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Sunset or sunrise? Understanding the barriers and options for the massive deployment of solar technologies in Chile

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ABSTRACT

The use of solar technologies should proliferate in Chile as half of the country has a solar irradiance (GHI) above 5 kWh/(m^2d). Moreover, the Atacama Desert exhibits further advantageous conditions with 7 kWh/(m^2d), clear skies and a large energy-consuming mining industry. Since 2012 the solar sector takes off, totalizing over 1600 MW_e of solar power and about 100 MW_t of solar heat installed by the end of 2016. However, only about 10% of the filed projects are operative; many barriers are slowing down the further development of solar technologies. While several barrier studies for solar technologies exist in the literature, they are often country-specific and there is no publication found regarding the Chilean solar sector. In the present paper, the barriers obstructing the way of Chile becoming a solar power country are found through interviews and then analyzed and classified into six groups (economic, market, system integration, technical, regulatory and information barriers). For these barriers, an overview of emerging mitigation options are provided and future solutions, including opportunities for research, are proposed.

1. Introduction

Solar irradiation levels above 5 kWh/(m^2d) in central Chile and 7 kWh/(m^2d) in the Atacama Desert (which additionally has a large heat and power consumer, the copper mines) make the country a prime candidate for solar energy. However, are solar technologies proliferating as expected?

Barriers to mass deployment of variable renewable generation technologies in industrialized countries have been widely studied (Foxon et al., 2005; Mundo-Hernández et al., 2014; Nasirov et al., 2015; Painuly, 2001; Strupeit and Palm, 2015; Sudhakara Reddy, 2013). There has also been some analysis of barriers for developing countries (Alam Hossain Mondal et al., 2010; Ansari et al., 2013; Ohunakin et al., 2014; Zhang et al., 2012), but little attention has been given to Latin America. Moreover, reported barriers prove to be very country-specific. Therefore, a particular analysis to cater to every country's specific context is necessary. For the Chilean renewable energy sector, only one barrier study is found (Nasirov et al., 2015). However, a profound understanding of the challenges of the solar sector remains missing. Additionally, several barrier mitigation actions are currently being discussed or implemented on a government level, but have yet to be presented clearly in the literature.

This paper makes three contributions to the existing literature: i) it provides an updated summary of the status quo of Chile's solar sector;

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ii) it identifies a broad number of barriers in the solar sector in Chile, including large- and small-scale solar power plants, as well as industrial and residential solar water heaters; iii) it provides an overview of the emerging solar promotion policies and proposes solution strategies to the detected barriers. Prioritizing these strategies is out of the scope of this work.

After this introduction, the current status of Chile's solar sector is described and analyzed in Section 2. In Section 3, the barriers are explained and classified. In Section 4, mitigation strategies are proposed. Finally, Section 5 draws the conclusions and illustrates the outlook.

2. Chile's solar sector

2.1. Chile's solar history (1872–2003)

Chile's solar history starts in 1872 when Wilson builds the world's first solar desalination plant in the Atacama Desert (Frick and Hirschmann, 1973). *Las Salinas*, the distiller of 5.000 m^2 -roughly 2 MW_t- (Arellano Escudero, 2011; Harding, 1883), would remain the largest installation of its kind for almost 100 years (Eibling et al., 1971).

50 years later, U.S. researchers Moore and Abbot travel to Chile in the quest of measuring the solar constant (1918). From the 1920s until the 1950s, the Smithsonian Institution supported a solar monitoring station in the Andes (Devorkin, 1998).

After the Second World War, low fossil fuel prices discourage most solar technologies. A major exception is the utilization of solar ponds for nitrate production. Direct evaporation is still used for large-scale production of nitrates, iodine salts, and lithium carbonate from the Atacama Salt Flats (Garrett, 2004).

In the late 1950s, interest in solar technologies resurges. Universities *Católica del Norte* and *Santa María* inaugurate their solar research centers (Arellano Escudero, 2011), paving the way for the first national solar research.

2.2. Flourishing of the solar sector (2004–2016)

After a 40-year borderline complete hibernation of initiatives, in 2004 incentives for small (< 9 MW_e) renewable power plants appear. A new law (Ministry of Economy, 2004) allows them to participate in the spot market, guarantees them access to distribution networks, exempts them of transmission charges and simplifies trading (Palma et al., 2009). In 2007, over 3000 small-scale (< 0.15 kW_e) stand-alone photovoltaic (PV) systems are installed in a program for rural electrification in the north of Chile (Rodriguez, 2012). Furthermore, in 2008 the government approves a renewable electricity quota system demanding a share of 10% by 2024, which is updated five years later to 20% by 2025 (Ministerio de Energía, 2013). In 2010, the first broad solar measurement campaign is conducted in the north of Chile (Santana et al., 2014). Concurrently, the country's first microgrid based on renewable energies is inaugurated in *Huatacondo* (Jimenez-Estevez et al., 2014). However, its 23 kW_e PV array would hold the poor record of being Chile´s largest solar power plant for three years.

After these foundations, in 2012 the solar sector warms-up: the first five large solar plants (all of some MWs) finalize construction, including PV power plants, a flat plate solar water heater (SWH) plant and a concentrated solar thermal (CST) plant. Boosted by what is known to be the only subsidy for renewables in Chile (Ministerio de Hacienda, 2016), residential SWH reach approximately 20 MW_t in the same year. 2012 concludes with the start of Chile's first Excellence Research Cluster in solar energy: SERC-Chile (CONICYT, 2015).

Three *sunny* years follow (Table 1): the total installed capacity of PV jumped to 1600 MW_e by 2016 (CIFES, 2016a); thus, positioning PV in front of the installed capacities of wind, small hydro and biomass power. Residential SWH, after a slowdown in 2015 due to a short interruption of their subsidy, retake speed and totalize over 50 MW_t by the end of 2016. Chile's national copper company (CODELCO) inaugurates the largest SWH plant; thus, summing up to almost 50 MW_t in the industrial sector. Additionally, the regulation for rooftop systems catches up. Nearing the end of 2014, the net-billing scheme comes into power, easing the connection of small and medium (< 0.1 MW_e) PV systems to the distribution network. Its initial success is modest. However, 2016 shows high growth rates, computing 5 MW_e (over 700 systems) by the end of the year (National Energy Commission of Chile (CNE), 2017).

2.3. Today, solar stagnation?

Many of the installed systems were motivated by Chile's energy crisis (2008–2014). High energy prices (e.g. annual averages above 150 USD/MWh_e in the spot and contract market) plagued the industry. The current situation is different: low fossil fuel prices compete with solar technologies. Moreover, new large coal generators entered the market and, coupled with more hydropower generation (due to more rainfall in contrast to the extended drought), electricity price plummeted as a direct result.

By September 2017, almost 2100 MW_e of solar power are in operation and 400 MW_e are under construction. However, these numbers contrast strongly with the 17400 MW_e of solar projects that have an environmental permit and the additional 8300 MW_e that are currently being evaluated (Fig. 1-a). What is happening to these remaining 23200 MW_e?

Table 1
Cumulative installed capacity [MW] and number of systems (in brackets) of solar systems[a].

Technology	Source	Comment	2012	2013	2014	2015	2016
Large PV	(CNE, 2017; National Energy Commission of Chile (CNE), 2016)	Large grid-tied systems only	2 (3)	7 (7)	362 (19)	750 (27)	1645[b] (49)
Rooftop PV	(Superintendency of Electricity and Fuels of Chile (SEC), 2015)	Net-billing systems only	0 (0)	0 (0)	0(0)	1 (92)	5 (714)
Industrial SWH	(Centro de Energía, 2014)	Not centrally reported[c]	< 1 (1)	38 (3)	38 (4)	44 (4)[d]	45 (5)
Residential SWH	(Superintendency of Electricity and Fuels of Chile (SEC), 2016a)	Systems with subsidy only[e]	18 (23k)	35 (45k)	42 (54k)	49 (64k)	52 (69k)

[a] Table does not include solar ponds used in nitrate production.
[b] This number is an estimate for plants in operation and in pilot phase, which explains the difference to the 1040 MW reported by other sources.
[c] As systems are not openly informed, the numbers might underestimate the real capacity.
[d] One plant extended their capacity, thus not affecting the total number of plants.
[e] Number of systems as reported by the corresponding source and installed capacity based on own calculations.

