keeps surprising us with costs lower than those assumed in energy planning exercises [179], which would only underline our message: mines have to shift towards renewables, fast. Uncertainty quantification is still incipient in the field and the numerous uncertainties inherent to planning future water-energy systems (technological, economic, political, and climate-related) should be addressed in future studies. The comprehensive analysis of environmental impacts remains open as well. Only direct carbon dioxide emissions are analyzed, but a more complete analysis should include different types of impacts from a lifecycle perspective.

While different vectors are endogenously considered in the model (to transform one into another), the final demands are bounded to a specific vector. Using the final *service* that energy provides in a process as input to the optimization model could enable further flexibility potential in the system and allow for an even better design of systems, especially for future mines.

The scope of our study is limited to energy and water supply systems and eventual modifications in the production processes are not considered. This means, from the perspective of the mining industry, that we do not consider cost differences in the mining equipment when replacing trucks' current onboard generators with batteries (as in [180]) and/or a hydrogen system (as in [181]). Modeling on-board batteries or hydrogen systems and their load profiles with more detail would also allow estimating its potential as a source of flexibility for the power sector. The effect of the process design and operation on its energy demand needs to be assessed along the entire production process. For example, at the smelting stage, the specific demand for electricity and fuels depends on the selected equipment [57] and the operation mode (e.g. increasing the injection of oxygen lowers the demand for fuels [182]). Indeed, looking at the mining side of the system opens the door for exploring a series of options for demand-side energy management that could help integrate renewables at even lower costs. Moreover, in countries where the copper industry poses a significant energy demand (like Chile and Peru), it is worth exploring the contributions to the energy systems that the flexible operation of production processes could make, i.e. large-scale demand-side management from copper production.

4.4. Conclusions

We present a new optimization model for the simultaneous design of water and energy systems, including a concept for integrated seawater desalination with pumped hydro storage (IPHRO). This model is used to design the energy and water supply system for a copper mine in a multi-vector setup, motivated by enabling a more sustainable production of such a key material for the energy transition. The results indicate that:

- Fully renewable systems result in similar costs compared to conventional designs that resort to fossil fuels, at current costs. A renewables-based desalinated water and energy supply for copper production processes is economically attractive.
- Solar generation dominates the solutions for the case study, given the excellent irradiation in the region of the case study.
- By 2030, a 100% renewable and sector-coupled supply is the least-cost alternative in the deterministic scenarios.
- The integrated concept for seawater pumped-hydro storage and reserve osmosis desalination (IPHRO) lowers the costs of fully renewable scenarios and phases-out fossil generation earlier in conventional scenarios.

When considered, IPHRO is always identified to be cost-effective by the model. In the fully renewable configuration, it allows lowering one-fifth of the total costs of the system at current costs and an 8% reduction in 2050. In configurations with fossil technologies, IPHRO reduces carbon emissions by increasing the cost-optimal hosting capacity for solar energy.

Monte Carlo simulations show that, in a ten-year horizon, our conclusions are robust against uncertainty in the capital costs of seawater storage and water transport, the lifetime of the seawater pump-turbines, and the prices of fossil fuels. When considering these sources of uncertainty, extreme costs are found in the scenarios considering fossil fuels.

The alternatives presented in this work are an economically viable option to improve the carbon footprint of copper production processes and, in turn, that of the ongoing transformation of the global energy systems. The insights presented in this work are relevant for researchers and decision-makers interested in improving the performance of highly renewable energy systems and those aiming at lowering the carbon emissions in the mining industry.

As future work, we propose to assess the potential of the flexible operation of production processes to lower the costs of the systems, as well as considering a deep integration of renewable generation at the design phase of new mines. For the copper industry to profit from the low-cost clean alternatives proposed here, the industry should accelerate electrification and/or *hydrogenization* of demand (e.g. electro-heat, fuel cell trucks). In addition, for copper-producing countries, the potential of demand-side management in the copper industry should be explored.

Chapter 5. Integration of capacity-based industrial energy demand flexibility in multi-vector energy system planning

This chapter is based on the publication "Flexible copper: exploring capacity-based energy demand flexibility in the industry" by Simón Moreno-Leiva, Jannik Haas, Wolfgang Nowak, Willy Kracht, Ludger Eltrop, Christian Breyer. To be submitted.

Executive summary

Different forms of flexibility can help in balancing variable generation in highly renewable energy systems. Here we focus on demand-side flexibility in the copper industry, whose energy demand is expected to grow as a result of the intensive use of this metal in future energy systems. While explorations of demand-side flexibility are available in the literature for other industries, here we present the first for the entire production process of copper.

We aim to assess the potential of capacity-based energy demand flexibility (over-sizing production processes) in a copper industry embedded in fully renewable energy systems. For this, we extend an optimization model for multi-vector energy systems planning so that it also includes the sizing and operation of a production process. We apply it to a case study for copper production and project greenfield results until 2050.

Our results show that flexibility at the concentration and refining stages belongs to the cost-optimal system design, at least over the next decade. At current costs, the potential cost savings in the energy system for the production process through capacity-based demand flexibility range from 5% to 12%, depending on the technology scenario. The preferred stages for implementing demand flexibility are concentration and electro-refining. Technology scenarios considering seawater pumped-hydro energy storage yield lower costs over the entire projected period. Potential savings are expected to decrease over time if the costs projections of renewable energy generation and storage technologies materialize.

In upcoming studies, other factors beyond costs, such as offsetting the need for critical materials, should be analyzed to thoroughly understand the contribution of industrial demand flexibility in future fully renewable energy systems.

5.1. Introduction

Flexibility for accommodating increasing shares of variable renewable energy sources can come from different sources: flexible generation, energy storage, transmission, sector coupling (or multi-energy systems), and demand-side flexibility [13]. In this chapter, we focus on the latter. While demand flexibility can be integrated into energy systems planning considering all consumers [183], we focus on industrial demand. With this, in this chapter we focus on recommendation (e) presented in chapter 2.

Industrial demand-side flexibility means modifying the energy demand of a certain industry to help in balancing out the energy system. Following reference [184], *demand-side management* comprehends measures that foster flexible energy consumption, and it is to be differentiated from *demand response*, as the latter refers to market incentives for demand flexibility provision. This way, demand-side management would englobe demand response. We introduce an additional distinction. Namely, that industrial demand-side management can be either operational flexibility or capacity-based flexibility (Not to be confused with the distinction presented in reference [185], where operational flexibility refers to *how* energy is used and temporal flexibility to *when*). On the one hand, operational flexibility focuses on changes in the form, magnitude, and/or timing of the energy demand of existing production processes. On the other hand, capacity-based flexibility refers to treating process capacities as a decision variable in optimization models for planning energy systems. This way, flexibility is considered already in the design stage: additional capacity for a given process (or a given stage in it) can be built so that it can be operated flexibly based purely on its oversized capacity.

Most of the literature focuses on operational flexibility (more specifically, on adapting the demand profiles of existing production processes to the dynamics in energy systems). In the following, we mention several examples from various industries, aiming to show that the copper industry is rarely covered. Load shifting was investigated as a means to reduce costs or energy-related carbon emissions in the cement industry, achieving cost savings of around 4% [186]. When judging such savings, one should consider that already a small reduction in costs can have a much larger benefit in terms of profit. In reference [187], the potential of demand response (through market incentives) to foster the use of wind energy by industrial clients was analyzed. Specifically, for a cold storage warehouse and a manufacturing plant, finding potential savings in the monthly average unit price of energy ranging from 5 to 15%. These savings have a seasonality determined by the dynamics of the local power market and they are achieved mostly by shifting load to nighttime. The effect of implementing industrial flexibility as demand response was also investigated for the chemicals industry, with a focus on characterizing the required market incentives [188]. Demand-side management has also been explored for the pulp and paper industry along with an assessment of its potential ability to participate in the flexibility market for a case study in Finland [189]. In particular, the industry's costs of bidding in a flexibility market are calculated and found to range between 60-70€/MWh depending on the size (MW) of the bid. In reference [190], the role of industrial demand flexibility in the German electricity market was investigated, for the chemical (chloride production), pulp, aluminum, steel, and cement industries. The use of electrolyzers that supply energy to a pulp mill for offering power grid services (for frequency regulation) was shown to be profitable [191]. In the mining industry, the potential for re-scheduling the operation of de-watering and slurry transport processes was explored, findings cost reductions of 10% and 36% each [192]. For stainless steel production, an optimal daily scheduling method has been proposed that considers the participation in different markets within the energy system as well as distributed energy generation [193].

On capacity-based industrial flexibility, only a handful of publications are found. The desalination sector was included in such an analysis, resulting in a limited flexibility offer for the system [175]. In reference [194], capacity-based industrial flexibility was integrated into the planning of fully renewable energy systems, including the chemical, pulp and paper, steel, cement, and aluminum industries. In this study, high value is found for hydrogen-based solutions, as low-cost electrolyzers and hydrogen storage enable an effective decoupling of variable renewable electricity feed-in and baseload fuel synthesis units.

Despite the relevance of the copper industry, only a limited number of studies in the literature explore the energy demand flexibility of copper production processes. Specifically, two studies look at managing rock hardness in the feed of mills as a means to accommodate solar generation at lower costs [51,52]. A systematic analysis of the potential for capacity-based flexibility across the entire production chain of copper is still missing in the literature.

The goal of this chapter is to assess the role of capacity-based energy demand flexibility of copper production processes in a fully renewable energy system. This is to be distinguished from a quantification of the incentives required in a hypothetical market for flexibility. Instead, we focus on a different paradigm for the integrated design of production processes and fully renewable energy systems that cover their needs. We aim to answer the following research question: *can capacity-based demand-side flexibility help lower the cost of fully renewable energy systems for the copper industry?* In particular, we contribute with the following novelties:

- Proposing a new method for the endogenous optimization of production capacities of industrial processes within a multi-energy system planning model.
- Applying it to the copper industry and identifying the process stages where capacity-based flexibility is economically attractive (Power-to-Copper).
- Assessing the evolution of the role of this source of flexibility in future energy systems for the copper industry.

We will test the aspects above with a set of cost assumptions (of both the copper production processes and renewable energy technologies). Altogether, the present work is relevant for improving the understanding for lower integration costs of variable renewable energy sources in industrial processes, and thus at contributing to a faster energy transition.

