Copper mining: 100% solar electricity by 2030?

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ABSTRACT

Extracting copper is energy-intensive. At the same time, copper is a key material for building the energy systems of the future. Both facts call for clean copper production. The present work addresses the greenhouse gas emissions of this industry and 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 consider the 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. For the next steps, we recommend representing the demand with further detail, including other vectors such as heat and fuels. In addition, we recommend to include the embodied emissions of the technologies to get a more complete picture of the environmental footprint of the energy supply for copper production.

Keywords (6): generation expansion planning; cleaner production; integration of solar photovoltaic; low-carbon systems; responsible copper; energy in mining;

1 Introduction

When somebody decides to buy an electric car, environmental impacts are likely on the table. Likewise, as awareness about and the urgency for sustainability rises, industries need to provide cleaner products while supplying for the needs of humanity. Particularly interesting is the case of copper, a key material for the development of sustainable energy systems of the future, whose production is intensive in energy and emissions [1][2]. The electric vehicle industry alone is expected to demand around 1.9 M tons/year of copper by 2027 [3]. With the current production of the metal around 20 M tons/year [4], significant efforts would be required to effectively meet future demand. For sustainability purposes of the sector, that demand should be met with clean sources. Moreover, copper mining plays a role in the supply of the materials required to build the infrastructure needed to successfully deliver the Sustainable Development Goals of the United Nations [5].

Among the various types of environmental impacts in the lifecycle of copper, global warming potential (GWP) is especially susceptible to being reduced by using renewable energy. For example, a previous study for the Chilean case shows GWP reductions of at least 60% can be achieved when substituting conventional electricity sources from the grid with solar electricity [6]. For further reduction, the remaining energy demand, such as fuels and heat, must be addressed. The scientific literature already offers some insights into the use of renewable energy for copper mining. For example, the direct use of photovoltaic (PV) electricity in the copper electro-winning operation, aimed at avoiding the losses due to AC/DC conversions, is investigated in reference [7]. Also, the use of PV and a battery energy storage system for rock grinding has been investigated. An operational strategy is proposed where the harder mineral is milled during daylight so that peak demand matches the availability of solar electricity, thus significantly reducing the need for batteries [8]. In a later study, the authors consider a geometallurgical model of a mine to assess the effect that the uncertainty of rock hardness has on the performance of the proposed system [9,10]; again, finding that all considered renewable-based systems are economically attractive. The use of solar-thermal technologies has been studied as well. Reference [11] looked at financing mechanisms of concentrated solar power (CSP) for copper mining operations in northern Chile, which at the time (2014) were more expensive than market prices. In [12], the authors address the use of concentrated solar heat for smelting copper concentrate with flexible demand. This flexibility comes from the ability to control the flows of air and fuel into the reactor, as well as the pre-heating of the feed, all of these variables being subject to the restrictions of the thermo-chemical processes in the operation.

There is also scientific progress in the design of multi-energy (more than one vector) renewable systems for copper production. A cost-optimal design for heat and electricity supply using PV, CSP, and three energy storage technologies has been reported for a location in the north of Chile [13]. This study was later extended to account for the variability of renewable energy, by introducing modifications in widely used reliability indexes [14]. The last step of this investigation presents the simultaneous optimization of costs and reliability by determining the corresponding Pareto front for the case study [15]. The last study found, specific to solar energy for copper operations is reference [16], which explored the use of combined PV with a novel wind-based technology and hydrogen energy storage. The cost of the proposed system is significantly higher than those of systems relying on conventional renewable energy technologies. In fact, many recent studies on energy system design support the technical feasibility and economic viability of fully renewable energy systems [17,18]. In addition, a recent review provides recommendations for the development of methods in the design of renewable energy systems for copper production [19]. The first recommendation is to improve the energy demand models. This means, among others, to consider the effect of the geography and location of the mines on both the demand itself and the availability of renewable 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 [20], Chile, has been deploying these technologies without subsidies for many years [21,22]. This country's favorable conditions for the deployment of solar technologies [23] 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 [24], 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 [1]. Or, if freshwater is scarce, seawater must be desalinated and transported, thereby increasing electricity demand [25]. 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 [26], for example, systematized the energy storage needs for power systems with increasing shares of renewable generation; or references [27] and [28] 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 study 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, 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 4, we present the conclusions.