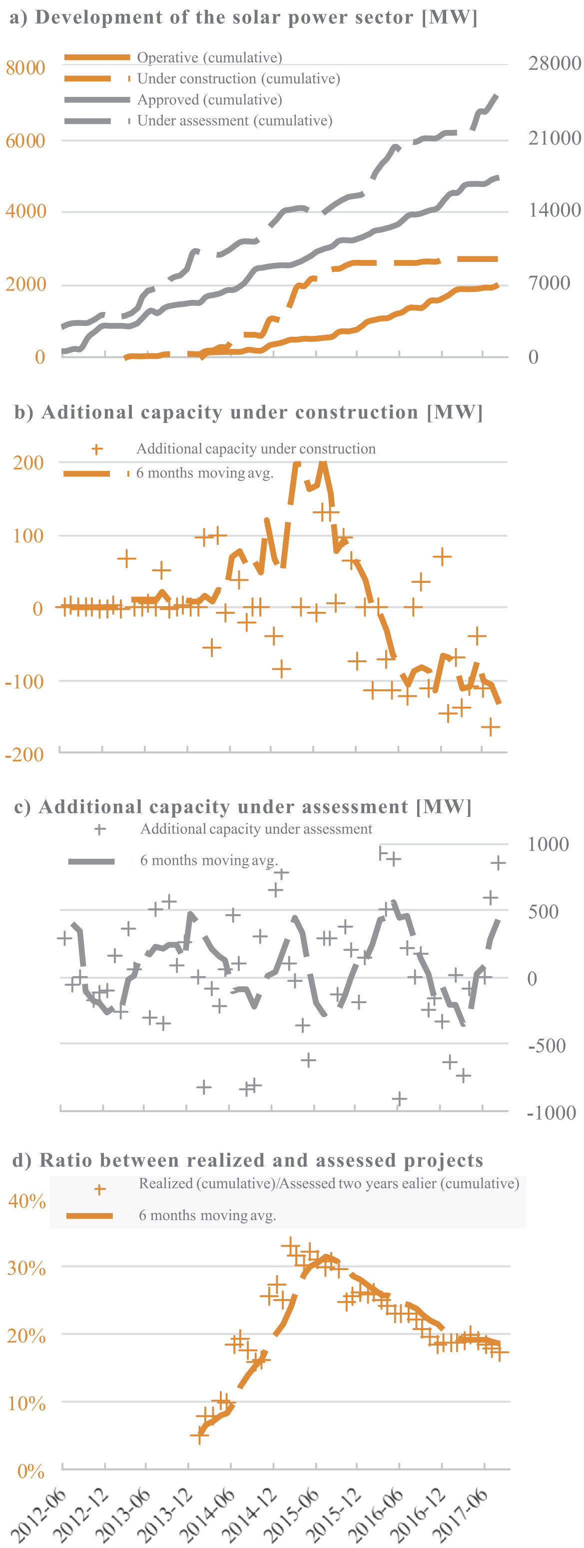

Fig. 1. The solar power sector (CSP and PV) in Chile. Data from CIFES (2016a) and CNE (CNE, 2017). a) Cumulative capacities of solar power systems in operation and under construction (on the left axis), and with their environmental permit approved and under assessment (on the right axis). b) Monthly difference of projects under construction and its 6-months moving average. c) Monthly difference of projects under assessment and its 6-months moving average. d) Ratio between realized projects (in operation and under construction) and the assessed projects (approved and under assessment) of 24 months earlier (as a typical time-lag between the moment a project enters the environmental assessment phase and the moment the construction starts).

The statistics show the first signs of a slower solar market development. Fig. 1-b reveals a strong and systematic decrease of additional capacities under construction, showing a mid-term slow-down of the sector. Only the additional solar capacities under environmental assessment (signal for a *potential* long-term deployment) seem to recover (Fig. 1-c). Furthermore, the ratio between the cumulative realized projects and the cumulative projects in evaluation peaked mid 2015 and is declining ever since (Fig. 1-d).

Do these numbers show only a minor drawback in Chile's solar trend? Or are there concrete barriers severely affecting the integration of solar technologies? Is it time for sunrise or sunset?

2.4. Energy policies development in Chile

The Chilean development of energy policies begins only recently, in 2005, after an acute energy crisis and a review about the environmental performance of Chilean policies (OECD, 2005). This OECD-report criticizes the little efforts made in reducing air pollutants and greenhouse gases, the discontinuity of energy efficiency programs and the lack of instruments to internalize environmental impacts of the energy sector. In 2008, the National Commission of Energy (CNE, 2008) provides for the first time strategic recommendations for the Chilean energy development. Analyses from the International Energy Agency (IEA, 2009) and Asia-Pacific Economic Cooperation (APEC, 2009) follow in 2009. These set the base for the creation of the Ministry of Energy in 2010.

The Ministry of Energy releases in 2014 a series of actions for the short-term and starts a range of participative processes to feed the long-term *Energy Policy 2050*. The latter finalizes in 2016, targeting a 70% of renewable electricity generation, among other cross-sectorial targets of energy efficiency and clean energy production. Also in 2016, the Chilean Government -through the Chilean Economic Development Agency (CORFO)- develops a participative process to draft the *Strategic Solar Program*. This roadmap seeks to exploit the Atacama Desert's unique features to develop an export-oriented national solar power manufacturing industry. To this end, an initial portfolio of 50 initiatives is identified with a total budget of 800 million USD (Fundación Chile, 2015).

Our paper is motivated by this context. SERC-Chile aims to make Chile a country driven by solar energy. This includes solar heat, solar fuels, solar power, access to water, the creation of a solar culture at a community level and a local solar-based industrial development. One specific target is to supply 30% of South America's electric consumption with solar technologies by 2035 through an *Atacama Solar Pole* (Jimenez-Estevez et al., 2015). This might be the basis of a future *solar belt* around the world. What barriers stand between today's Chile and its envisioned future? And more importantly, what solutions can be applied?

3. Identification of barriers to solar technologies in Chile

Barrier detection is usually based on a combination of literature review, existing projects analysis, and interaction with stakeholders (Ansari et al., 2013; Luthra et al., 2014; Painuly, 2001; Sudhakara Reddy, 2013). It aims to understand the underlying problems to focus mitigation efforts. For this reason, methodological approaches target to identify and disaggregate the barriers, as well as the drivers, in decision-making related to the development of new solar projects. This establishes the basis for proposing countermeasures that could be adopted by stakeholders, including policy and promotion mechanisms.

Diverse methodological approaches for the barriers analysis can be found in the literature. The simplest method is to make a broad barrier review based on interviews (Nasirov et al., 2015). Others study the

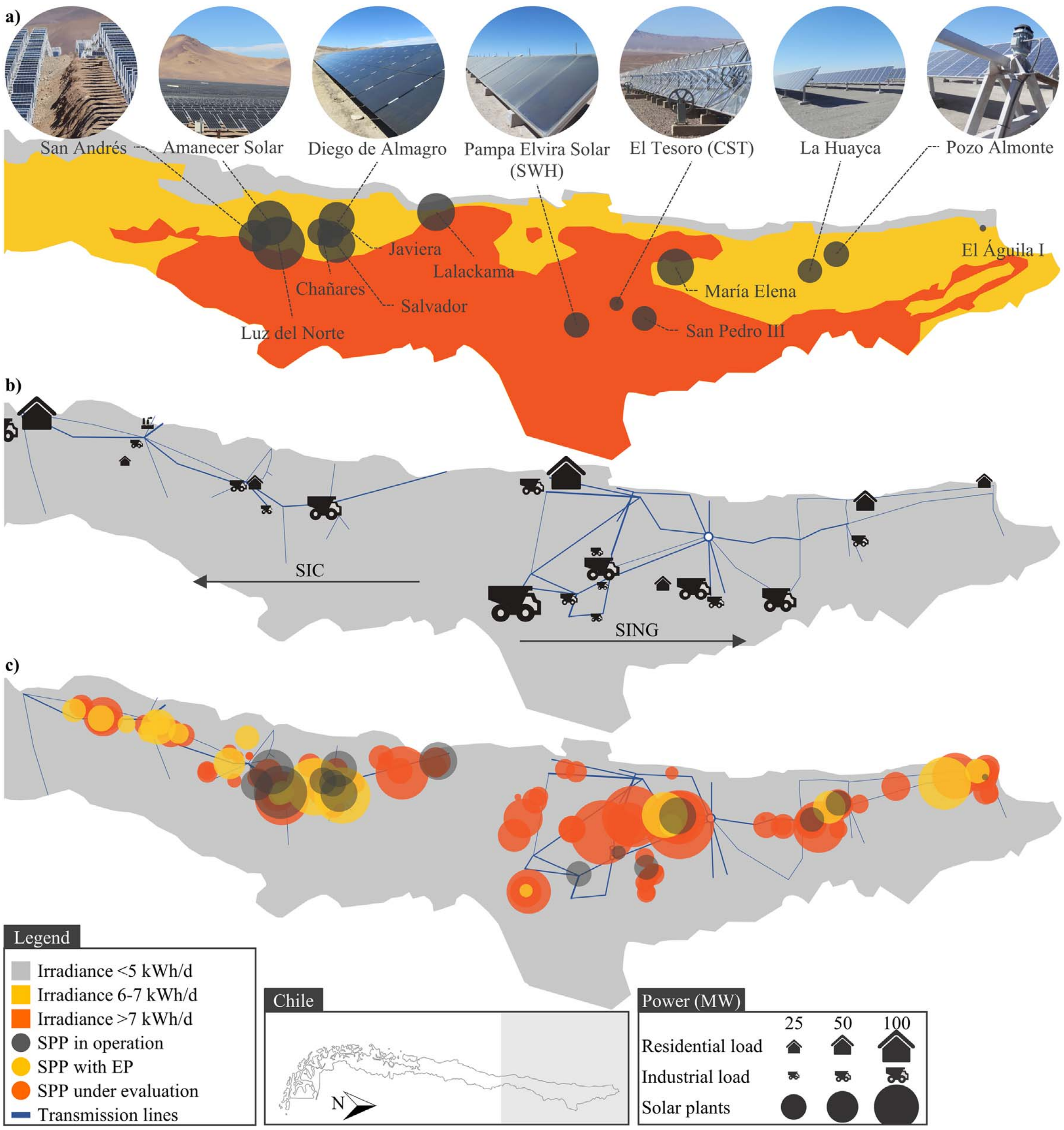

Fig. 2. Overview of the solar sector in Chile. a) Map of the main (> 3 MW_e) solar energy plants in operation (end 2015, (Power System Operator (CDEC), 2016a)) and irradiance levels (Department of Geophysics - University of Chile and Ministry of Energy of Chile, 2012). b) Load centers in Chile's Central Interconnected Power System (SIC) and Northern Interconnected Power System (SING) (Power System Operator (CDEC), 2016a). c) Solar power plants (SPP) larger than 3 MW in operation, evaluation and with an environmental permit (EP) SEA (SEA, 2016).

drivers and dependence, classifying barriers into four categories: autonomous barriers, linkage barriers, dependent and independent barriers (Ansari et al., 2013). Understanding the interactions of the problems also helps to steer mitigation efforts. A frequent focus in the literature is on taxonomic classification of found barriers (Eleftheriadis and Anagnostopoulou, 2015; Painuly, 2001; Sudhakara Reddy, 2013; Yaqoot et al., 2016).