In section 5.2, our methods are explained. Section 5.3 presents and discusses the results obtained for a case study in northern Chile. Later, in section 5.4, the limitations of this study are discussed and our recommendations for future research are presented. Finally, the conclusions are presented in section 5.5.

5.2. Methods

For answering our research question, we use optimization-based modeling and analyze different scenarios. In the upcoming subsections, the general setup of the modeling approach is presented (section 5.2.1), followed by a description of the optimization problem (section 5.2.2), the inputs to the model -including a case study- (section 5.2.3), and an explanation of the defined scenarios (section 5.2.4).

5.2.1. General setup of the model

We analyze the role of capacity-based energy demand flexibility in the copper industry under different scenarios for cost and technology and for current and future costs of components. An optimization model is at the core of our methods. We represent these different scenarios by different sets of inputs to the optimization model. In particular, we vary the investment costs of the production processes and allow different energy storage technologies (technological configuration). Figure 27 presents an overview of the methods.

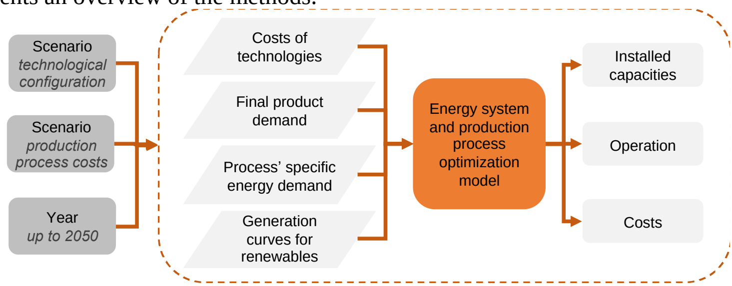

Figure 27: Overview of the methods in chapter 5

5.2.2. Optimization model

We develop a new optimization model that allows calculating the cost-optimal installed capacities and operation of the components of a multi-vector energy system and a copper production process. We extend an existing model for multi-energy systems design [3] so that it can endogenously optimize the capacity and operation of production process technologies. While the model can be used for modeling different industrial processes, we will apply it specifically to copper production. The power system-version of this model, called Long-term Energy Expansion Linear

Optimization (LEELO) has been validated in multiple publications [2,115,153,154]. We name the model employed in this study Long-term Energy Expansion Linear Optimization for Production Processes *LEELO-PrPr*.

The model is a cost minimization problem, where the objective function z is the sum of annualized costs for the components of the multi-energy system and the production process. Then, in **equation 5.1**, x_{opt} represents the optimal design of the system. The decision variables (x) of the model are the capacities of energy generation, conversion and storage technologies, and the capacities of the different stages of the production process, as well as the operation of all these components over one year at an hourly resolution (i.e., 8760 timesteps).

$$x_{opt} = argmin\, z(x) \tag{5.1}$$

The main restrictions of the model are the mass and energy balances for the different energy vectors and for the species in the production process. For the energy sector, the model considers electricity, heat, and hydrogen supply. The water sector is implicitly considered with its energy demand. The balance of hydrogen and heat have the form illustrated in **equation 5.2**, where v can be either of both energy vectors. At each node n in the system and at each timestep t, the demand for the energy vector $d_{v,n,t}$ must be equal to the production of the vector $fC_{n,c,t}$ with conversion technology c (multiplied by the corresponding efficiency η_c), minus the energy converted from v into another vector, minus the difference in the storage level $S_{n,s,t}$ relative to the next timestep $t+1$, minus the losses in the storage $lS_{n,s,t}$. Primary generation of solar heat is modeled as a conversion technology.

$$\sum_{c:\,x\to v} fC_{n,c,t}\eta_c - \sum_{c:v\to x} fC_{n,c,t}\eta_c - \sum_{s:stores\ v} (S_{n,s,t+1} - S_{n,s,t}) - \sum_{s:stores\ v} lS_{n,s,t} = d_{v,n,t}\ , \forall v, n, t \tag{5.2}$$

Equation 5.3 shows the energy balance of the electric bus, where the electric demand $d_{elec,n,t}$ must equal the sum of the electricity produced by the power plants $fR_{n,r,t}$ corresponding to the different generation technologies r plus the amount of energy converted $fC_{n,c,t}$ into electricity ($c: x \to e$) minus the electricity converted into another vector ($c: e \to x$), plus the electricity transported to the corresponding node $fT_{n,T,t}$.

$$\sum_{r} fR_{n,r,t} + \sum_{c:\,x\to e} fC_{n,c,t}\eta_c - \sum_{c:\,e\to x} fC_{n,c,t}\eta_c + \sum_{T} fT_{n,T,t} = d_{elec,n,t}\ , \forall n, t \tag{5.3}$$

There are three types of balances for the stages of production processes, depending on the position of the given stage within the process. **Equation 5.4** shows the balance for stages in the main production chain except the last one, where $fP_{n,p,t}$ is the production flow of product p produced at a given stage or used in the next one, and $PS_{n,ps,t}$is the storage level of the product.

$$\sum_{p:x\to p} fP_{n,p,t} - \sum_{p:p\to x} fP_{n,p,t} = \sum_{ps:\,stores\ p} (PS_{n,ps,t+1} - PS_{n,ps,t}), \forall p,n,t \qquad (5.4)$$

For process stages that are parallel to the main production chain, the balance is analogous to equation 4 but the flows are determined by the production level of the stage in the main chain that they supply. For the final stage in the production process, the demand for the final product $d_{p,n,t}$ is included, as presented in **equation 5.5**.

$$\sum_{p:x\to p} fP_{n,p,t} - \sum_{p:p\to x} fP_{n,p,t} = \sum_{ps:\,stores\ p} (PS_{n,ps,t+1} - PS_{n,ps,t}) + d_{p,n,t}\ , \qquad (5)$$
$$\forall n,t\ \ and\ p\text{: } final\ product$$

The flows and stocks of energy and products are bounded by the capacity of the corresponding generation, conversion, storage, or production technology. This is expressed in **equations 5.6 to 5.10**, where $pP_{n,p}$ is the capacity of the stages of production processes, $pR_{n,r}$ are the capacities of renewable energy generation technologies, $pC_{n,c}$ are the capacities of energy conversion technologies, $ePS_{n,ps}$ are product storage capacities, and $eS_{n,s}$ are energy storage capacities. **Equation 5.7** also bounds renewable energy generation to the normalized generation profiles resulting from the availability of the corresponding resource (e.g., wind or solar irradiation).

$$fP_{n,p,t} \leq pP_{n,p} \quad ,\forall n,p,t \qquad (5.6)$$
$$fR_{n,r,t} \leq pR_{n,r} \cdot profile_{n,r,t} \quad ,\forall n,r,t \qquad (5.7)$$
$$fC_{n,c,t} \leq pC_{n,c} \quad ,\forall n,c,t \qquad (5.8)$$
$$PS_{n,ps,t} \leq ePS_{n,ps} \quad ,\forall n,ps,t \qquad (5.9)$$
$$S_{n,s,t} \leq eS_{n,s} \quad ,\forall n,s,t \qquad (5.10)$$

Energy demand curves are not an input to the optimization model but a result of the operation of the production process as decided by the model. For this, specific energy demands per mass of produced product are employed (see section 5.2.3). Then, the demand for a vector v (and for electricity) is defined as shown in **equation 5.11**, where $D_{p,v}$ is the specific demand to produce p. The production demand (not energy) for the final product is defined in the case study and the mass and energy flows are scaled as a consequence of the mass balances (**equations 5.4 and 5.5**).

$$d_{v,n,t} = \sum_{p} fP_{n,p,t} \cdot D_{p,v} \qquad ,\forall v,n,t \tag{5.11}$$

5.2.3. Inputs

In the following, the approach to model and select inputs and scenarios is presented.

Case study

The new model is demonstrated for the copper industry with a generic case study located in the north of Chile, which is the main copper producing country worldwide [156]. Additionally, the aggregated energy demand of this industry in Chile is publicly available and periodically updated via industrial survey [137]. Using that data source allows having representative estimates for the energy consumption of a generic copper production operation.

The production level for the case study is set at 1000 tons of refined copper per day. Further detail about the production process and how its energy demand is modeled are presented in the next subsection.

Production process and its energy demand

Figure 28 presents the operations selected to represent the production process of copper. The production process is assumed to follow a pyrometallurgical route, which is indicated for primary copper sulfide ores, which in turn makes up for most of the global primary production of copper [169]. We base the characterization of the process on a textbook on copper production processes [169] and the modeling of its energy demand on an industrial survey [137]. This continuously updated survey reports specific fossil fuels and electricity demand for each stage of the process and is applied in the Chilean copper industry.

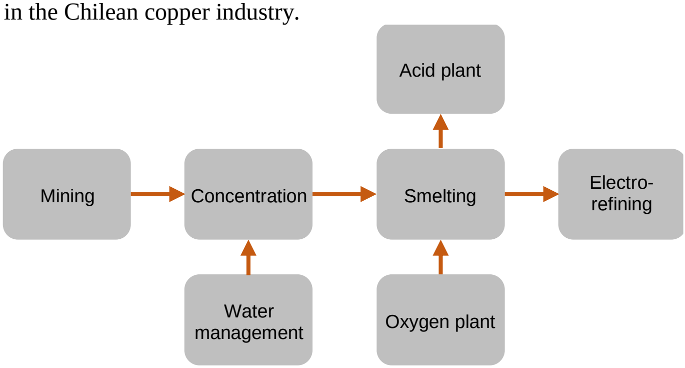

Figure 28: Implemented model for copper production via pyrometallurgical methods. *Based on* [169].

The process begins with the mining stage, where the ore is extracted from the ground, loaded onto trucks, and ground (primary comminution). Although standard mining trucks have an electric drivetrain, they usually resort to an onboard diesel generator. An efficiency of 0.4 is assumed for onboard generators to infer electric demand from available industrial survey data. In the setup of our case study, we assume that batteries are used instead so that a fully renewable supply is enabled. The ore is later concentrated with consecutive operations of comminution (large semi-autogenous mills are used for this) and froth flotation. We assume that the minor share of fossil fuel demand reported in the survey at this stage is used for on-site electricity generation with 40% efficiency. A parallel stage for tailings and water management is defined.