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 2.1), followed by the inputs and assumptions (subsection 2.2), the scenarios assessed for our case study (subsection 2.3), and the methods to project the future specific energy costs for the different mines (subsection 2.4). Figure 1 depicts a general summary of the methods.

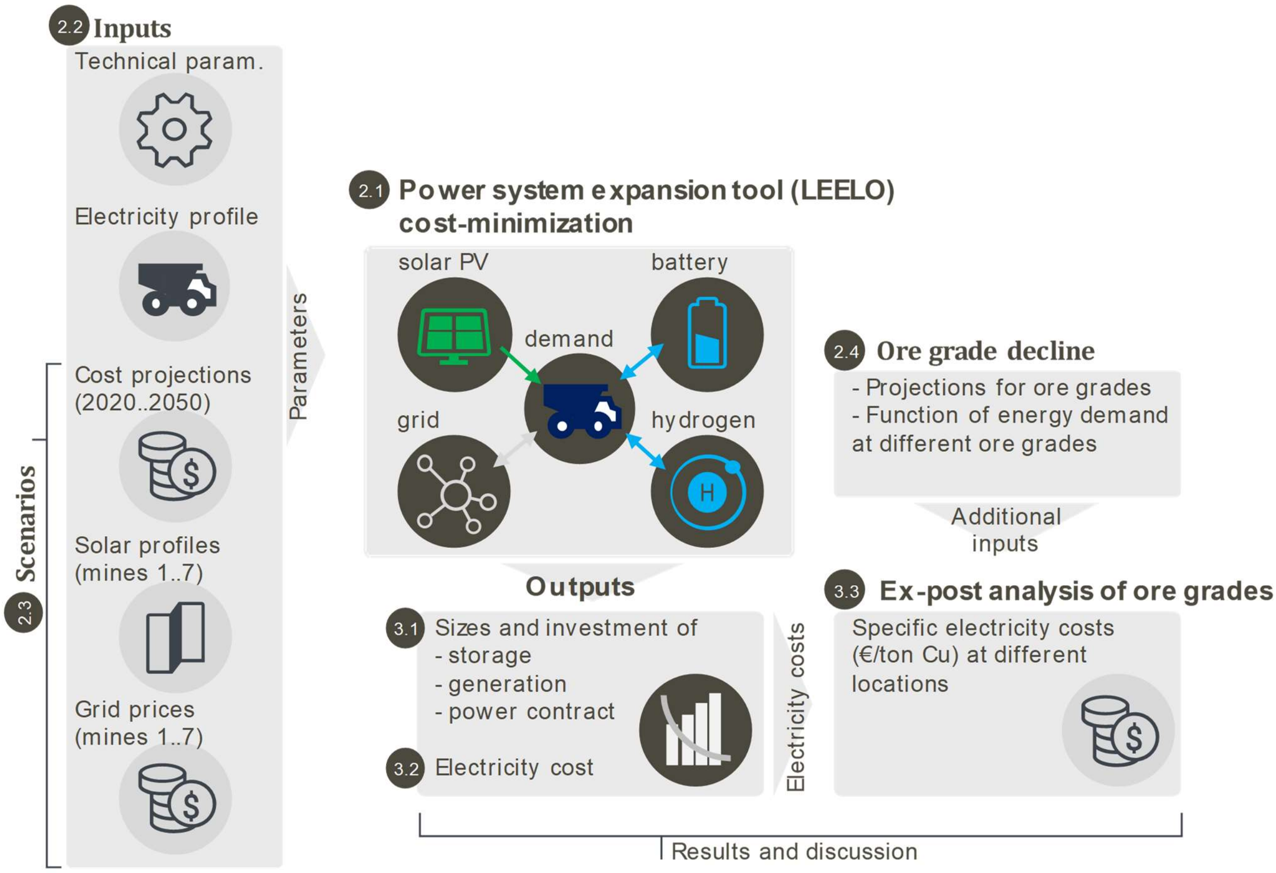

Figure 1 *Flowchart of methods. Black circles indicate the corresponding section in the document.*

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 [29] and has been validated in multiple other publications [30,31]. 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 [8]. 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.

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 [32].