In this section, we used data triangulation for detecting the barriers for deployment of solar technologies in Chile. First, we applied a semi-structured face-to-face interview to about 50 experts, including technology providers, industry, academia and research institutes, regulators and government, and solar system operators. Fig. 3 shows the distribution of these experts per field. We then systemized and classified the barriers according to their taxonomy, into economic and financial, market, system integration, solar-technical, regulatory, and information barriers. And second, we enriched the discussion of each barrier with an international literature review to enhance the understanding of the elements for which mitigation is necessary. The remainder of this section explores the detected barriers.

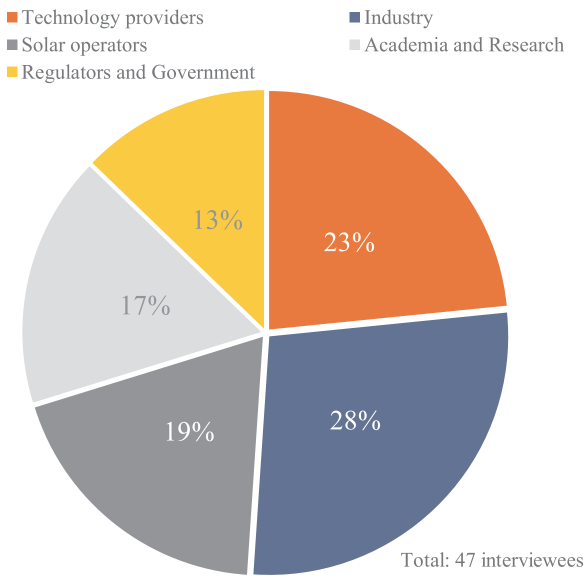

Fig. 3. Distribution of interviewed experts per field.

3.1. Economic and financial barriers

3.1.1. Insufficient financing schemes

Renewable energy technologies show low operational costs and extensive lifetimes, in trade of high investment costs. Solar technologies are no exception, although Chile's solar resource helps to achieve faster payback times than less sunny regions. A serious drawback lies in the local finance sector because it lacks experience in assessing solar projects. Furthermore, project financing is locally a virtually inexistent scheme (Nasirov et al., 2015). Therefore, it is particularly challenging for smaller projects that do not possess the financial backup for funding.

Solar projects may become bankable if a power purchase agreement (PPA) can be reached. However, interviews report that PPAs have become scarce as the future income of projects is plagued by uncertainty conditioned by volatile energy prices (Section 3.1.2). Additionally, the negotiations between a few large consumers and many smaller solar companies imply an asymmetric bargaining situation. Moreover, low copper prices (the main economic driver of Chile mining sector) have delayed, postponed and canceled projects that are economically feasible. Some solar projects have been funded by international banks or large mining companies. However, the majority of built projects are financed directly by large solar companies that manage their debts abroad.

Small PV systems also lack financing options. There are neither tailored solar credits nor options to include them in the mortgage. Local consumer loans exhibit high-interest rates, around 20%/a, which result in exponentially growing payback times. Additionally, Chilean companies usually have high-profit expectations of their investments with internal rates of return above 15% and payback expectations of 5–6 years (GIZ, 2016a), which makes investing in PV unattractive for them.

Nevertheless, for new housing, there is a support mechanism. Construction companies can apply for a tax deduction to install SWH. Recently, this support mechanism was extended until 2020 (Ministerio de Hacienda, 2016). However, there are still no loans available for retrofitting.

3.1.2. Volatile energy prices

The electricity spot price of Chile has been highly variable during the last decade due to dynamic fossil prices and rainfall. Currently, the power sector exhibits additional short-term cycles, including a drop in the spot prices during peak solar hours produced by transmission constraints in specific areas of the grid. Although Chile was one of the first countries where solar technologies reached grid parity, the current oil price depression makes it improbable finding financing when only relying sales on spot prices.

Solar power projects smaller than 9 MW_e can alternatively sell their energy under the scheme *stabilized nodal prices*, which average the costs over time. Until 2014, this mechanism was virtually unused as these prices were systematically lower than the hourly spot prices.

Small PV projects (< 0.1 MW_e) are not subjected to these issues to such an extent. Under a net-billing scheme (Ministry of Energy of Chile, 2012), they can since late 2014 connect to the distribution grids with relatively transparent procedures and stable energy prices. Nevertheless, additional relevant costs appear as a result of the technical requirements, an immature market of energy service companies, and delays in the connection process.

SWH imply direct savings in terms of displaced natural gas that at consumer level shows more stable prices. Hence, they remain unaffected by this barrier.

3.2. Market barriers

3.2.1. Immature solar market

Both, the solar heat and power market show an immature development with only a few local companies. For example, Chile's PV-price-index (Fig. 10) of November 2015 and 2016 (GIZ, 2016b, 2015a) shows that PV systems under 1 MW_e in Chile are in average 30–45% more expensive than in Germany, depending on the system size. This difference can mostly be explained by the higher costs for pre-sale. The low number of participating companies in Chile's PV-price-index might be another sign of an immature market.

For SWH technologies, previous efforts include the tax exemption scheme, which indeed was successful in regards to the high number of installations (Table 1). However, it failed in maintaining the systems and in creating an economically sustainable environment for solar installers. The regulatory framework of the corresponding law is currently under revision.

3.2.2. Insufficient local products

Solar technologies in Chile are imported. This might be understandable for high-tech components, such as PV cells or inverters, as Chile lacks a developed semiconductor industry. However, other components that could currently be constructed locally also come from abroad, such as steel structures. This results in higher costs and delays. In the SWH branch, the exceptions are water storage tanks, which are mostly Chilean made (Superintendency of Electricity and Fuels of Chile (SEC), 2016a).

Moreover, in the Atacama Desert, an internal supply problem arises.

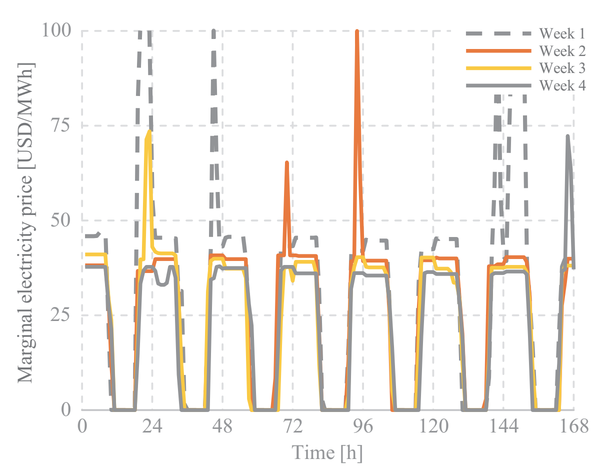

Fig. 4. Marginal electricity price at Diego de Almagro busbar (northern tip of the SIC) for four weeks of December 2015, based on (Power System Operator (CDEC), 2016a).

Many of the required components do not show stocks and are frequently shipped on demand from the 1200-km-distant capital. This is partially due to a market distortion originating from the mining industry, whose high-resource demand results in elevated local prices. Consequently, external shipping becomes a cheaper option.

3.2.3. Market concentration

Solar companies arise as new actors, positively diluting the strong market concentration of Chile's energy sector. However, the solar power sector is dominated by large solar companies, including Enel, First Solar, SolarPack, SunEdison, and Abengoa. An issue inherent to market concentration is high-risk exposure, such as the insolvency that some of these companies are confronting. Dispersed actors as in Germany, with many distributed systems, and with a wide range of ownerships (households, municipal utilities, small industries, and farmers), have not yet been observed in Chile.

Concerning the deployment of residential PV and SWH, no clear statistics exist yet. This also reveals an incipient market.

3.3. System integration barriers

3.3.1. Limited transmission capacities

The existing PV projects are concentrated in the northern part of the SIC and the center of the SING (Fig. 2-c). Particularly, the limited transmission capacity in the former stresses the income of PV plants, because the marginal price of those nodes drops close to zero during solar peak hours (Fig. 4). This price-decoupling between zones of a same power system implies that projects with PPA might only be an alternative if the client is within the same zone.

Recalling Fig. 1, for each solar-MW constructed there are seven that are approved, but their implementation is uncertain. This intensive speculation of solar projects makes the identification of sites with available transmission capacity increasingly more difficult. Furthermore, there is a physical gap between the SIC and SING (Fig. 2-c). Fortunately, their interconnection is already under construction. If completed on time, it should be able to solve the current bottlenecks by the end of 2017. For the vision of *Atacama Solar Pole* to be fulfilled, new international transmission corridors are needed.

Especially in the SING and the northern part of the SIC, frequent disconnections of PV plants have been reported due to voltage problems and security criteria. A recent publication (Nasirov et al., 2015) also alludes to missing infrastructure for accommodating renewables in Chile. The solar power variability does not necessarily contribute to an improved reliability and stability of the system.