Copper concentrate produced at the previous stages goes into the smelting stage, where consecutive operations of smelting, converting and refining take place to produce 99.5%-pure copper anodes. Despite exothermal reactions taking place at this stage, energy is still required to reach the required operating conditions. Fossil fuels are usually used for this. In our case study, we assume the use of hydrogen instead. Two stages parallel to smelting are defined. Namely, an acid plant where electricity is required to treat the gases and produce sulfuric acid, and an oxygen plant that also demands electricity. In the survey that we use as a reference for energy consumption, these two operations are considered within the smelting stage. In our case study, energy demand is allocated to these two operations assuming that 35% and 32% of the total electricity demand of the smelting stage is used at the oxygen and acid plant, respectively, based on data for the Outokumpu flash smelting process [68].

Finally, copper anodes are refined using electrochemical reactions. At this stage, both electricity and low-temperature heat are required for driving the reactions and for maintaining the operational parameters. We assume that the fossil fuel consumption reported in the survey is used for heat generation. Recall that heat supply is endogenously modeled with a bus in our multi-energy model, so that it can be supplied with different technologies such as electro-heat or solar heat.

Storing intermediate products is allowed in the model (see equations 4 and 5), which allows to flexibilize the demand of different stages independently, without creating bottlenecks.

As the operation of the processes is also planned endogenously within the model, its energy demand is not exogenously inputted as a time series. Instead, specific energy consumption factors $D_{p,v}$ represent the energy demand of each operation per unit of product. Then, the product of that factor and the product flows represent the energy demand at a given timestep. This product is represented in **equation 12** and it is included in the energy balance of the corresponding bus. Table 6 shows the values of these parameters. Note that these values are strongly influenced by the specific conditions of the mining site, such as the metal concentration in the mineral (ore grade). Our assumptions stem from the energy consumption reported for the year 2017 in the Chilean copper industry [137]. The reported average ore grade in that country in 2017 was 0.65%.

Table 6: Specific energy demand for each stage of the process.

Vector	Mining	Concen-tration	Water manag.	Smelt.	Oxygen plant	Acid plant	Electro-refining
Electricity	1.41	3.48	0.48	0.34	0.35	0.32	0.37
Heat	-	-	-	-	-	-	0.58
Hydrogen	-	-	-	1.45	-	-	-

Expressed in MWh per ton of fine copper content in the product [MWh/tCu]. Based on [137] and [68].

Costs of the production process

Since the model endogenously optimizes the capacities of the different stages of the production process, the specific costs for each stage are an input parameter. Our assumptions are taken from the literature [195], adjusted by inflation, and transformed into euros with an exchange rate of 0.85 €/USD. The authors of [195] indicate that the costs are applicable for mines in North and South America and are thought to be similar for other regions.

Our assumptions for the capital costs of each stage of the process are presented in Table 7. These costs serve merely as a reference since the actual costs vary depending on local conditions. We explore the effect of different process-cost scenarios relative to these reference values (see scenarios in section 5.2.4). These costs are assumed to remain constant in time, as no learning effects are expected for widely deployed process technologies. Non-energy-related operating costs (such as reagents, grinding media, and other supplies) are not included in the model as they are assumed to depend on total production. Therefore, they would remain constant regardless of *when* production is taking place. The impact of this assumption is discussed in section 5.4. Energy supply costs are endogenously considered in the model.

Table 7: Capital costs for each process stage.

	Mining	Concen-tration	Water manag.	Smelting	Oxygen plant	Acid plant	Electro-refining
Capex	88.6	44.3	44.3	47.8	8.0	23.9	8.9

In M€/(tCu/hour) and based on [195]

Selected technologies for the energy system

The energy system considers technologies for energy generation, conversion, and storage. Technologies for primary energy generation consider exclusively renewable sources. In particular, we consider wind power and photovoltaics (PV) for electricity generation and concentrated solar heat. Conversion technologies include electrolyzers for hydrogen production using electricity, a power block (steam turbine) for electricity generation using high-temperature heat, heating rods and heat pumps for electro-heat, heat exchangers, and hydrogen turbines for electricity generation (from 2030). Storage technologies consider lithium-ion batteries, thermal storage (low and high temperature), hydrogen storage in salt caverns, and pumped-hydro storage (PHES) using seawater.

The interfaces of storage technologies are modeled as a separate entity in the model, meaning that the power and energy capacities of storage technologies are sized independently (a power-to-energy ratio is not fixed).

Costs of energy system components

The costs of energy system technologies change over time as a result of learning curves. Most assumptions are taken from LUT's (University in Lappeenranta) multi-sector energy model [159], which gathers almost 10 years of modeling experience and has been validated in numerous publications. How these costs assumptions compare to other studies can be consulted in reference [179]. We complemented LUT's assumptions with other sources as follows (for the specific costs see the appendix).

Costs of PV and lithium-ion batteries are based on [163] and obtained by allocating the costs of the inverters and the batteries using an energy-to-power ratio of six. Assumptions for the costs of hydrogen-related technologies are taken from [158] and completing the gaps in the cost projections over time with linear interpolation. Assumptions for the power block fed by the high-temperature energy storage come from [106], as well as those for the seawater-PHES. For the interface of seawater-PHES, corrosion-proofing the materials is assumed to increase capital costs by a factor of 1.8 [166]. Low-temperature heat storage assumptions are based on [196] and those of the heat exchanger on [144].

Performance of energy system components

The energy generation profile of variable renewable energy technologies depends on its location. We use external models to calculate these profiles, which are input to the optimization model. Specifically, we use *renewables.ninja* for wind power [167], *explorador solar* for PV [110], and NREL's *SAM* for solar heat [168]. The latter is used to produce the generation profiles of the solar field for high-temperature heat generation. Energy generation from the power block is endogenously optimized in our model.

The performance of energy conversion and storage technologies is defined by their efficiencies. Our assumptions for these efficiencies come from [106].

5.2.4. Scenarios

We define two technological scenarios, with three scenarios for process costs each. The scenarios are projected until 2050. The first technological scenario (T1) does not consider the use of energy storage with seawater pumped-hydro. T2 considers all available technologies. We isolate the effect of including seawater pumped-hydro since it is the most novel of the energy storage technologies considered here, with only one installed plant in Japan [160]. The three cost scenarios explore what happens when the reference capital costs of process equipment are lower than estimated. Specifically, we explore the reference costs (C100), 25% reduced costs (C75), and 50% reduced costs (C50). This allows us to explore how the potential for capacity-based demand flexibility changes with decreasing process costs. Each scenario is calculated for current costs and for projected costs in the years 2025, 2030, 2035, 2040, 2045, 2050 (in which mainly the costs of renewable technologies change). Finally, a reference (baseline) is calculated for each scenario at each year, which does not allow for any capacity-based demand-side flexibility. Every scenario is based exclusively on renewable energy.

5.3. Results and discussion

In this section, we first look at the optimal installed capacities and at the operation of the processes from our model. Later, we discuss the effects on system costs.

5.3.1. Cost-optimal systems resort to capacity-based flexibility

We will first explore the resulting copper production process and then its energy system.

Figure 29 presents the cost-optimal capacities for each stage of the process in the first technological scenario T1 (without building seawater-PHES). Each column corresponds to the greenfield infrastructure plan for a given year and it is separated into three sections, for the different scenarios for process costs (C100, C75, C50). Rows represent the stages of the production process under a given cost scenario. The first seven rows correspond to the optimal capacities under the reference scenario for process costs (C100), the next seven to the optimal capacities assuming that process costs are 25% lower (C75), and the last seven correspond to C50. Capacities presented in the matrix are normalized by the mean demand for the final product (here: refined copper). In other words, a stage with a normalized capacity of 1 will operate all year round at maximum capacity to be able to supply the demand. Stages with a capacity higher than one (or "oversized stages") allow flexibility in operation so that the demand profile better fits the availability of renewable energy.

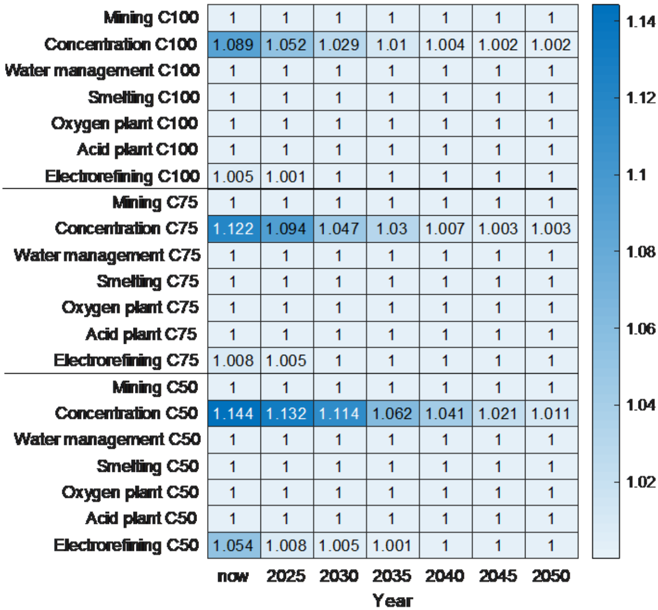

Figure 29: Results for process sizing under scenario T1.
Optimal capacities of processes operations (rows) normalized by mean hourly demand for final product, with cost projections until 2050 and three different scenarios for the costs of production processes (C100, C75, and C50). For an energy system without pumped-hydro energy storage (T1). Color scale: normalized capacity, where values above one represent oversized capacity.

The preferred stages for implementing flexibility are concentration and refining. At current cost-conditions for the components of the energy system, the cost-optimal capacity of the concentration stage is 8.9% higher than the mean demand under C100 and 14.4% higher under C50. In other words, at current costs, oversizing the concentration stage by 10% is part of the least-cost option for balancing out the energy system. For the refining stage, optimal capacities are 0.5% higher than the mean demand under C100 and 5.4% under C50. The oversizing effect is higher as the costs of copper production capacity decreases.

Figure 30 shows the cost-optimal installed capacities for each process stage under the technological scenario T2, where seawater-PHES is considered. Under this scenario, the stages with enough capacity for providing demand flexibility are again concentration and refining. However, this technological configuration favors flexibility at the refining stage over the concentration stage, as opposed to what happens under T1. In particular, for the current costs of energy system components, the concentration plant is oversized by 2.7% and the refining plant by 6.2% under C100, and by 8.9% and 9.2% under C50. Again, this is consistent with more intensive use of capacity-based flexibility when the costs of installing further process capacity are lower.