2.2.1 Mines considered

We focus on the major copper-producing countries of the world [33], as shown in Table 1, 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 (subsection 2.2.3) and the grid energy cost (subsection 2.2.5). The shape of the profile of electricity demand is assumed to be the same for all mines (subsection 2.2.2).

Table 1 *Overview of considered copper-producing countries and mines (and their ranking in the global primary copper production) with data for 2016* [33]

Country	Rank of country	Copper production (kT/year)	% of world production	% of world production (cumulative)	Main mine	Rank of mine	Copper production (kT/year)	% of world production	% of world production (cumulative)
Chile	1	5500	25.0%	25.0%	Escondida	1	1270	5.8%	5.8%
Peru	2	2300	10.5%	35.5%	Cerro Verde	5	500	2.3%	8.1%
China	3	1900	8.6%	44.1%	Dexing	20+	125	0.6%	8.7%
United States	4	1400	6.4%	50.5%	Morenci	3	520	2.4%	11.1%
Australia	5	900	4.1%	54.6%	Olympic Dam	19	225	1.1%	12.2%
Mexico	10	800	3.6%	58.2%	Buenavista del Cobre	4	510	2.3%	14.5%
Indonesia	11	750	3.4%	61.6%	Grasberg	2	750	3.4%	17.9%

2.2.2 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.

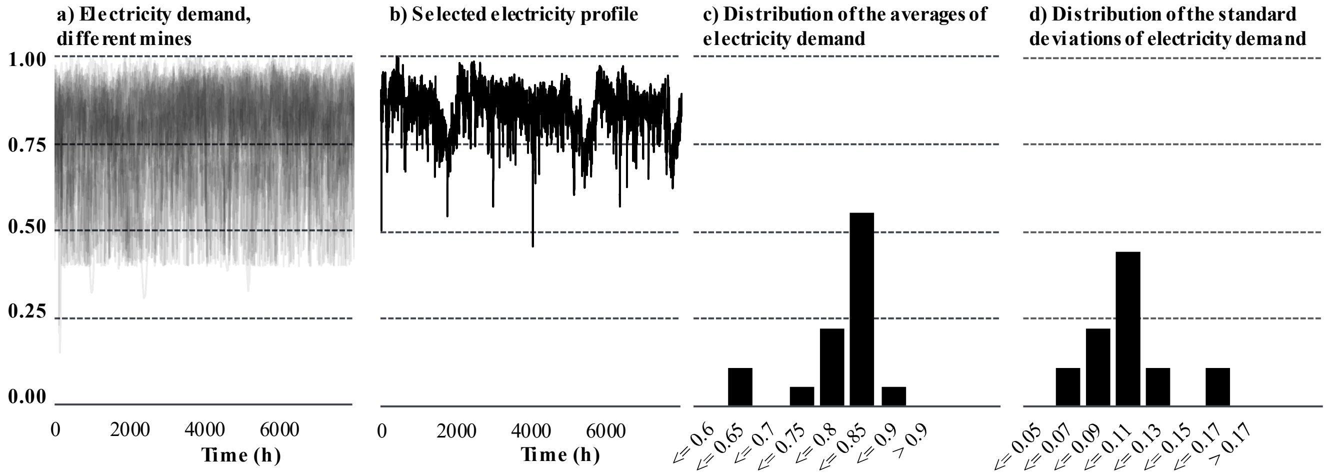

Figure 2: Electricity demand profiles. In a) and b) the y-axis represents the power demand normalized by its maximum value. In c) and d) the y-axis represents relative frequency. a) Normalized power demand of different mines and years b) Selected representative profile for the simulations c) histogram of the average of the normalized demand profiles d) histogram of the standard deviations of the 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 [34] and Peru [35] 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. **Error! Reference source not found.**-a shows all the demand profiles superimposed. To serve as a LEELO model input, a single profile (**Error! Reference source not found.**-b) was selected that represents all mining operations (the one that minimizes the variance to the other profiles). Figure 2-c shows a histogram for the normalized averages of the electricity demand profiles, while in Figure 2-d, we show the distribution of their standard deviations.

2.2.3 Solar profiles

For each mine, we use a different hourly resolved solar profile. These profiles are produced by *renewables.ninja* [36], based on NASA's ERRA and MERRA-2 global meteorological reanalysis and Meteosat-based CM-SAF SARAH satellite dataset [37]. 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 [36].