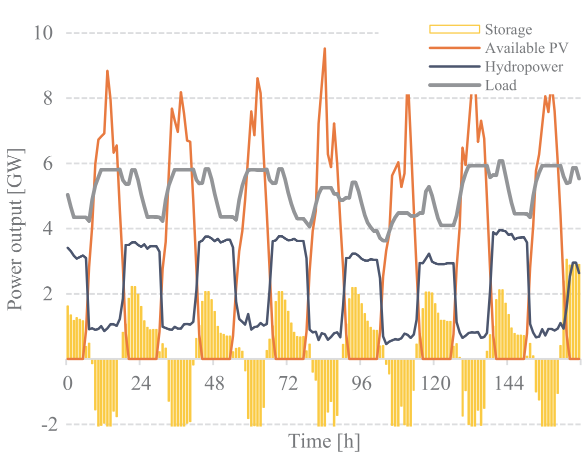

Fig. 5. Night storage requirements, in addition to the current hydro-park of SIC, to operate a (hypothetical) PV-hydro system. Simulation done with the unit commitment tool MIP-UC (Olivares et al., 2015) with data from (Haas et al., 2015; Power System Operator (CDEC), 2016b) for an example week of 2013.

Deployment of rooftop PV, on the other hand, is still incipient. Hence, critical limits have not been reached.

SWH and CST technologies are related to heat grid limitations. District heating is seemingly non-existent in Chile, imposing even larger barriers for these technologies.

3.3.2. Backup flexibility

Because conventional power plants operate at their technical limits in the same critical areas, the problems with respect to the limited transmission capacities are exacerbated. Moreover, recent impositions of improved emission mitigation controls for fossil power plants have led the power plants' operators to declare more stringent operational constraints. This translates into a lower system flexibility, which already starts to complicate the operation with variable renewable technologies.

Furthermore, the lack of sunlight during the night calls for backup flexibility. In the SING this renders challenging as it is based on older fossil technologies. In Chile's SIC, the large hydropower reservoirs can to some extent provide day/night storage. However, their power capacity is currently insufficient to back up a, say, full solar-hydro system (Fig. 5).

SWH are designed with heat storage tanks, so the short- and mid-term variability is irrelevant. Seasonal fluctuations cannot be solved in the absence of district heating or an additional energy source.

3.3.3. Distant energy supply and energy demand centers

From the solar potential point of view, the residential power demand in Chile is more than 1000 km away, concentrated in central Chile. Hence, strengthening the transmission is a key aspect. However, some demand from the copper mining industry is located in the middle of the Desert, which makes it closer but not necessarily more accessible. Mines are usually in the high mountains. The issue is again the transmission system and available labor force; both are scarce and the latter additionally competes with a high paying industry.

Most of the remaining un-electrified settlements of Chile are distributed in the north. Some of them do not have access to adequate roads and infrastructure. When thinking about solar technology miss-deployments, the program that installed the 3000 PV stand-alone systems in 2004 is a frequent contender. Maintenance of the many remote systems was difficult due to remote demand and lack of technology transfer to locals (Section 3.6).

3.4. Solar-technical barriers

3.4.1. Solar mapping and forecasting

The mapping of the solar resource was a barrier some years ago. Nowadays, to decrease the investment risks of solar power plants, meteorological data have been made publicly available (Santana et al., 2014). Thus, the mapping is not widely perceived as an obstacle. However, long-term measurements are still missing for most locations.

The dry Atacama Desert makes daily solar forecasting easier than in other locations. However, forecasting during the cloudy season still poses a challenge. In the center and south of Chile, the forecasting challenges are similar to those of central Europe. Moreover, as solar shares grow, forecasting short-term fluctuations (e.g. from partially shaded PV power plants) may become a future issue regarding system reliability and stability.

3.4.2. Harsh environment (soiling, corrosion, degradation)

Soiling has two sources in the Atacama Desert: a fine dust (*Chusca)* and mining operations. The severity of soiling varies strongly. The amount of *Chusca* in the air has local dependencies, such as the desert's crust, and when it combines with coastal fog, a thick hard layer is deposited on the collectors, intensifying the soiling effect. Mining-dust originates mainly from crushing and excavation, and also from unpaved roads. Consequently, the cleaning frequency of solar plants in the desert

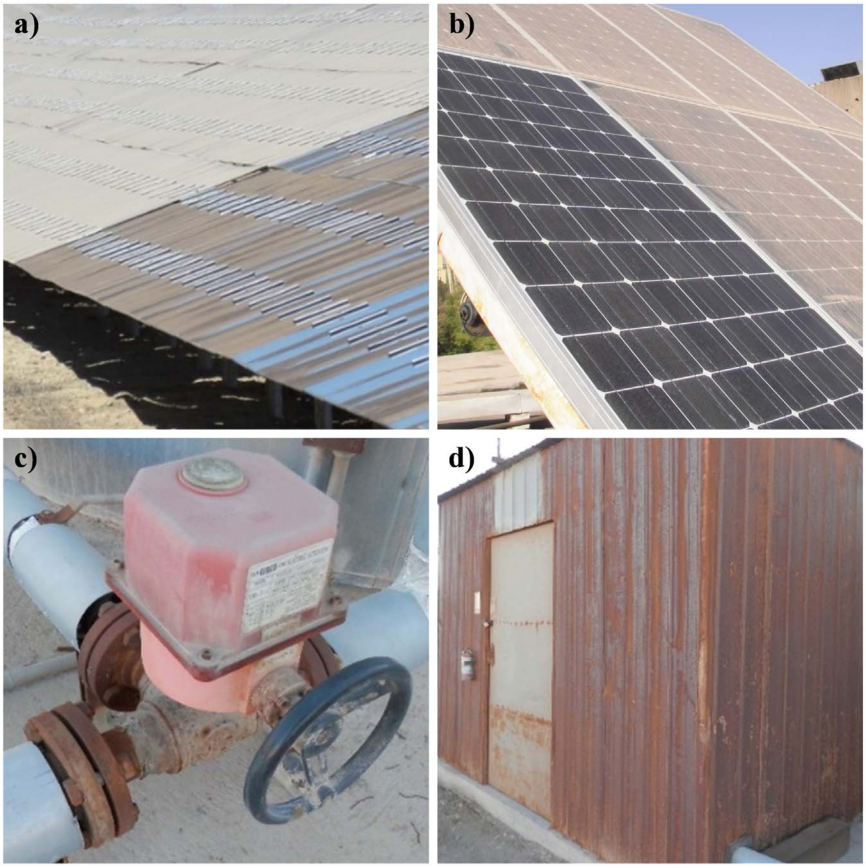

Fig. 6. Soiling on PV systems after approximately three months in a) the Atacama Desert close to unpaved roads and b) Santiago. Corrosion due to acid mists within 20 months on c) a pump and d) a control house of a solar thermal plant.

is widespread, between once a month and twice a year. Soiling is an issue also in large cities. In Santiago, particulate matter is responsible for about 5% of power output loss (Cáceres et al., 2014). Another study reported performance decays of 0.1–0.5% per day due to soiling in Santiago (Urrejola et al., 2016). Fig. 6-a and -b show the soiling in selected cases of Atacama and Santiago after approximately 3 months.

Corrosion has also been observed in the desert. In addition to coastal fogs, acid mists with a high content of sulfuric acid arise from the leaching and electrowinning process of copper mines. Unless the solar field is strategically located, mist may affect the collectors in terms of soiling and functionality. The corrosion due to acid mist is exemplified in Fig. 6-c and -d.

Chile's irradiance has a strong UV component, measured for selected sites only recently (Cordero et al., 2016), posing a higher degradation risk for some commercial PV solutions. Its effect on solar technologies still has to be evaluated.

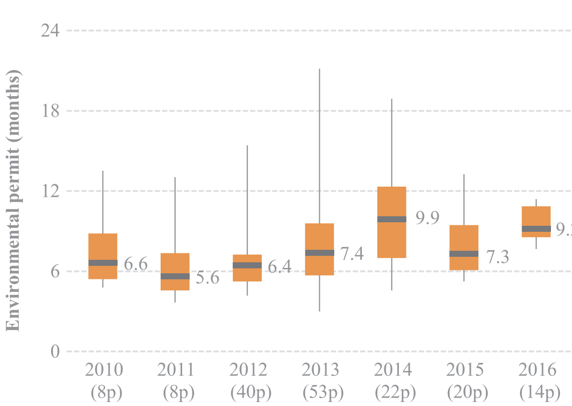

Fig. 7. Time required for a solar project to attain its environmental permit. Ciphers in brackets indicate the number of projects considered and numbers on the right side of each box, the median. Data from SEA (2016).

The Atacama Desert is not particularly hot, but the high irradiance on PV modules generates heat. Fortunately, cyclic winds blow from the sea to the Andes in the morning and backward during the afternoons, which force cooling of the array. However, the wind reverses when solar irradiation is at its highest, depressing the PV power output around midday. SWH and CST correlate positively with ambient temperature and consequently are not affected by this issue.

Finally, the combination of coastal fogs, acid mists, dust and high UV levels make out of Chile a harsh environment, whose effects on solar technologies, especially on the long-term, are not entirely understood.