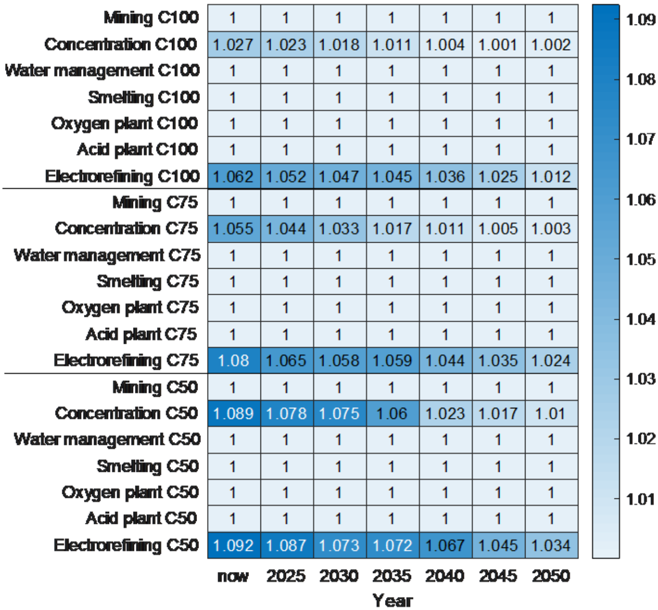

Figure 30: Results for process sizing under scenario T2.

Optimal capacities of processes operations (rows) normalized by mean hourly demand for final product, with cost projections until 2050 and three different scenarios for the costs of production processes (C100, C75, and C50). For an energy system considering pumped-hydro energy storage (T2). Color scale: normalized capacity, where values above one represent oversized capacity.

For both technological scenarios and under the three scenarios for process costs, the optimal oversizing of the production process to provide flexibility decreases in time. Indeed, by 2050, the largest oversizing occurs under T2 and C50 at the refining stage, with an oversize of only 3.2%. This is consistent with our assumptions for the costs of the components of the energy system. As we consider the learning effect of rapidly deploying technologies such as PV and batteries, oversizing production processes (whose costs are assumed to remain constant) becomes less economically attractive. In section 5.3.2, we explore the effect of this phenomenon on the overall costs of the system.

We will now explore the resulting configurations for selected scenarios only, for the sake of space. In particular, the full process-cost scenarios (C100) without and with seawater PHES (T1 and T2, respectively) are analyzed in further detail for the year 2030. Figure 31a shows the installed capacities of energy generation and conversion technologies, while Figure 31b does it for energy storage technologies.

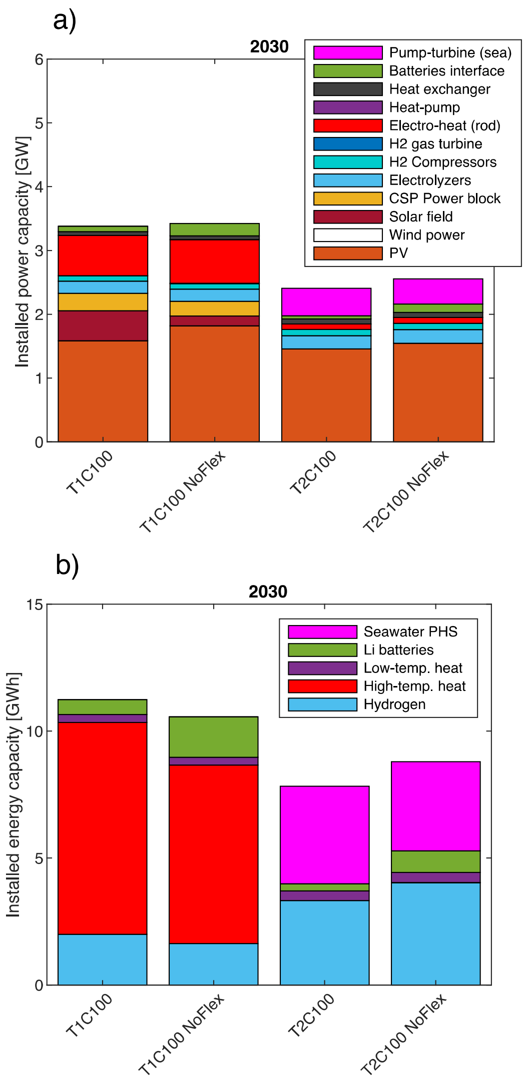

Figure 31: Composition of the energy system for selected scenarios in 2030.
a) Installed capacities of energy generation and conversion technologies. b) Installed capacities of energy storage technologies

As Figure 31a shows, the system is solar-dominated, with PV being responsible for primary electricity generation. Also, installed capacity of solar heat (solar field) is observed for scenarios without seawater-PHES (T1). This is consistent with the case study being located in the Atacama Desert, which has excellent climate conditions for solar energy [197]. However, when seawater-PHES is included, high-temperature heat storage is not recommended, and solar fields are not installed. The total installed capacities are higher for scenarios without demand flexibility, which is consistent with the model looking for other sources of flexibility. Counter-intuitively, under T1, the total installed capacity of storage technologies is lower for the reference case without demand flexibility (see Figure 31b). However, the composition of the storage mix changes. In particular, more batteries are installed, which have a better roundtrip efficiency but higher costs. Seawater-PHES is identified as a cost-effective option, when allowed (scenarios T2). Figure 31b shows that using seawater-PHES results in the system completely dispensing with high-temperature heat storage and in less installed capacity of batteries. In turn, hydrogen storage has higher energy capacities under T2.

Figure 32 presents the operation of the two stages of the production process that are operated flexibly (concentration and refining). Panel a) shows no seawater-PHES and panel b) with seawater-PHES. The operation modes presented in the figures correspond to the year 2030, under the reference scenario for process-costs C100. The results are normalized by the cost-optimal capacity of each stage.

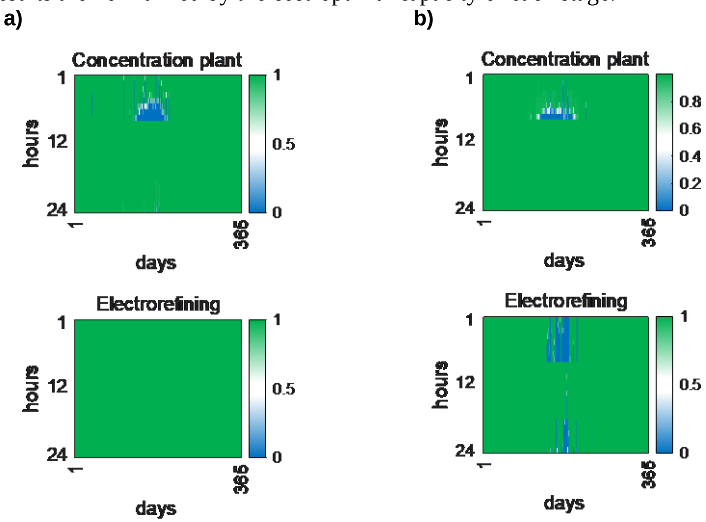

Figure 32: Operation of the concentration and electrorefining plants for the full cost scenario (C100) in the year 2030 without (a) and with (b) seawater pumped-hydro storage

The operation plots show that the system uses demand flexibility mostly during the winter (the case study is located in the southern hemisphere). The system resorts to steep reductions in production levels (blue areas), rather than performing less steep cuts (white areas) over longer periods of time. In both technological scenarios, T1 and T2, the concentration plant lowers its output during the morning of winter days. Recall from Figure 29 that in T1 by 2030, there is no oversizing of the refining stage for flexibility in the optimal design. This is consistent with the flat constant operation at maximum capacity shown in the bottom plot in Figure 32a. Under T2 (Figure 32b), the refining operation provides demand flexibility to the system. Specifically, it lowers its production levels during nighttime in the middle of the winter. Reductions in the first half of the day take place over a longer period of time than those in the evening.

For both technological configurations, demand flexibility operates is activated in the early morning in the middle of the winter. Hydrogen storage usually plays a similar role in renewable energy systems, balancing out at a seasonal scale. We do not observe that demand flexibility is directly competing with hydrogen. From Figure 31b it can be observed that, while hydrogen storage capacity increases with the integration of flexibility under T1, it decreases under T2. Recall that, in this application, there is a final demand for hydrogen (at the smelter). Therefore, from a power system perspective, hydrogen operates as a flexible demand and not as an alternative to store electricity (no relevant gas-to-power capacity observed). In the case of batteries, the results indicate that its deployment competes with the implementation of demand flexibility. In Figure 31, we observe that implementing demand flexibility significantly reduces the requirement for battery energy storage systems. This is consistent with batteries operating at maximum power capacity in the middle of the winter for intra-day balancing, the same operating period observed for demand flexibility.

The observed dynamics of demand flexibility are consistent with a solar-dominated system, with reductions in production levels in low irradiation periods. This contrasts with the case studies presented in [187], where loads are shifted to nighttime. In that case, the industrial processes participate in a large power market with other consumers and where the clearance price in low-cost periods is dominated by wind power. In our case study, the energy system is supplying the copper production process only.

In summary, oversized process stages for providing capacity-based demand flexibility are part of the cost-optimal system, but the role of this flexibility source fades over time. Ore concentration and copper refining are identified as the optimal stages for proving flexibility and they do it at a seasonal level.

5.3.2. Capacity-based flexibility offers economic benefits at least during the next decade

In the following, we present the evolution of the costs of the energy system (with demand flexibility) and the corresponding savings relative to the reference scenarios without demand flexibility. Recall that the objective function of the optimization problem considers both process and energy system costs. To calculate energy costs (and the corresponding savings), all costs of every component of the energy system are considered as well as the oversizing costs in the production process. In other words, the objective function minus the costs of building the production process, except for those costs that correspond to the oversized capacity.

Figure 33 shows the evolution of energy costs per ton of produced copper (orange curves, with demand flexibility) and the savings obtained through demand flexibility (blue bars). Energy system savings of 7.5% and 4.6% are observed for T1 (left plot) and T2 (right plot), under C100 and for current costs of energy components. By 2030 these savings decrease to 1.5% and 3.1%, respectively, as a result of decreasing renewable generation and storage costs. The use of seawater-PHES in T2 provides a low-cost source of flexibility, thus partially offsetting the relative benefits of implementing demand flexibility. Note that the use of this technology also results in scenario T2 being consistently cheaper than T1 over the entire analyzed period. This gap between the energy costs of T1 and T2 is expected to narrow over time as the cost of renewable energy generation and storage decreases.