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 [38].

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 [39]. 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

2.2.4 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 [40]. This database uses learning curves to project costs to the year 2050 and has been validated in numerous journal publications [24,40–44]. 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 [40].

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 [45].

2.2.5 *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 [46–52], 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.

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.

2.4 Ex-post analysis of 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 [53] 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 [54]. Note that this source [54] shows values in terms of primary energy, which we transformed into electrical demand following their assumptions and using statistical data from Chile [55]. The resulting values of the two latter elements are shown in subsection 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.

3.1 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 3 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.

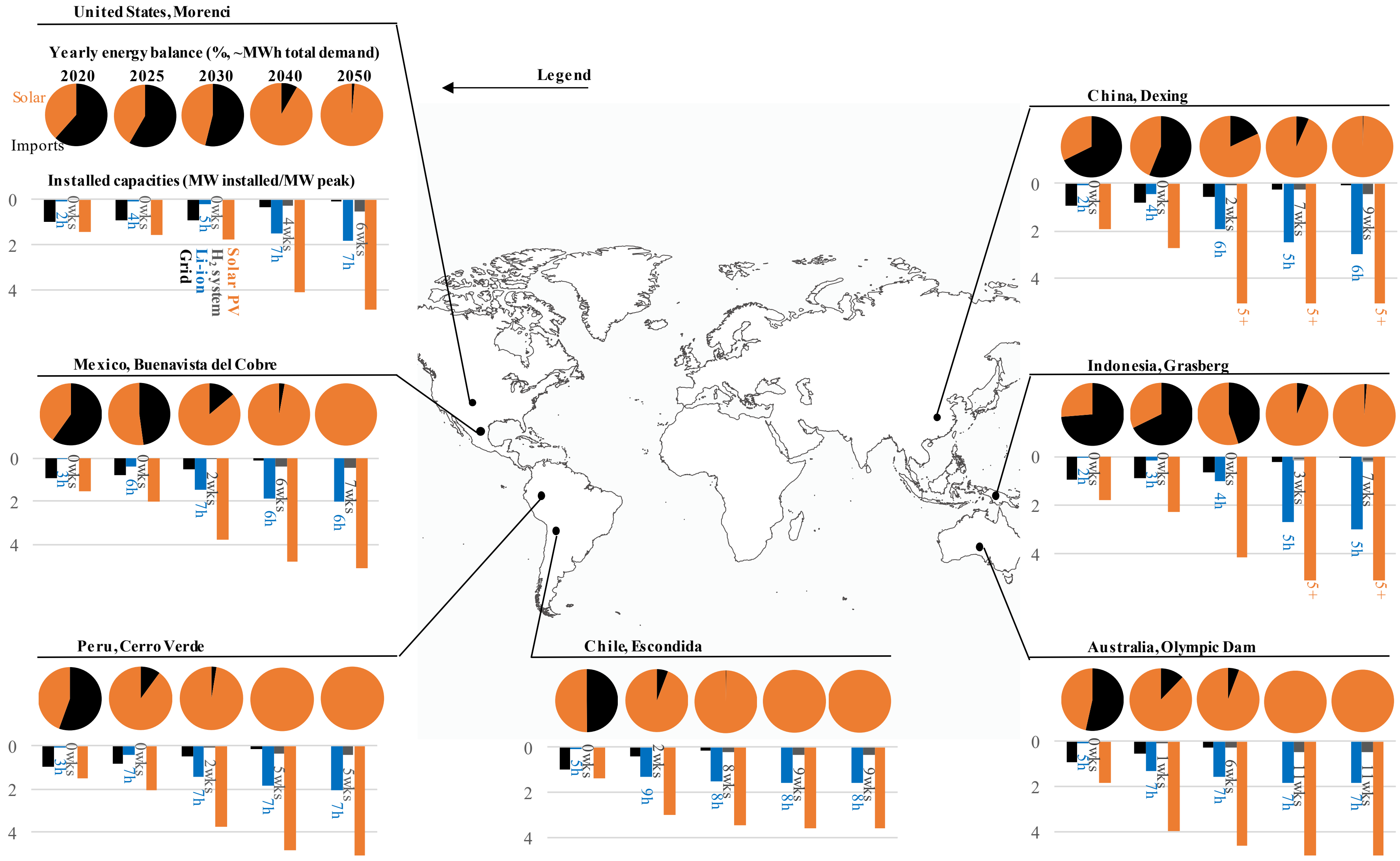

Figure 3 Solar share and investment decisions (grid contract, and battery, hydrogen, and solar system) at each mine for the years 2020 to 2050.