3.4.3. *Access to water*

Cleaning the collector field in the desert can impose high demands on a scarce resource: water. Unfortunately, only treated water can be used, as the impurities found in simply pumped water may reduce the transmissivity of glass and corrode the structures. For each MW installed, about 0.5 m^3 of water is required per cleaning. The actual amount of water varies strongly with the cleaning technology used and

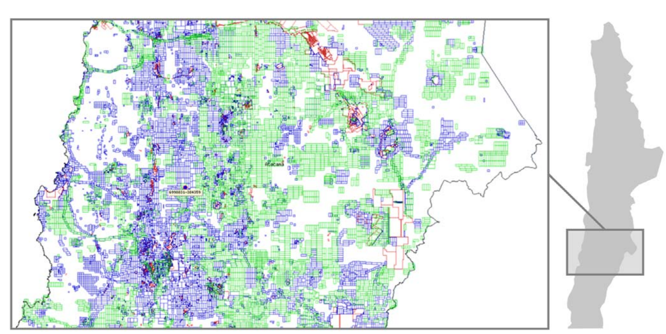

Fig. 8. Example of number of mining concessions (green: pending, blue: granted) in the north of Chile (Sernageomin, 2016).

the frequency of cleanings with the location. In CSP, water is also required for cooling (unless dry-cooling is used in a trade-off of the plant's efficiency). Water demand and reduction options have to be studied to avoid competing with needs of communities.

3.5. Regulatory barriers

3.5.1. Delays in the environmental assessment process

Energy projects greater than 3 MW need an environmental permit (EP) from the Environmental Assessment Service (SEA). The time required to get such a permit (Fig. 7) ranges from 5 to 10 months for most of the cases. This time is significant in the context of the short construction period of solar projects (PV). The initial lack of experience of the authority may explain the long processing times in 2010. SEA was able to reduce it in the two following years. Nevertheless, from 2012 on the processing time increased again, with medians ranging between 7 and 10 months.

Projects below 3 MW, do not require an environmental assessment. This has led many companies to design projects in very opposed sizes: either many small ones (below this limit) or few large ones opting to scale economies.

3.5.2. Difficulties in getting land concessions

Receiving land concessions for larger territories might be a difficult task. At one hand, private landowners suddenly see value in their remote piece of desert and make tough negotiations. Dealing with the Ministry of National Assets can prove more difficult, as the law is not robust on the project evaluation method, thus, leading to potentially discretionary granting decisions (Agostini et al., 2015). The land inventory is also aged and shows update issues. Together, this may lead to project delays between several months and years (Nasirov et al., 2015).

The desert might give the illusion of being unused land. However, mining concessions are a simple and cheap procedure to secure the exploitation right of minerals on a piece of land. Therefore, speculators frequently register massive amounts of mining concessions (Fig. 8) to resell them not only to mining companies but also to solar developers (Nasirov et al., 2015). The vast amount of existing mining concessions make the optimal positioning of solar plants and their transmission lines challenging.

With the recent boom of PV projects and the grid-congestion in the north of SIC, more projects are being built in central Chile. This leads to a competition with agricultural lands.

3.5.3. Difficulties in grid connections

The regulatory framework of the power sector establishes open network access to all generators. However, in practice, the grid connection process is complicated, particularly for new actors (Nasirov et al., 2015), including delays and excessively costly procedures. Although the legal framework establishes maximum time limits for connections of new projects, for large installations it neither set fines for exceeding those nor is clear on the maximum costs of these studies and procedures. This weak legal framework makes the regulation capacity of authorities very limited.

For PV installations under the net-billing scheme, the situation has improved in 2016, as the distribution companies are becoming more experienced with connecting these systems. The legal framework sets a maximum of ten working days for the distribution company to respond to a client's information request about the technical details of a connection point. In 2015, only 50% of the cases met the deadline versus 75% in 2016 (Fig. 9). The other procedures (*connection request* and *connection notification*) have a 20-day deadline. In 2016, more than 75% of the connection requests, but less than 50% of the connection notifications, were within the deadline. In 2017, an online system for the grid-connection procedures under the net-billing scheme will be introduced to further reduce the connection times.

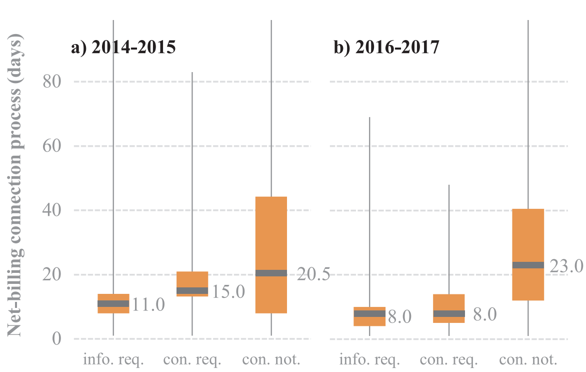

Fig. 9. Response times of the distribution companies for the different procedures along the net-billing connection process (information request, connection request, connection notification). Ciphers in brackets indicate the number of projects considered and numbers on the right side of each box, the median. Data from SEC (2016b).

3.6. Information barriers

3.6.1. Lack of technical skills and training institutes

Solar companies have repeatedly stated the lack of human capital along the whole value chain of their projects. Unlike e.g. Germany, Chile does not have a strong market of local solar installers. Many professionals come from abroad only for given projects. The situation with technicians is similar.

Furthermore, there are only a few local training institutes that focus on the topic. Although there is still no existing solar engineering program, recently, some initiatives for solar training have emerged in various universities and technical institutions, predominately in the north of Chile (GIZ, 2016c).

Only the segment of residential SWH shows more developed human capital. This was conditioned by the tax exemption scheme that started in 2009.

3.6.2. Lack of social awareness and social involvement

Communities are consistently uninvolved and left out in the making of energy policies and projects. This has led to conflicts in all other energy technologies, including geothermal and wind power. An emblematic example is the environmental movement *Patagonia sin Represas* against a series of large hydropower plants in Patagonia (*HydroAysen)*. As a side-effect, this generated interest in energy issues in Chile (Schaeffer and Smits, 2015). So far, local opposition to solar projects has not been reported.

Moreover, rural electrification projects in Chile are usually conceived as turn-key solutions, with little or no community involvement. These initiatives are prone to technical problems due to a lack of local workforce skills, proper consideration of project site conditions and appropriate maintenance procedures.

Social awareness of solar technologies shares two opposing views. Although solar technologies in Chile have proven economic even without subsidies, a common misconception of policymakers is that these are expensive and will necessarily lead to a cost increase (Agostini et al., 2015). Moreover, people are frequently unaware of their benefits and positive externalities and do not consider them as a possible investment (GIZ, 2016a). The citizens who could afford solar investments are only willing to invest if there is a return-on-investment at least similar to alternative investments. Conversely, communities of the north, have a widespread perception that solar energy is free. As a result, residents show an unwillingness to pay for solar energy based systems.

4. Barrier mitigation and discussion

In this section, emerging mitigation options and new solution strategies are presented. The set of solutions is based on investigator and data triangulation. Most of the emerging solutions are based on local literature, whereas the new strategies are based on expert knowledge from the team of authors. The discussion of all mitigation alternatives is further enriched with international literature. The remainder of this sections details these solutions, structured in direct response to the barriers mentioned in Section 3.

4.1. Economic and financing strategies

Economic strategies aim to support financing of solar projects. These directly mitigate the barriers related to financing capital and volatile energy prices; and indirectly, the market barriers. Mitigation is accomplished by giving impulses through economic instruments for the installation of new solar projects, which then impact market concentration and add dynamism to the immature market.

4.1.1. Create daylight blocks in electricity tenders

In November 2015, a new tender system for providing electricity to regulated clients (homes and other consumers below 0.5 MW_e) was introduced. It defined three time-blocks: nighttime, daylight, and afternoon block (23–8, 8–18 and 18–23 h, respectively). For each, a certain amount of energy had to be offered. This was done to ease the entry of solar technologies, especially during the day block.

The result of the tender of November 2015 was historic in the sense that all awarded energy blocks correspond to renewable energy companies. During the day slot, about 80% of the energy will come from solar technologies. Surprisingly, during the night and peak blocks, winning solar offers (CSP) are also found next to wind power offers. The average price is 79 USD/MWh_e, therefore 40% cheaper than in 2013 (Government of Chile, 2015).

The next tender, awarded in August 2016, broke a world record with a price of 29 USD/MWh from PV. The average price resulted in 48 USD/MWh and more than half of the tendered energy was awarded to PV or wind generation, with the rest being a mix of renewable and conventional generation (Empresas Eléctricas, 2016).

4.1.2. Associate in virtual generators

Virtual or swarm generators are a scheme where different projects are grouped in a financial and technical sense. For example, many solar plants can be clustered into a portfolio and then be managed as one project. The operation of each plant can be coordinated through the portfolio manager, which remotely connects to them via electronic systems. This concept can be extended to storage systems (such as in Germany, where Caterva (Brehler, 2016) aggregates small battery systems of rooftop PV installations, reaching MW-scales) to provide frequency support. Nationally, one initiative can be found: Antuko (2016) groups different renewable energy projects into an economic portfolio.

Swarm systems have at least two advantages: it makes funding easier (e.g. better interest rates or PPA negotiation) and smoothens the overall power output due to geographic and technologic dispersion. However, its application is limited to zones without transmission bottlenecks. Several regulatory changes are required to implement swarm solutions in Chile on a massive level.

For remote locations, microgrids are an analog solution. Local examples are Huatacondo (Jimenez-Estevez et al., 2014) and Ollagüe, which combine solar PV, wind, diesel and battery systems.