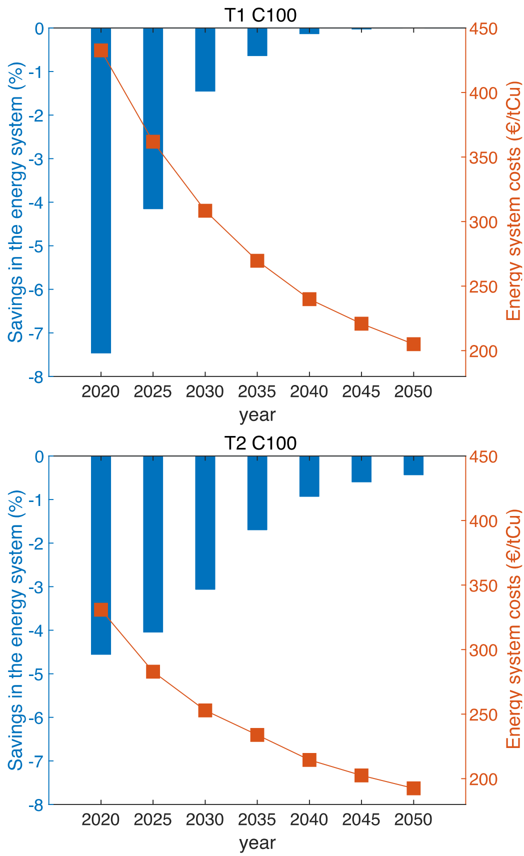

Figure 33: Costs of the energy system and the corresponding savings obtained when implementing industrial flexibility for the cost scenario C100.

Without and with seawater PHES (upper and lower plot).

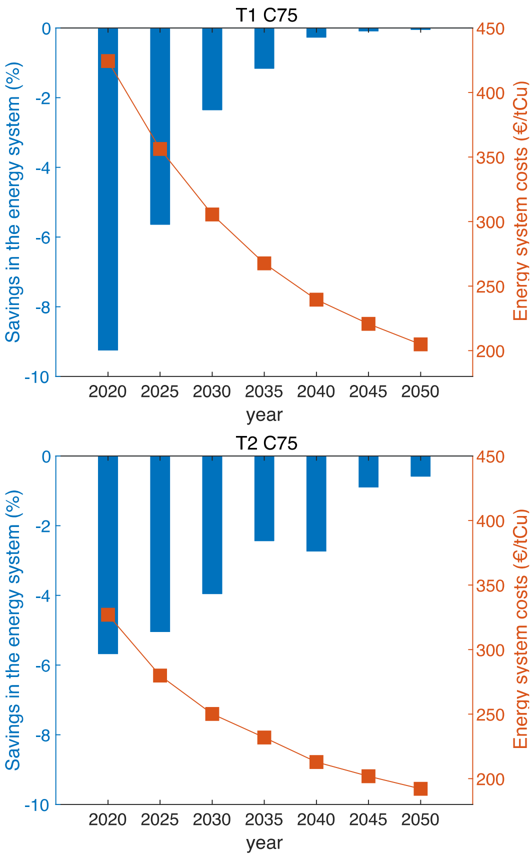

Figure 34: Costs of the energy system and the corresponding savings obtained when implementing industrial flexibility for the cost scenario C75.
Without and with seawater PHES (upper and lower plot).

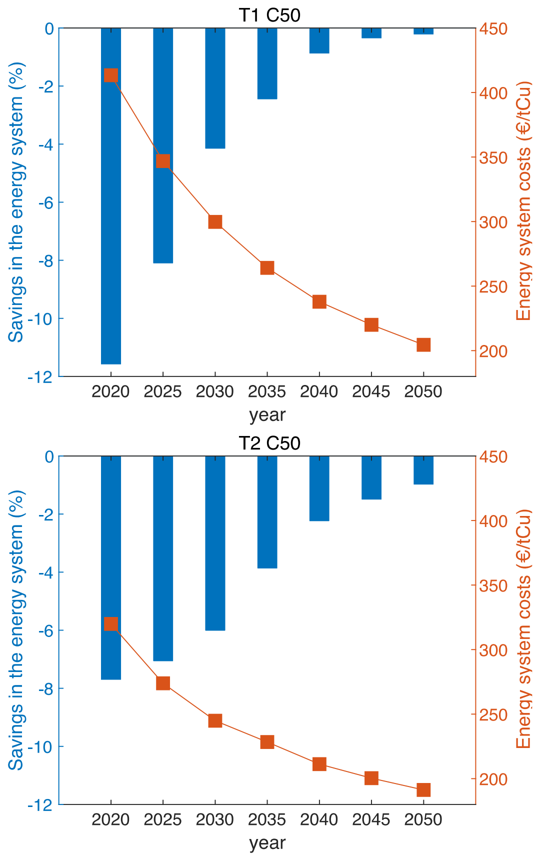

Figure 35: Costs of the energy system and the corresponding savings obtained when implementing industrial flexibility for the cost scenario C50.
Without and with seawater PHES (upper and lower plot).

Figure 34 presents the evolution of the specific energy costs of the system for both technological scenarios, assuming a -25% deviation from the reference costs of the production processes (C75). Under this scenario, energy cost reductions of 9.3% and 5.7% for T1 and T2 are achieved at current costs. By 2030, these savings decline to 2.4% and 4.0%, respectively. These savings are larger than in the C100 scenario, because oversizing production capacity is cheaper, adding value to the implementation of capacity-based demand flexibility. Figure 35 presents the same information but for the scenarios where process costs are half of the original reference values (C50). For these scenarios, the savings that can be currently achieved when implementing demand flexibility are 11.6% and 7.7%. By 2030, the savings in the energy side of the system decline to 4.2% and 6.0%. Due to the same reasons as in the comparison between C100 and C75, these savings are again larger.

In the long run, also in scenarios where lower costs for process equipment are assumed, the decreasing costs of renewable energy generation and storage fade the contributions of demand flexibility. In other words, it becomes cheaper to balance the system using energy storage and generation capacity than increasing the capacity of the production processes to operate them flexibly. This effect is starker in T1 since we have not considered a learning effect (decreasing specific costs over time) for seawater-PHES. Still, this comparison is exclusively cost-based. Other factors are also relevant when planning energy systems. For example, from a lifecycle perspective, the raw materials needed for building a larger mill would be different from those needed to build more batteries. In more general words, there could be hidden benefits of using demand flexibility instead of more storage that a simple cost-analysis cannot assess.

Note that the reference scenarios that do not consider capacity-based demand flexibility do consider other flexibility sources. In particular, they consider -apart from energy storage- a multi-vector or sector-coupled planning approach. With this, the relative economic benefit of capacity-based demand flexibility could be starker if compared against a scenario without sector coupling. In other words, capacity-based demand flexibility makes economic sense even when planning an integrated energy system, at least during the next decade. Also, capacity-based flexibility is not the only option to re-allocate industrial energy demand. Resorting to operational decisions is suggested in section 5.4.

To test our results against a reference, we make a top-down estimate of the current energy costs in the copper industry, based on the same survey data used to define the parameters of our models. For this, we consider the aggregated specific demand for fuels and electricity for the following process stages as reported in [137]: mining, concentration, smelting, refining, and water and services. This results in a specific demand for electricity and fuels of 5.4 and 4.9 MWh per ton of copper, respectively. Assuming average fuel and electricity costs at 30 and 70 €/MWh, we estimate the current specific energy costs of the industry at roughly 530 €/tCu. This value suggests that the renewable energy systems proposed in this work are economically attractive. Moreover, opting for renewables-based systems eliminates the risks associated with the volatility of fossil fuel prices.

In summary, capacity-based demand flexibility offers economic benefits, especially if aiming at a fast transition towards a fully renewable energy supply (within the next decade). The comparative economic benefits of this source of energy flexibility decrease over time if the projections of decreasing costs for renewable energy generation and storage materialize. Also, integrating seawater pumped-hydro storage (T2) results in lower systems costs and it makes the economic benefit of integrating demand flexibility starker.

5.4. Limitations and future work

In this study, we go beyond a black-box approach (that would size the production processes as a whole) to an approach with better process resolution. This allows discovering the potential for flexibility at single operations. However, there is still room for improvement in this direction, as suggested by the results in [192]. Concretely, we recommend more detailed modeling of stages that could still be hiding some flexibility potential, like:

- *Flexible operation modes at the smelting stage*: Even though the model decides consistently against flexibilizing the energy demand of the oxygen production plant, there is at least one ongoing project at a large industrial gas supplier that aims at exploiting the potential for demand flexibility in this type of plant [198]. Also, the oxygen obtained as a by-product of water electrolysis could be used in the process. In other words, electrolyzers could be used as co-generation devices for hydrogen and oxygen, as suggested in [199]. Regarding the use of hydrogen at the concentrate smelting stage, it needs to be investigated in detail as it could result in the undesired formation of sulfuric acid. Alternatively, further operational parameters, such as pre-heating, fuel flow, and oxygen flow can be modified (within the corresponding operational restrictions). The required heat could also come from electric technologies such as microwave ovens, electric arcs, or induction heat.
- *Smart operation of regenerative conveyor belts*: when the mineral is transported from a higher to a lower point (e.g. from the mining site to the concentration plant), a regenerative conveyor belt can be installed, like in *Minera los Pelambres* [197]. More detailed modeling of this alternative could find benefits in operating the conveyor belt at higher capacities when renewable energy resources are scarce.
- *Combination with rock hardness management*: reference [52] explores demand-side management at a comminution operation within copper production (semi-autogenous grinding), based on rock hardness. Combining this alternative in a comprehensive assessment of energy flexibility in the copper industry is recommended.
- *Smart scheduling of maintenances*: planned maintenances of the equipment in the production processes means partially (when parallel capacity is installed) or completely shutting down the corresponding stage. These events could be planned for periods when renewable energy resources are scarce.
- *Use of turbines to recover energy in water recirculation systems*: more detailed modeling of the water management system could uncover opportunities to flexibilize its demand, also integrating energy recovery in downhill pipes.