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 4). These costs consider all investment and operational costs from local solar and storage systems and the grid imports/exports.

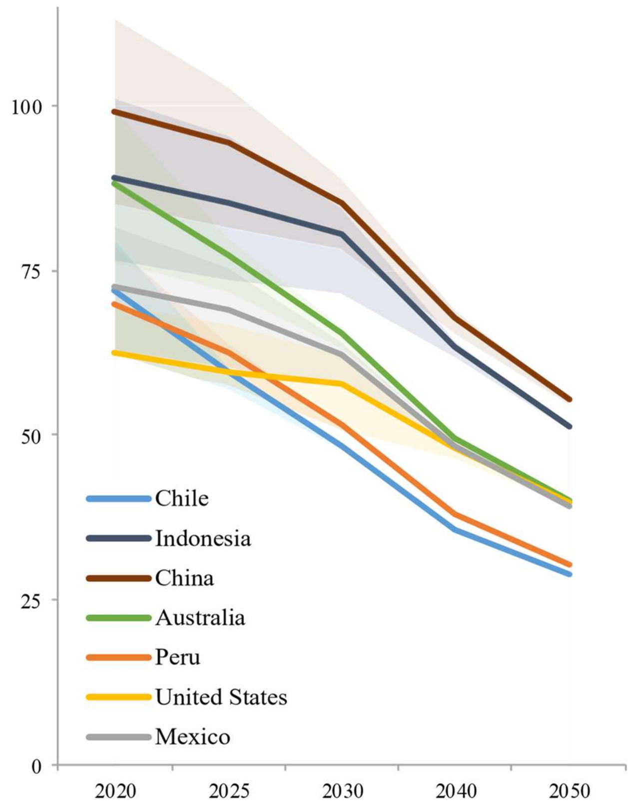

Figure 4 *Average costs of electricity (solar, storage, grid) in each region. The shaded areas represent the spread resulting from the grid price scenarios.*

Figures 4 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 [56], 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 *4*** Average costs of electricity (solar, storage, grid) in each region. The shaded areas represent the spread resulting from the grid price scenarios.Figure 4 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 3.4.1.

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 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 5a). This, in turn, results in increased specific energy demand (MWh/ton Cu, Figure 5b). 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 5c. 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.