4.1.3. Finance through energy service companies

Energy service companies can help overcome the financial barriers, in which private clients are hesitant to invest their own funds in solar systems (mainly rooftop PV) due to high-profit expectations (Section

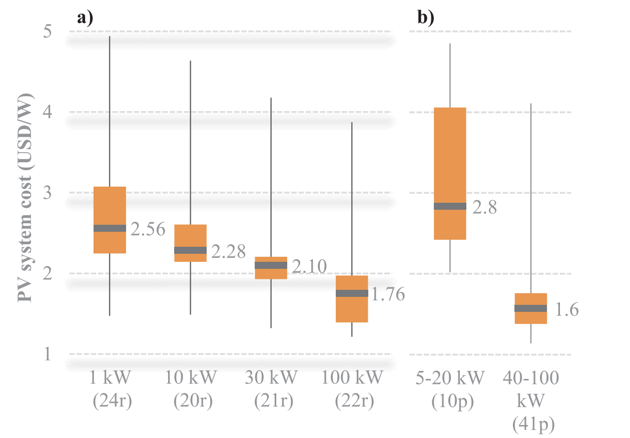

Fig. 10. a) Net cost of PV systems offered in Chile relying on voluntary quotations, based on (GIZ, 2016b). b) Offered PV system cost in *Public Solar Roof Program*, based on (Ministry of Energy of Chile, 2015). Ciphers in brackets indicate the number of projects considered and numbers on the right side of each box, the median.

3.1.1). A large interest in that scheme on behalf of the clients is detected. In fact, the first energy service companies already offer leasing or sale of electricity, but they have difficulties financing their expansion (GIZ, 2015b).

4.1.4. Establish guarantee funds for loans to small-scale solar projects

Banks usually offer project finance only for investment volumes above 10 million USD due to the high overhead costs in risk assessment. Banks would be more willing to reduce the information requirements in their due-diligence, if they could share or reduce their financial risk of defaulting projects, for instance through a guarantee fund. This way, banks could also finance smaller projects. One such fund, with 8 million EUR for credit guarantees for renewable energy self-supply projects, will support the provision of loans by financial institutions, leveraging investments of about 100 million USD (NAMA Facility, 2016).

4.1.5. Create other finance options (green credits, ancillary services, and emission taxes)

No specific credits for solar technologies exist in Chile. To overcome this issue, *green credits* could be designed (Jacobson et al., 2014). Upon recognizing the low economic risk of solar systems, they should be able to achieve convenient interest rates. Moreover, regulation changes are required to include solar household systems in the mortgage.

Projects may become more attractive, if additional income streams are implemented, such as power capacity payments and CO_2 taxes. The national regulation considers capacity payments to the expected availability of generators, which for solar systems is, unfortunately, low due to the lack of long-term data on these technologies and a clear methodology to evaluate such expected availability. Regulation changes based on the accumulated experience should address this issue. CO_2 taxes are an alternative to internalize that solar technologies avoid GHG emissions. The current tax reform is considering to impose a carbon tax of 5 USD/tCO_2 starting from 2017 (Ministerio de Hacienda, 2014).

4.2. Market development

Associations among market stakeholders aim for direct mitigation of the market barriers by propelling the solar market. As a consequence of a healthy market, many other barriers are solved. For example, training, research, and data collecting initiatives would arise. Together, these may contribute to overcoming technical and economic barriers.

4.2.1. Ripen the distributed PV market: the Public Solar Roof Program

To affront the immature PV market, the government launched the

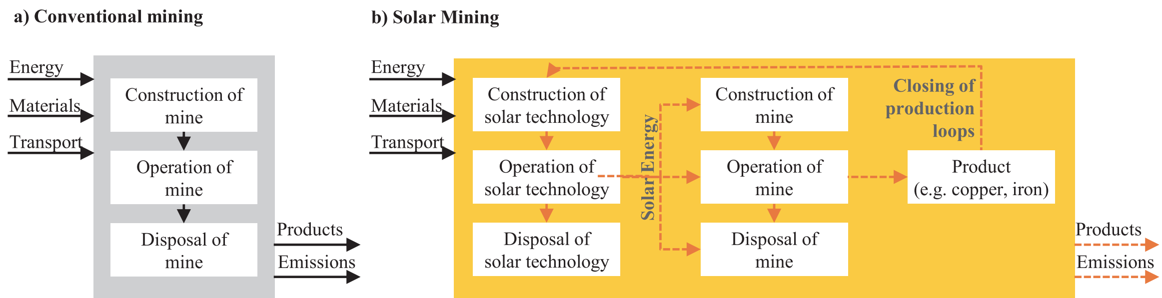

Fig. 11. Schematic representation of the life cycle stages of a) a conventional mining process and b) the *Solar Mining* concept.

Public Solar Roof Program in 2014. It creates demand by tendering PV systems for public buildings, and thus develops expertise in the installation, connection and technical norms of the net-billing framework. The program, funded with 13 million USD, also publishes information about benefits, costs and technical procedures of those systems (Ministry of Energy of Chile, 2016). The contractors are assigned through open tenders, which decreases the solar companies' cost for client acquisition (publicity) and allows the publishing of the participating offers. In those tenders, offers for PV systems between 40–100 kW_e are located around 1.6 USD/W_e with a very large dispersion (Fig. 10). The winning bids are within the range of Germany's prices (1–1.6 USD/W_e) (Ministry of Energy of Chile, 2015). Smaller systems, however, still show offers much higher than those of international levels.

4.2.2. Strengthen the nexus between mining and solar

Mining operations, as major energy consumers in Chile, will have to play a crucial role in solar barrier mitigation. They can integrate solar technologies into their processes and also nurture the local solar industry with valuable resources, such as copper for PV and CSP technologies, lithium for batteries, nitrate salts for molten salt storage, or iron for the support structures. The bidirectional interaction and synergies between solar technologies and mining operations are herein coined *Solar Mining*. These interactions have several dimensions, such as power and heat security, emissions, economic criteria, technical developments and social impact. Consequently, *Solar Mining* addresses not only the market but also economic barriers. The economic and environmental benefits, however, are not yet understood and are currently being investigated. Thus far, *Solar Mining* is an academic initiative. Its deployment depends on whether extensive support and coordination among industry and government are achieved.

Integration of solar technologies can be realized in diverse parts of the existing mining processes. Within the copper production, the highest potential can be seen replacing conventional electricity and heat, which both originate from fossil sources (Moreno-Leiva et al., 2017; Pamparana et al., 2017). Exemplary solar installations in copper mining operations in Chile are *Pampa Elvira Solar* (34 MW_t SWH) and *Planta Solar El Tesoro* (10 MW_t CST). They substitute about 80% and 55% of the electrowinning process' fossil fuel demand at *Gabriela Mistral* and *Centinela* mines, respectively. Several installations of the company *Enermine*, under 1 MW_t, show further applications of solar heat in the copper industry.

To show the positive environmental impact of solar technologies on mining operations, the life cycle in its entirety has to be assessed. This includes the construction, operation, and disposal of the mines and solar technologies. The schematic of the life cycle (LCA) stages in conventional mining and *Solar Mining* are shown in Fig. 11. Solar LCA emissions in Chile are found to be low. For example, for radiation levels of Atacama, they are below 27 for CSP (Corona and San Miguel, 2015) and between 10–25 $gCO2_{eq}/kWh_e$ for PV (depending on the cell type) (Leccisi et al., 2016). This stands in great contrast with the power grid's emissions of 700 $gCO2_{eq}/kWh_e$ (Palma et al., 2009).

4.2.3. Cooperate in the solar sector: the solar cluster Antofagasta

A solar cluster involves synergetic actors that enable the attraction of leading companies and institutions of the solar industry in the region to allow training of skills and technology transfer (Padmore and Gibson, 1998). Subsequently, research and development of local solutions, human capital formation, job creation and value capturing along multiple stages of the value chain will occur. This allows local companies and institutions to bloom and effectively satisfy the necessities of the developing solar industry.

There are interesting opportunities arising in the mining region of Antofagasta, in terms of research, development, innovation and deployment, and creation and capturing of value in related solar products and services. Nevertheless, the capability to address the barriers presented in Section 3.2 and coordinate efforts to effectively seize the opportunities require an important degree of organization, which can be structured as a solar cluster initiative.

The *Solar Cluster Antofagasta* concept is currently being evaluated by the government. The resulting lines of action of a solar cluster (based on empirical evidence, and financial and socioeconomic feasibility) involve the following areas: strengthening human capital; science, technology and innovation for competitiveness; market development; enabling an environment for industrial development; and institutional framework for competitiveness.

4.3. Systems integration

Several mitigation options focus on overcoming the barriers related to the limited transmission capacity of networks, the variability of the solar resource and the remote energy demand, which stakeholders frequently classify as main barriers. These concerns can be addressed on several fronts: reinforcement of transmission, investment in storage technologies, and other flexibility options.

4.3.1. Reinforce the transmission system

Transmission infrastructure is frequently targeted as a convenient solution to control the spatial variability of solar technologies (Haller et al., 2012; Hedayati et al., 2014; Hu et al., 2012). Nevertheless, its expansion is often delayed due to several reasons including the social opposition.

Solutions involve an anticipated planning of transmission, especially in the areas of a high solar resource. A *transmission highway* was discussed in Congress during the previous government but has been withdrawn for further review. The interconnection of Chile's main power grids SIC and SING is under construction (E-CL, 2014). However, Chile remains an island system with known weak spots.