The assessment of the above alternatives can be influenced by factors beyond the energy sector. Mining factors may include short-term variations in the copper price, which will impact the necessary incentives for producers to decide their production level (the modeling approach would need to be modified to explore the interactions of the copper industry with a flexibility market). The effect of including fixed operating costs that depend on the capacity of productive processes rather than on actual production, such as maintenance or eventual increases in labor demand, is still to be explored. Also, it remains open to assess the effect of non-linear phenomena in the energy demand of processes as a function of production flow at a given stage.

From the perspective of energy system planning, the aggregated role of demand flexibility in balancing out the power grid of a copper-producing country is yet to be explored. This is especially interesting for countries like Chile, where the copper industry accounts for around a third of the national electricity consumption. The same holds, for example, for the mining sector as a whole in Peru [200]. Furthermore, the contribution of this flexibility source to the power system should be assessed in different scenarios for the development of the industry, both in terms of production levels and technological selection.

From a mining perspective, other potential benefits from oversized processes were not addressed in the present work, such as an eventually extended lifetime of equipment, which would further underline the attractiveness of our findings. Considering the flexibility potential in the design phase of future production processes calls for a change in current planning paradigms in mining. It means going beyond the analysis of the throughput and the resulting cash flow into a comprehensive analysis of other factors that determine the economic performance of the process, in particular those regarding the dynamics of highly renewable energy systems.

5.5. Conclusions

We propose a model that endogenously calculates the capacity and operation of industrial production processes within an optimization problem for multi-vector energy systems. This model allows assessing the potential for capacity-based energy demand flexibility in industrial processes embedded in highly renewable energy systems. Moreover, it works at a high process-resolution (meaning that several process stages are considered as opposed to having one large black box for the whole process). This allows identifying the steps within production processes with the most potential for capacity-based demand flexibility. We conduct a case study in copper production, given this metal’s relevance for the global energy transition.

The model identified capacity-based flexibility as a cost-efficient alternative. Specifically, oversizing the concentration and refining stages are selected for providing this flexibly. Today, the optimal oversizing of the concentration and refining stage goes from 2.7-8.9% (depending on the technological configuration) and 0.5-6.2%, respectively. This source of flexibility operates mainly during the winter to compensate for the lower availability of solar energy. In the year 2050, the recommended oversizing of the concentration and refining stages drop to 0.0-0.2% and 0.0-1.2% due to competition from other sources of flexibility. Specifically, due to the drop in costs projected for renewable energy generation and storage technologies.

For the reference process costs, oversizing these stages translates today into cost reductions of 5-12% (depending on the technological scenario) for the whole production system, as compared to an inflexible demand. If the costs projections of competing flexibility options materialize, these benefits fade over time. When seawater pumped-hydro storage is considered, which yields the lowest costs for the energy system, these savings are expected to be below 1% for new production capacity installed after 2040. Going back to our main research question, the results indicate that capacity-based demand-side flexibility in the copper industry can help to lower the cost of fully renewable energy systems. This alternative is particularly relevant when going for a fast transition in the next decade.

From the perspective of the mining industry, oversized processes could result in other types of benefits not quantified in this study, like an extended lifetime of the equipment. Additionally, an even more detailed exploration of the copper processes could reveal further opportunities. We proposed a list of these processes as a starting point (see section 5.4). Finally, the aggregated role of this industry's flexibility in larger national systems is yet to be explored, along with the corresponding market designs for energy flexibility.

Part III – Epilogue

Chapter 6. Conclusions

This chapter contains text fragments of my previous publications:

"*Renewable energy in copper production: a review on systems design and methodological approaches*" by Simón Moreno-Leiva, Jannik Haas, Tobias Junne, Felipe Valencia, Hélène Godin, Willy Kracht, Wolfgang Nowak, and Ludger Eltrop, published in the *Journal of Cleaner Production* in 2020.

"*Copper mining: 100% solar electricity by 2030?*" by Jannik Haas, Simón Moreno-Leiva, Tobias Junne, Po-Jung Chen, Giovanni Pamparana, Wolfgang Nowak, Willy Kracht, Julián M. Ortiz, published in the *Applied Energy Journal* in 2020. My focus in this publication was the investigation of the tradeoff between ore grade decline and declining costs of solar energy generation and storage.

"*Integration of seawater pumped storage and desalination in multi-energy systems planning: the case of copper as a key material for the energy transition*" by Simón Moreno-Leiva, Jannik Haas, Wolfgang Nowak, Willy Kracht, Ludger Eltrop, Christian Breyer, published in the *Applied Energy Journal* in 2021.

"*Flexible copper: exploring capacity-based energy demand flexibility in the industry*" by Simón Moreno-Leiva, Jannik Haas, Wolfgang Nowak, Willy Kracht, Ludger Eltrop, Christian Breyer. To be submitted.

6.1. Introduction

This thesis is devoted to the model-based optimal design of integrated water and renewable energy systems. In particular, it aims at elucidating *how should we plan the water and energy systems for the copper production of the future to be fully renewable and to use no freshwater*. To answer this question, four specific goals were defined:

- Understand the existing body of knowledge on renewable energy integration in copper mining and draw lessons from the literature on energy systems design for industrial, local, and regional energy systems.
- Elucidate geographical tradeoffs between mineral depletion and climate in the design of solar power systems for some of the world's main copper mines.
- Develop a method for the integrated planning of cost-effective desalinated water and multi-vector industrial energy systems, applied to the case of copper.
- Analyze the potential of capacity-based energy demand flexibility in the copper industry in a fully renewable multi-energy system.

These goals were achieved with the main contributions and findings of this work, which are summarized in the following. Later, these findings are discussed and an outlook for future research is presented.

6.2. Summary of contributions

First, a comprehensive literature review on methodological approaches for designing renewable energy systems in the copper industry was exposed in chapter 2, as presented in [1]. The analysis was complemented with literature on energy systems design applied to other fields beyond copper, including other industries and regional systems. Based on the analysis of the literature, research gaps were identified.

Second, in chapter 3 [2], the cost-optimal adoption of solar electricity was assessed for different mines in the world's main copper-producing countries. The tradeoff between declining costs of solar electricity generation and storage against depleting mineral resources was also analyzed.

Third, a model was presented in chapter 4 [3] for designing multi-vector desalinated water and energy systems. This is the first time such a system design is presented for copper processes. This model also considers an integrated concept for seawater reverse osmosis desalination and pumped-hydro energy storage. The greenfield planning of the system for a generic copper production process was presented for milestone years until 2050, under different technological scenarios.

Last, an extension of the model that integrates capacity-based industrial demand flexibility was presented in chapter 5 [4]. With this model, the cost-optimal capacity and operation of the different stages of a production process can be endogenously calculated within an energy system planning model. This allows discovering relevant process operations to implement demand flexibility. The model was applied for a copper production process simulated for milestone years until 2050.

6.3. Summary of conclusions

The first contribution [1] recommends directions for research efforts in energy systems planning in the copper industry, based on the identified research gaps and aiming at achieving economically feasible cleaner energy systems:

a. Improve the characterization of the energy demand of production processes in the models. In particular, in terms of time resolution, location, and final use, and in consideration of the different factors that determine energy demand.
b. Endogenously integrate multiple energy vectors in the models to achieve more flexibility.
c. Integrate the water supply system into the model for energy system planning.
d. Explore the implementation of operational demand-side management of existing copper production processes.
e. Consider demand flexibility at the design stage of future copper production capacity and its role in regional energy systems.
f. Include a comprehensive assessment of the environmental implications of the proposed systems at the design stage of production processes and energy systems.

The second contribution [2] responds to recommendation (a), by assessing the effect of declining ore grades (copper concentration) on the total electricity demand for copper production and the resulting costs for the proposed solar electricity systems in different locations around the world. The results indicate that by 2030 the cost-optimal supply for mines located in sunny regions will be almost fully solar, with other regions achieving highly solar systems by 2040. Finally, the declining costs of generating and storing solar electricity are expected to compensate for declining ore grades and the resulting rise in energy demand, in terms of specific electricity costs per ton of copper.

The third contribution [3], responds to recommendation (b) and (c). It found that already at current costs fully renewable multi-vector water and energy systems can be economically attractive when compared against conventional de-coupled systems that resort to fossil fuels. Also, the tipping point when a fully renewable energy supply becomes the lowest cost alternative happens 10 years sooner when using integrated seawater desalination and pumped-hydro storage (IPHRO): already by 2030. Furthermore, IPHROS enables higher shares of renewable energy in the cost-optimal system in the conventional scenarios, thus lowering their carbon footprint.

The fourth contribution [4], responds to recommendation (e). It indicates that capacity-based demand-side flexibility in copper production processes can help lower the costs of fully renewable energy systems. In particular, savings around 5-8% can be achieved in the corresponding energy system when considering this source of flexibility. Since demand-flexibility competes with declining costs of renewable energy generation and storage, its relative savings in energy costs decrease over time. However, it is still a relevant alternative to consider, as the timing of the energy transition is key: the sooner, the better.

The remaining recommendations (d and f) were not addressed in the course of this dissertation and are proposed for future work (see section 6.5).

6.4. Overall discussion

Far from a costly imperative (as thought a decade ago), renewable energy systems are now an economically attractive option and going *fully* renewable will soon become the least-cost alternative. For the copper industry, we expect this to happen within ten years, at least in sunny regions. Moreover, this holds not only for the electricity supply: integrated reverse osmosis and pumped-hydro storage makes 100% renewable systems the least cost alternative by 2030, also when considering the complete energy demand of copper production and desalinated water supply. This means considering also heat, fuels, and transport needs.

From the case studies analyzed in this work, we learn that the specific costs of electricity for copper mines can be lowered by adopting solar energy from the current 60-100 €/MWh to 30-50 €/MWh by 2050, depending on location. Mines located in sunnier regions—like Chile and Peru—will have an edge in compensating for increased electricity demand due to ore grade decline by means of using solar electricity. Regarding multi-vector systems (electricity, heat, fuels, and water), the IPHRO concept can lower the costs of a fully renewable system by 20% at today's costs and by 8% in 2050, giving the declining costs of other technologies for renewable energy generation and storage. Also, the current supply costs of a fully renewable multi-vector system practically equal those of a de-coupled fossil-based system without IPHRO. Moreover, the current costs of a fully renewable multi-vector energy supply can be lowered in 5-8% by integrating capacity-based demand flexibility. These savings fade over time as the costs of renewable energy generation and storage are expected to keep on falling. However, other benefits may remain: capacity-based industrial demand flexibility can be a favorable alternative when considering material criticality since its demand for raw materials differs from that of storage technologies such as lithium-ion batteries.