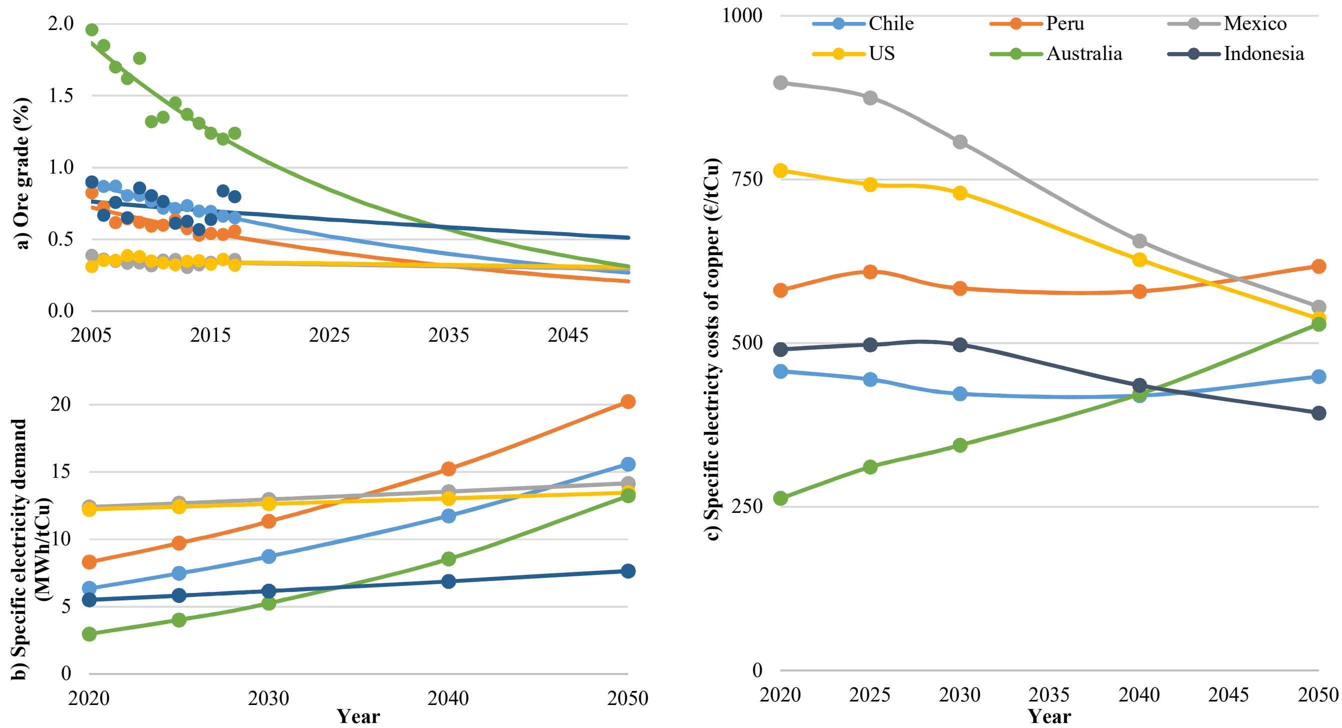

***Figure 5** a) Reported and forecasted (from 2018) ore grade by country. b) Forecasted specific electricity demand for copper production, by country.c) Obtained electricity costs per ton of copper for the different countries over the next decades, considering declining ore grades and the adoption of 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 6, 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.

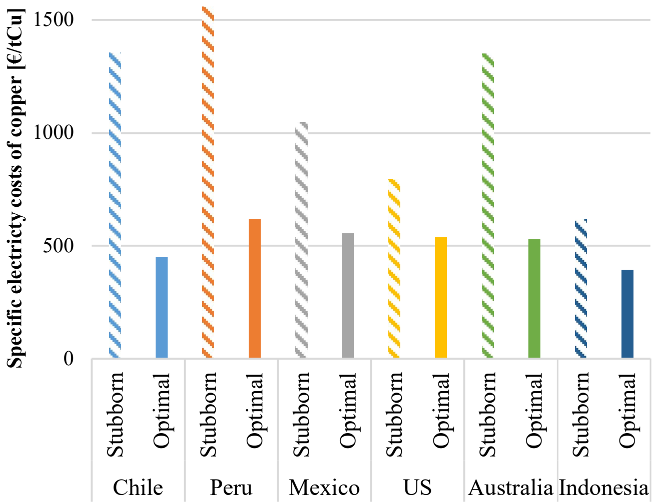

Figure 6 *Electricity costs per ton of copper for 2050 by country:*
optimal solar mixes versus a stubborn scenario (current grid mix and costs remain constant)

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.

3.4 Limitations and outlook

3.4.1 Cost assumptions

Planning the future is inherently plagued with uncertainty. So are 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 [9,10], 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 to consider 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 [57], 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.

3.4.2 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. [58] [59]), 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 [60], 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.

3.4.3 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 [55]. Some processes, such as haulage, have been transitioning to hybrid or fully electrical motors [61]. 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 [62]. While there is already experience in the industry on the use of solar thermal technologies for low-temperature applications [22] and several other solar technologies have been proposed for supplying the entire energy needs of the copper industry [63], a research gap remains in the integrated design of multi-energy systems for copper production.

4 Conclusions and future work

We explored the future electricity supply of copper mines by using 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. At the same time, producing copper with a low CO_2 footprint enables the production of cleaner components for the energy systems of the future.

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 terms of future work, we recommend to further detail the demand vectors, especially extending the approach to heat and fuels, and to look at the environmental footprint of energy technologies.

Back to the title of our work, *100% solar electricity by 2030*? Yes. For the first copper mines, with many to follow in the years after.

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 [32].

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