The new transmission law identifies future development scenarios based on the identification of so-called *generation poles*. Solar energy is a clear candidate for a definition of strategic generation poles in the north of Chile. Thus, the timely development of the corresponding transmission infrastructure becomes more feasible.

Additionally, the use of smart grid technologies, like dynamic line rating and FACTS devices, is envisioned for the Chilean system. With them, the flexibility degree of the system operation will be enhanced.

In future, Latin America is expected to be interconnected through the Pacific corridor with Peru, Ecuador, and Colombia, and through the Andean region with Argentina, Bolivia and Brazil (Jimenez-Estevez et al., 2015), for which some memorandums of mutual understanding exist.

4.3.2. Identify the needs for energy storage

Aside from spatial variability of solar technologies, the temporal variability, ranging from seconds to years (Curtright and Apt, 2008), needs to be addressed. Consequently, solar technologies impose a need for storage. A smart combination of storage technologies, such as batteries for the short-, pumped hydro or molten salts for the mid-, and reservoirs or H_2 for the long-term, might be the answer (Haas et al., 2017). Luckily, the south of Chile also offers hydropower solutions. Traditional up- and re-powering strategies can be applied, as well as more recent concepts of reconverting cascade hydropower plants into pumped hydro systems. Additionally, excess solar power can be transformed to hydrogen (H_2) via electrolyzers and be converted back to power by gas turbines. The latter have been massively deployed during the 2000s when Argentina still supplied gas. The optimal combination of storage technologies needs to be studied.

The local market shows some advances in these aspects. Abengoa is currently building a 210 MW_e hybrid project, based on approximately 50% of PV and 50% CSP, to achieve a steady day and night output (SEA, 2016). Valhalla also recently attained the environmental permit for its 300 MW_e pumped hydro storage with sea water and its 600 MW_e PV power plant (SEA, 2016). Solar heat, such as in Pampa Elvira Solar, can contribute to the reduction of heat requirements of the mining industry with the use of sensible heat storage tanks.

Solar plants with increased storage capacity improve their firm capacity (Madaeni et al., 2013; Tomaschek et al., 2015), which can then contribute to grid stability and reliability. However, the lack of acknowledgment of the firm capacity and frequency support mechanisms for solar technologies are regulatory issues that require attention.

4.3.3. Enforce flexible operation in the power sector

In terms of stability, large solar plants can easily offer dynamic voltage power management, fault ride-through capacity and frequency droop control. In slow power systems with vast shares of PV, fast power output variations due to partial shading become more critical. Here, mitigation control actions can be implemented, such as *MICAPAS* (Rahmann et al., 2016) that proposes to operate PV plants below their maximum power point allowing them to smartly ramp up or down.

Joint operation of industry and solar technologies is another flexibility source. The mining sector, in particular, offers great potential in concentrating load during daytime and also for cogeneration with CSP as it possesses large heat demand in the low-temperature level. *Solar Mining* (Section 4.2.2) will explore these ideas in more detail.

Furthermore, smart grid strategies like the dynamic rating and the incorporation of Automatic Generation Control for secondary control are pressing solutions.

4.3.4. Deploy renewable microgrids

Currently, in Chile, there are more than 3500 isolated rural communities with no access to electricity. In those cases, small solar systems arise as a cost-effective alternative to the traditional Diesel generators, also due to access difficulties (4000 m.a.s.l., extreme weather conditions, remote locations). Experience has shown that solar microgrids might trigger additional dynamics that strengthen current economic areas and foster the creation of new economic activities, such as in the microgrid of Huatacondo (Jimenez-Estevez et al., 2014), where tourism is growing.

4.4. Research and development

Research promotion is a mitigation action that directly addresses the technical barriers of solar technologies and, indirectly, market and information barriers. However, the research itself has important barriers, which should be taken into account.

4.4.1. Maintain the continuity of research initiatives

Research funds are scarce in Chile. In fact, Chile presents the lowest spending on research among OECD countries (OECD, 2016), dedicating only 0.4% of its GDP. Nevertheless, the recent creation of excellence centers like SERC-Chile, Fraunhofer Chile, Laborelec, and CSIRO put dynamism into solar research. Additionally, the government recently approved new funds for the development of a national solar strategy (CIFES, 2016b). Nevertheless, after the seed capital and first local efforts, the consolidation of a sustainable R&D cluster for solar energy remains a challenge.

4.4.2. Support the Plataforma Solar de Atacama (Solar Platform Atacama)

The detected technical barriers mainly refer to local peculiarities of climate (UV, fog) and physical conditions (acid mist, dust, lack of water), such that only little international experience on their interaction with solar technologies is available. The direct answer is to create a national laboratory, such as the *Plataforma Solar de Atacama* (PSDA) that allows testing in a natural environment.

The PSDA's objectives comprise of optimizing solar technologies to local conditions, integrating local content, testing and developing new solar technologies by local R&D centers in cooperation with international alliances, expanding local intellectual property and human capital, and testing and certification. Overall, this creates a fertile environment with positive feedback for strategic associations among academia, research, industry, the public sector, and society.

PSDA is currently in the first stage, having raised about 1 million USD for preparing the basic testing site. Additional 50 million USD is the required estimate for establishing the laboratory (Portillo et al., 2015).

4.4.3. Improve the solar resource mapping and forecasting

To understand the impact of high UV radiation on solar systems, measurements of the solar spectra are essential. A campaign involving seven measurement sites was recently published (Cordero et al., 2016). To draw more generalized conclusions, further exploration, as well as understanding the roles of such high UV levels on the aging of solar technologies and the opportunities regarding the use of higher radiation in the visible and infrared spectrum, are required.

Concerning the forecasting tools, studies about the applicability of existing forecast tools (and the potentially required adaptions) to the wide range of Chile's climate need to be performed. A centralized power forecast system could reduce the costs for smaller players.

4.4.4. Develop a PV module adapted to the Atacama and a national module production

The harsh environment of Atacama should be taken into account in solar technology design and deployment. The International Solar Research Center Konstanz, SERC-Chile, Fraunhofer Chile, the French National Solar Energy Institute (INES) and other 19 companies are together developing a PV module -the *AtaMo*- that suits these particular conditions (Cabrera et al., 2016, 2015).

Further ongoing initiatives propose to set up local PV-module production capacities. This would be synergistic with Solar Mining (Section 4.2.2), which targets to exploit the synergies between mining products and solar energy, and the Solar Cluster (Section 4.2.3), which aims to establish a cooperation ecosystem of solar technologies in the Atacama.

4.5. Regulatory changes

Gaps or lack of the Chilean regulation can be mitigated through regulatory changes. Hence, each regulatory strategy focuses on a corresponding regulatory barrier. An additional strategy is added to summarize transversal needs for regulatory changes that arise from other barriers.

4.5.1. Simplify the environmental assessment process for solar technologies

Assuming that bureaucratic congestion is the main issue for the delays in attaining the environmental permit (EP), strengthening the SEA with more personnel, as well as training it, are direct alternatives. This might reduce the processing times to 6 months, which was the level of 2011. Further reductions can be achieved by simplifying the procedure itself. For example, a standardized PV layout (or a layout similar to approved ones) could be quicker in getting the EP, if the surrounding environmental conditions share a similar baseline. Finally, a systematization of the projects' baselines presented to the SEA could also contribute in savings.

The speculation of solar projects, regarding large numbers of projects with EP that have not been materialized, was recently addressed by an update of SEA regulations. Now, EPs that do not begin construction within the first five years will expire. This creates more clarity about which connection points still have remaining transmission capacities.

4.5.2. Revise the system for land concession-assignments

To address the difficulties of getting public land concessions due to outdated databases of the Ministry of National Assets, the direct solution is to realize a complete overhaul of the information technology system. Furthermore, the ongoing governmental initiative of public land tenders, which in 2015 included over 400 km^2, allows solving many legal and administrative procedures beforehand, thus saving time to the project developer. This procedure could be further enhanced, for example by choosing not only *sunny* public land but also grid points with guaranteed available capacity and other land suitability criteria (Fthenakis et al., 2014; Grágeda et al., 2016).

The high density of unexploited mining concessions requires a change in the mining law, to act on the quantity and duration of these concessions. Increasing the price of the concessions, implementing an in-time price-increasing scheme for unused concessions and forcing a quicker expiration of concessions are some examples to address the ongoing speculation. Moreover, the *Energy Policy 2050* (Ministerio de Energía, 2015) considers land management criteria, in which the assignment of concessions should be examined.

4.5.3. Set priority grid connections for solar technologies

The lengthy time required for grid connection of large solar power projects can be handled passively by performing the required procedures ahead in time (approximately 1 year in advance). Active measures need to focus on setting maximum time limits. These then need to be audited and, in the case of non-compliance, penalized. Further improvements can be achieved through governmental articulated associations with companies that own connection points. The cost of the connection studies can be mitigated by government developed software required for these studies.

To speed up the grid connection of residential and small commercial PV projects, several changes in the regulatory framework of the net-billing scheme are required. Recommendations include simplification and digitalization of the procedure, as well as setting standardized penalties for unfulfilled time limits. The Ministry of Energy together with the Superintendency of Electricity and Fuels (SEC) of Chile are currently revising this legal framework, with a focus on simplifying the connection process, especially for small residential installations and in areas with few distributed generation systems.

4.5.4. Ease the access to the power grid

Solar District is a concept that proposes the preparation of a zone of the Atacama Desert for the deployment of 1 GW_e of solar power (Fundación Chile, 2015). That setup includes permits and transmission and power substation requirements. Hence, this measure is in essence not a regulatory change, but a mechanism to remove the regulatory and technical barriers to the participating projects.