Going beyond the copper industry and from an energy modeling perspective, we can understand different sources of flexibility—such as sector-coupling, storage, transmission, and demand flexibility—as competing alternatives within an optimization problem. However, this may suggest a false polychotomy because these are not conflicting options. It is best to understand them as complementary elements of modern and flexible renewable energy systems. Understanding the role that each source should play, and assessing the contribution of each source, requires careful modeling of the specific system. In other words, the role of the different flexibility sources depends on the specific characteristics of the system where they participate, such as final use, magnitude and timing of energy demand, geography, climate, and size, to mention a few.

Going back to the copper industry case, our results indicate that a cleaner supply chain for the energy transition is affordable. In particular, when integrating sector-coupling, demand flexibility, and considering the declining costs of renewable energy generation and storage.

6.5. Outlook

In the following, an outlook for future research and final thoughts on the implications of the work presented in this thesis are offered.

A comprehensive analysis of the environmental implications is needed: in this work, we assessed only direct carbon dioxide emissions from the combustion of fossil fuels. To understand the full scope of the impacts, an environmental assessment of the systems is required that considers all relevant types of impact as well as a lifecycle perspective., as proposed in recommendation (f).

Future modeling efforts in energy systems planning should consider IPHROS: we include this concept for integrated desalination and energy storage in our model for water and energy systems planning. This concept was always identified as a cost-efficient alternative, with a major role in balancing out fully renewable systems. Then, we recommend its integration into models for energy systems planning. The technical potential of this technology depends on the geographical conditions of the region of interest. In the original paper proposing this concept, different locations around the world are assessed [152], which could serve as a starting point for assessing the potential of this alternative in global systems.

Energy demand flexibility in the copper industry should be further investigated: both the opportunities for capacity-independent operational flexibility and its role in larger regional systems should be explored, as proposed in recommendation (d). This way, the actual potential of demand flexibility in the copper industry to improve the performance of energy systems can be assessed.

Enabling technologies for renewable energy use: we have proposed designs for fully renewable water and energy systems that cover all energy needs for copper production. However, in the production process-side of the system, there is still equipment that needs to be adapted to be operated with renewable vectors. This means for the operations that currently operate with fossil fuels to be, for example, *electrified* or *hydrogenized*. Although there are advances in this direction (e.g. e-trucks), the deployment of these adaptations must be accelerated for the industry to profit from the low-cost/low-emissions energy that fully renewable systems offer.

New renewables-based copper commodity: we have seen that the question is no longer *if* production processes should go fully renewable but rather *when* and *how* to do it. Moreover, as more manufactures of final goods and services and costumers start caring about the environmental footprint of their supply chains, new markets could open. In particular, premiums could be paid for cleaner copper, or two (or more) commodity markets could arise: one for conventional copper and one for renewables-based one. In this context, companies mastering the design and operation of fully renewable energy systems will have an edge.

Do not forget about efficiency: having access to low-cost and comparatively cleaner renewable energy sources should not result in neglecting the need for improved efficiency. This includes efficiency at two levels. First, energy-efficiency in industrial processes, copper production in this case. Second, materials (copper)-efficiency in the satisfaction of humanities' needs. The latter leading to the always tough question: what is it that humanity really needs?

Socio-economic factors and environmental justice should be considered in the energy transition, including its supply chain: fully renewable energy systems are affordable, technically feasible, and cleaner than conventional fossil-based systems. Moreover, in this thesis, we show that they are an alternative to lower the carbon footprint of the supply chain of the energy transition, in particular for copper. However, this does not mean that the sustainability of the energy systems of the future is guaranteed. Far from that, key issues remain open: whose final needs are satisfied with the cleaner systems we propose? Will the global energy transition consolidate existing relationships of domination, or will humanity take this opportunity to advance towards a more equitable world?

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Appendix from Chapter 4

Appendix 1: Cost assumptions in chapter 4

Year:	***2020***	***2025***	***2030***	***2035***	***2040***	***2045***	***2050***	***References***
Single-axis tracking PV								
CapEx (k€/MW)	431	333	275	235	204	181	164	[163]
OpEx fix (k€/MW/a)	8.8	7.4	6.4	5.6	5	4.6	4.2	[163]
OpEx var (€/MWh)	0	0	0	0	0	0	0	[163]
Lifetime (years)	30	35	35	35	40	40	40	[159]
On-shore wind power								[159]
CapEx (k€/MW)	1150	1060	1000	965	940	915	900	
OpEx fix (k€/MW/a)	23	21	20	19	19	18	18	
OpEx var (€/MWh)	0	0	0	0	0	0	0	
Lifetime (years)	25	25	25	25	25	25	25	
Geothermal power plant								[162]
CapEx (k€/MW)	4970	4720	4470	4245	4020	3815	3610	
OpEx fix (k€/MW/a)	80	80	80	80	80	80	80	
OpEx var (€/MWh)	0	0	0	0	0	0	0	
Lifetime (years)	40	40	40	40	40	40	40	
CC gas turbine								[159]
CapEx (k€/MW)	775	775	775	775	775	775	775	
OpEx fix (k€/MW/a)	19.4	19.4	19.4	19.4	19.4	19.4	19.4	
OpEx var (€/MWh)	2	2	2	2	2	2	2	
Lifetime (years)	35	35	35	35	35	35	35	
Li-Ion battery								Based on [163], split with energy-to-power ratio 6
CapEx (k€/MWh)	232	150	108	87	74	66	60	

OpEx fix (k€/MWh/a)	3.9	3.2	2.7	2.5	2.2	2.1	2	
OpEx var (€/MWh)	0	0	0	0	0	0	0	
Lifetime (years)	20	20	20	20	20	20	20	
Li-ion inverter								Based on [163], split with energy-to-power ratio 6
CapEx (k€/MW)	115.8	75.2	54.0	43.4	36.9	32.8	30.0	
OpEx fix (k€/MW/a)	0	0	0	0	0	0	0	
OpEx var (€/MWh)	0	0	0	0	0	0	0	
Lifetime (years)	20	20	20	20	20	20	20	
Hydrogen storage in salt caverns								[158], data for for years 25, 35, and 45 linearly interpolated
CapEx (k€/MWh$_{th}$)	0.386	0.38	0.374	0.372	0.37	0.3685	0.367	
OpEx fix (k€/MWh$_{th}$/a)	0.0154	0.0152	0.0150	0.0149	0.0148	0.0147	0.0147	
OpEx var (€/MWh$_{th}$)	0.2	0.2	0.2	0.2	0.2	0.2	0.2	
Lifetime (years)	30	30	30	30	30	30	30	
Hydrogen compressors								[158], data for for years 25, 35, and 45 linearly interpolated
CapEx (k€/MW$_{th}$)	29	29	29	29	29	29	29	
OpEx fix (k€/MW$_{th}$/a)	1.16	1.16	1.16	1.16	1.16	1.16	1.16	
OpEx var (€/MWh$_{th}$)	0	0	0	0	0	0	0	
Lifetime (years)	20	20	20	20	20	20	20	
Electrolyzer (alkaline)								[158], data for for years 25, 35, and 45 linearly interpolated
CapEx (k€/MW$_{H2}$)	685	533	380	338	296	272	248	
OpEx fix (k€/MW$_{H2}$/a)	24.0	18.6	13.3	11.8	10.4	9.5	8.7	

OpEx var ($€/MWh_{H2}$)	3.6	2.7	1.8	1.55	1.3	1.15	1	
Lifetime (years)	30	30	30	30	30	30	30	
Efficiency	0.73	0.75	0.76	0.78	0.79	0.81	0.82	
High-temperature heat storage								[159]
CapEx ($k€/MWh_{th}$)	41.8	32.7	26.8	23.3	21	19.3	17.5	
OpEx fix ($k€/MWh_{th}/a$)	0.63	0.49	0.4	0.35	0.32	0.29	0.26	
OpEx var ($€/MWh_{th}$)	0	0	0	0	0	0	0	
Lifetime (years)	25	25	25	30	30	30	30	
Electro-heat (rod)								[159]
CapEx (k€/MW)	100	100	75	75	75	75	75	
OpEx fix (k€/MW/a)	1.47	1.47	1.47	1.47	1.47	1.47	1.47	
OpEx var (€/MWh)	1	1	1	1	1	1	1	
Lifetime (years)	19	19	19	19	19	19	19	based on [201]
Solar heat (CSP array)								[159]
CapEx ($k€/MW_{th}$)	344.5	303.6	274.7	251.1	230.2	211.9	196	
OpEx fix ($k€/MW_{th}/a$)	7.9	7	6.3	5.8	5.3	4.9	4.5	
OpEx var ($€/MWh_{th}$)	0	0	0	0	0	0	0	
Lifetime (years)	25	25	25	25	25	25	25	
CSP steam turbine (power block)								[162]
CapEx (k€/MW)	740	720	700	670	640	615	600	
OpEx fix (k€/MW/a)	14.8	14.4	14	13.4	12.8	12.3	12	
OpEx var (€/MWh)	0	0	0	0	0	0	0	
Lifetime (years)	25	25	25	30	30	30	30	
RO desalination plant in IPHRO configuration								Based on [162] and [150]. Energy equivalent based on potential

								energy of required hydraulic head
CapEx (k€/MW$_{eq}$)	5395	4608	3916	3317	2814	2373	1963	
OpEx fix (k€/MW$_{eq}$/a)	242	210	183	159	139	121	105	
OpEx var (€/MWh$_{eq}$)	0	0	0	0	0	0	0	
Lifetime (years)	25	25	25	25	25	25	25	
Water efficiency	0.5	0.5	0.5	0.5	0.5	0.5	0.5	
Seawater pump-turbine for IPHRO								Based on [162] and [166]
CapEx (k€/MW)	1170	1170	1170	1170	1170	1170	1170	
OpEx fix (k€/MW/a)	0	0	0	0	0	0	0	
OpEx var (€/MWh)	0	0	0	0	0	0	0	
Lifetime (years)	50	50	50	50	50	50	50	
Heat exchanger								based on [144]
CapEx (k€/MW)	7	7	7	7	7	7	7	
OpEx fix (k€/MW/a)	0	0	0	0	0	0	0	
OpEx var (€/MWh)	0.7	0.7	0.7	0.7	0.7	0.7	0.7	
Lifetime (years)	30	30	30	30	30	30	30	
Heat pump								[159]
CapEx (k€/MW)	660	618	590	568	554	540	530	
OpEx fix (k€/MW/a)	2	2	2	2	2	2	2	
OpEx var (€/MWh)	2	2	2	2	2	2	2	
Lifetime (years)	25	25	25	25	25	25	25	
RO desalination plant with pumps								Based on [162] and [150]. Energy equivalent based on potential energy of

								required hydraulic head
CapEx (k€/MW)	6045	5258	4566	3967	3464	3023	2613	
OpEx fix (k€/MW/a)	242	210	183	159	139	121	105	
OpEx var (€/MWh)	0	0	0	0	0	0	0	
Lifetime (years)	25	25	25	25	25	25	25	
Seawater reservoir for IPHRO								Based on [162]
CapEx (k€/MWh)	7.7	7.7	7.7	7.7	7.7	7.7	7.7	
OpEx fix (k€/MWh/a)	1.335	1.335	1.335	1.335	1.335	1.335	1.335	
OpEx var (€/MWh)	0	0	0	0	0	0	0	
Lifetime (years)	50	50	50	50	50	50	50	
Desalinated water storage								[162]
CapEx (k€/m3)	0.065	0.065	0.065	0.065	0.065	0.065	0.065	
OpEx fix (k€/m3/a)	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	
OpEx var (€/MWh)	0	0	0	0	0	0	0	
Lifetime (years)	50	50	50	50	50	50	50	
Low temperature heat storage								Based on [196]
CapEx (k€/MWh)	5.7	5.7	5.7	5.7	5.7	5.7	5.7	
OpEx fix (k€/MWh/a)	0.8	0.8	0.8	0.8	0.8	0.8	0.8	
OpEx var (€/MWh)	0	0	0	0	0	0	0	
Lifetime (years)	30	30	30	30	30	30	30	
Hydrogen turbine (combined cycle)								[158], data for for years 35 and 45 linearly interpolated
CapEx (k€/MWh)	-	-	853.0	853.0	853.0	853.0	853.0	

OpEx fix (k€/MWh/a)	-	-	21.3	21.3	21.3	21.3	21.3
OpEx var (€/MWh)	-	-	2	2	2	2	2
Lifetime (years)	-	-	35	35	35	35	35
Efficiency (HHV)	-	-	0.522	0.531	0.54	0.54	0.54

Appendix 2: Demand characterization in chapter 4

The following tables show the specific demand (per unit of copper produced), total yearly demand for the case study, and maximum hourly demand for the case study, for all vectors.

Characterization of demands for S1 and S2

	Full process specific demand (kWh/tCu) or (m^3/tCu) for water	Total yearly demand for case study (GWh) or (10^6 m^3/h) for water	Maximum hourly demand for case study (MWh) or (m^3/h) for water
Electricity	4865	1776	238
Natural gas for heat	527	192	22 (constant)
Natural gas for smelting	1454	531	61 (constant)
Diesel for trucks	2678	977	112 (constant)
Water	119	43	4944

Characterization of demands for S3 and S4

	Full process specific demand (kWh/tCu) or (m^3/tCu) for water	Total yearly demand for case study (GWh) or (10^6 m^3/h) for water	Maximum hourly demand for case study (MWh) or (m^3/h) for water
Electricity	6271	2289	307
Low-temp. heat	527	192	44
Hydrogen	1454	531	61
Water	119	43	4944

Appendix from Chapter 5

Appendix 3: Cost assumptions for the components of the energy systems in Chapter 5

Year:	***2020***	***2025***	***2030***	***2035***	***2040***	***2045***	***2050***	***References***
Single-axis tracking PV								
CapEx (k€/MW)	431	333	275	235	204	181	164	[163]
OpEx fix (k€/MW/a)	8.8	7.4	6.4	5.6	5	4.6	4.2	[163]
OpEx var (€/MWh)	0	0	0	0	0	0	0	[163]
Lifetime (years)	30	35	35	35	40	40	40	[159]
On-shore wind power								[159]
CapEx (k€/MW)	1150	1060	1000	965	940	915	900	
OpEx fix (k€/MW/a)	23	21	20	19	19	18	18	
OpEx var (€/MWh)	0	0	0	0	0	0	0	
Lifetime (years)	25	25	25	25	25	25	25	
Li-Ion battery								Based on [163], split with energy-to-power ratio of 6
CapEx (k€/MWh)	232	150	108	87	74	66	60	
OpEx fix (k€/MWh/a)	3.9	3.2	2.7	2.5	2.2	2.1	2	
OpEx var (€/MWh)	0	0	0	0	0	0	0	
Lifetime (years)	20	20	20	20	20	20	20	
Li-ion inverter								Based on [163], split with energy-to-power ratio of 6
CapEx (k€/MW)	115.8	75.2	54.0	43.4	36.9	32.8	30.0	
OpEx fix (k€/MW/a)	0	0	0	0	0	0	0	
OpEx var (€/MWh)	0	0	0	0	0	0	0	
Lifetime (years)	20	20	20	20	20	20	20	
Hydrogen storage in salt caverns								[158], data for for years 25, 35, and 45 linearly

								interpolated
CapEx (k€/MWh$_{th}$)	0.386	0.38	0.374	0.372	0.37	0.3685	0.367	
OpEx fix (k€/MWh$_{th}$/a)	0.0154	0.0152	0.0150	0.0149	0.0148	0.0147	0.0147	
OpEx var (€/MWh$_{th}$)	0.2	0.2	0.2	0.2	0.2	0.2	0.2	
Lifetime (years)	30	30	30	30	30	30	30	
Hydrogen compressors								[158], data for years 25, 35, and 45 linearly interpolated
CapEx (k€/MW$_{th}$)	29	29	29	29	29	29	29	
OpEx fix (k€/MW$_{th}$/a)	1.16	1.16	1.16	1.16	1.16	1.16	1.16	
OpEx var (€/MWh$_{th}$)	0	0	0	0	0	0	0	
Lifetime (years)	20	20	20	20	20	20	20	
Electrolyzer (alkaline)								[158], data for years 25, 35, and 45 linearly interpolated
CapEx (k€/MW$_{H2}$)	685	533	380	338	296	272	248	
OpEx fix (k€/MW$_{H2}$/a)	24.0	18.6	13.3	11.8	10.4	9.5	8.7	
OpEx var (€/MWh$_{H2}$)	3.6	2.7	1.8	1.55	1.3	1.15	1	
Lifetime (years)	30	30	30	30	30	30	30	
Efficiency	0.73	0.75	0.76	0.78	0.79	0.81	0.82	
High-temperature heat storage								[159]
CapEx (k€/MWh$_{th}$)	41.8	32.7	26.8	23.3	21	19.3	17.5	
OpEx fix (k€/MWh$_{th}$/a)	0.63	0.49	0.4	0.35	0.32	0.29	0.26	
OpEx var (€/MWh$_{th}$)	0	0	0	0	0	0	0	
Lifetime (years)	25	25	25	30	30	30	30	
Electro-heat (rod)								[159]
CapEx (k€/MW)	100	100	75	75	75	75	75	
OpEx fix (k€/MW/a)	1.47	1.47	1.47	1.47	1.47	1.47	1.47	
OpEx var (€/MWh)	1	1	1	1	1	1	1	

Lifetime (years)	19	19	19	19	19	19	19	based on [201]
Solar heat (CSP array)								[159]
CapEx (k€/MW$_{th}$)	344.5	303.6	274.7	251.1	230.2	211.9	196	
OpEx fix (k€/MW$_{th}$/a)	7.9	7	6.3	5.8	5.3	4.9	4.5	
OpEx var (€/MWh$_{th}$)	0	0	0	0	0	0	0	
Lifetime (years)	25	25	25	25	25	25	25	
CSP steam turbine (power block)								[106]
CapEx (k€/MW)	740	720	700	670	640	615	600	
OpEx fix (k€/MW/a)	14.8	14.4	14	13.4	12.8	12.3	12	
OpEx var (€/MWh)	0	0	0	0	0	0	0	
Lifetime (years)	25	25	25	30	30	30	30	
Seawater pump-turbine for PHES								Based on [106] and [166]
CapEx (k€/MW)	1170	1170	1170	1170	1170	1170	1170	
OpEx fix (k€/MW/a)	0	0	0	0	0	0	0	
OpEx var (€/MWh)	0	0	0	0	0	0	0	
Lifetime (years)	50	50	50	50	50	50	50	
Heat exchanger								based on [144]
CapEx (k€/MW)	7	7	7	7	7	7	7	
OpEx fix (k€/MW/a)	0	0	0	0	0	0	0	
OpEx var (€/MWh)	0.7	0.7	0.7	0.7	0.7	0.7	0.7	
Lifetime (years)	30	30	30	30	30	30	30	
Heat pump								[159]
CapEx (k€/MW)	660	618	590	568	554	540	530	
OpEx fix (k€/MW/a)	2	2	2	2	2	2	2	
OpEx var (€/MWh)	2	2	2	2	2	2	2	
Lifetime (years)	25	25	25	25	25	25	25	
Seawater reservoir for PHES								Based on [106]
CapEx (k€/MWh)	7.7	7.7	7.7	7.7	7.7	7.7	7.7	
OpEx fix (k€/MWh/a)	1.335	1.335	1.335	1.335	1.335	1.335	1.335	

OpEx var (€/MWh)	0	0	0	0	0	0	0	
Lifetime (years)	50	50	50	50	50	50	50	
Low-temperature heat storage								Based on [196]
CapEx (k€/MWh)	5.7	5.7	5.7	5.7	5.7	5.7	5.7	
OpEx fix (k€/MWh/a)	0.8	0.8	0.8	0.8	0.8	0.8	0.8	
OpEx var (€/MWh)	0	0	0	0	0	0	0	
Lifetime (years)	30	30	30	30	30	30	30	
Hydrogen turbine (combined cycle)								[158], data for years 35 and 45 linearly interpolated
CapEx (k€/MWh)	-	-	853.0	853.0	853.0	853.0	853.0	
OpEx fix (k€/MWh/a)	-	-	21.3	21.3	21.3	21.3	21.3	
OpEx var (€/MWh)	-	-	2	2	2	2	2	
Lifetime (years)	-	-	35	35	35	35	35	
Efficiency (HHV)	-	-	0.522	0.531	0.54	0.54	0.54	

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