4.5.5. Improve other regulatory frame conditions

The new associative models for solar power, such as the association of customers, swarm generators and energy service companies inside the concession area of a distribution company, call for regulation adjustments to allow an easier development of projects. Additional modifications are required for the recognition of firm capacity and ability to provide ancillary services. Moreover, the banking sector might require regulatory changes to support funding mechanisms of solar technologies.

For projects above the capacity limit of net-billing (0.1 MW_e) and under 9 MW_e, the regulatory framework of "small and medium-sized distributed generators" (Ministry of Economy, 2015) applies, which has more complex administrative and technical procedures. Consequently, small projects suffer in profitability due to missing economies of scale for the overhead costs. Raising the capacity threshold for the net-billing law, to e.g. 0.5 MW_e, would, therefore, be a stimulus for the commercial and industrial rooftop market.

4.6. Education, training and awareness strategies

Information barriers, such as the lack of trained human capital, and social awareness and involvement, impact indirectly every other barrier for solar energy development. Therefore, mitigation strategies for these barriers should be considered as a key action, even if their impact proves difficult to be tracked or measured.

4.6.1. Train human capital for solar technologies

Solar energy is one of the most versatile energy sources, being applicable to all scales and segments (like residential and industrial). It is also an energy source that can create more jobs in comparison to other sources.

Training of human capital has only been reacting slowly to a rapidly growing solar sector. Given this paradigm, the minimum efforts involve further expanding and consolidating tertiary formation centers and a widespread training of installers for solar net-billing projects. However, in the vision of an empowered solar Chilean society, strong modifications for human capital formation are needed. This includes training across all education levels.

Concrete proposals include the creation of educational programs specific to solar technology deployment, system integration, cross-sectoral planning and development of new technologies with local content; collaboration alliances with international formation and research institutes for technology transfer; exchange and technology tours to solar energy installations, formation centers, and research institutes.

4.6.2. Train human capital for solar energy in the Atacama: Ayllu Solar

In the Atacama, there are particularly large opportunities for sustainable development. Here, Ayllu Solar (SERC-Chile, 2017) arises as an answer. The project, funded by the charity BHP Billiton Foundation, aims to create human capital towards a more cost-effective and socioeconomically relevant solar energy share at the community level. It proposes to develop: i) cost-effective, replicable and scalable solar energy solutions in key areas for community development; ii) human capital capabilities for the effective use and development of solar

Table 2
Summary of detected barriers, direct and indirect mitigation options, and outlook for advances in solving the barrier.

Barrier	Direct mitigation option	Indirect mitigation option	Advances towards solving barriers in the next 5 years
1 Economic and financial barriers			
Insufficient funding schemes	New tenders, swarm generators, ESCOs, others, guarantee funds, green credits	Public Solar Roof Program, Solar Mining, system integration options	• Ongoing changes towards solar system integration will indirectly contribute to more funding schemes
Volatile energy prices	New tenders, swarm generators	Enforced transmission, system integration options	• New tenders help the financing of large solar plants • Surge of ESCOs
2 Market barriers			
Immature solar market	Public Solar Roof Program, Solar Mining	All economic mitigation options, training of human capital	• Public Solar Roof Program could ripen the PV market • Extension of tax exemption of SWH could consolidate the corresponding market
Insufficient local products	Solar Cluster Antofagasta, Solar Mining		
Market concentration	Public Solar Roof Program, Solar Cluster Antofagasta, Solar Mining	All economic mitigation options, regulatory options especially those to enhance the net-billing scheme	• Solar Cluster Antofagasta is being considered by the government
3 System integration barriers			
Limited transmission capacities	Enforced transmission	Swarm generators, Solar Mining	• Interconnection of power grids will relieve bottlenecks
Backup flexibility	Energy storage, other flexibilities	Solar Mining	• First projects with storage are being designed
Remote energy demand	Microgrids	Ayllu Solar	• Ayllu Solar contributes with remote systems in the Atacama Desert
4 Technical barriers			
Mapping and forecasting of solar resource	Mapping and forecasting of solar resource, Plataforma Solar de Atacama, continuity of research centers		• First campaign of spectrum mapping ready • Natural learning curve from existing projects and ongoing research from established research centers. First solar power tower to be ready soon.
Harsh environment	Plataforma Solar de Atacama, continuity of research centers, Atacama-Module	Solar Mining, Solar Cluster Antofagasta	• Current surge of desalination plants could alleviate the water shortage
Access to water	Plataforma Solar de Atacama, continuity of research centers	Solar Mining	• Module for the Atacama -AtaMo- under development • Center for national module production recently approved
5 Regulatory barriers			
Delays in the environmental assessment process	Regulatory changes for environmental permits	Training of human capital	• Minor changes to tackle speculation via expiration of environmental permits
Difficulties in attaining land concessions	Regulatory changes for land concessions	Solar Mining	• Tenders of public lands for solar projects are increasing • Net-billing regulatory framework under review to further ease installation of distributed PV projects
Difficulties in grid connections	Regulatory changes for grid connection, Solar District	Public Solar Roof Program, Solar Mining	
6 Information barriers			
Lack of trained human capital	Ayllu Solar, training of human capital, PV-Pilot project		• Current governmental programs for training human capital in renewable energy in general
Lack of social awareness	Ayllu Solar, continued information campaigns		• Ayllu Solar in the Atacama to some degree • Byproduct of all barrier mitigation options in general as natural learning curve from a growing technology

energy solutions, achieved through continuing education and skill-building tools with active engagement of the whole community; iii) sustainability through including effective solar energy solutions, business models, support network, community involvement and a proper institutional framework.

The project will consequently tackle the lack of trained human capital and social awareness, as well as the technical barrier related to remote demand.

4.6.3. *Conduct continuous information campaigns*

To confront the lack of social awareness, in addition to the training mentioned above and local involvement strategies, continuous information campaigns should be run. These should address a wide spectrum of actors: from policymakers, project developers, and stakeholders, to local communities.

4.6.4. *Implement the Solar PV Pilot Project*

The *Solar PV Pilot Project* is part of the *National Strategy for Solar Energy* (Fundación Chile, 2015). It proposes to develop solar projects with local content. Concurrently, it includes a pilot plant, which gives the space to train local people and transfer experience in solar project development. The project will be funded by CORFO through competitive tenders. This is one of many initiatives, required to achieve social involvement in energy projects and policies.

5. Conclusions and policy implications

This paper studies the barriers preventing the mass deployment of solar energy technologies in Chile. For this, data acquired from 50 interviews with experts from industry, technology providers, academia, solar plant operators, and government were systematically evaluated in a barrier analysis. The identified barriers to solar power and solar heat technologies are classified into 1) economic and financial, 2) market, 3) system integration, 4) solar-technical, 5) regulatory, and 6) information barriers. A set of strategies is shown for these groups, based on expert knowledge, and national and international literature as summarized in Table 2.

The economic and financial barriers include volatile energy prices and insufficient funding schemes. For the former, the scheme of new tenders and swarm generators are direct solutions, whereas, for the latter, financing through energy service companies is an additional option, among others. As indirect alternatives, several system integration options arise for both issues, while the *Public Solar Roof Program (PSRP)* and *Solar Mining initiative* tackle the latter. To some extent, financing of large solar power plants is assisted by the new tenders for regulated customers. However, these do not solve the issue for large industrial clients. The solar thermal technologies, too, still require financial support schemes to achieve a massive deployment for the upcoming years.

The market barriers of solar technologies involve i) an immature solar market, ii) insufficient local products, and iii) a strong market concentration. Direct alternatives involve the *PSRP* for the first, the *Solar Cluster Antofagasta* for the second, and both for the third point. *Solar Mining*, aiming to bring the solar and mining sector closer together, appears as a transversal solution. All economic strategies arise as indirect mitigation options as more systems installed imply maturing the market. For a 5-year outlook, the *PSRP* is promising, as it has already shown some advances in ripening the PV market. The recently extended tax exemption of SWH could play a similar role in the solar thermal market. Moreover, the *Solar Cluster Antofagasta* is currently being evaluated by the government, potentially impacting all solar technologies. *Solar Mining* is a currently funded academic initiative, but for practical deployment, support from government and industry is an integral part of the process.

The system integration of solar power is hampered by limited transmission capacities and backup flexibility, and distant energy demand and supply centers. Enforced transmission, energy storage technologies, and other flexibility options need to be implemented. Furthermore, swarm generators and an industrial deployment of *Solar Mining* can assist indirectly. The interconnection between Chile's two main power grids (SIC and SING) will relieve the current bottlenecks. The first large-scale storage projects under development will add operational flexibility. The energy demand in remote sites of Chile can be an opportunity for the surge of solar microgrids, which can be assisted through solutions developed by Ayllu Solar in the next couple of years. These efforts are a good starting point, but they need to be multiplied to assist Chile in its mission towards becoming a solar country.

The technical barriers to solar technologies in Chile involve the need for mapping and forecasting of the solar resource, understanding the harsh environment (UV, fogs, dust, acid mist) and solving the access to water. The continuity of Chile's solar research centers and the *Plataforma Solar de Atacama* are direct responses to these barriers. *Solar Mining* and the *Solar Cluster Antofagasta* are options that could further help solve the technical barriers. Regarding the outlook for the next half decade, concerning the resource mapping, the first solar spectrum campaign concluded recently. The local R&D centers together with strong international partnerships and alliances with the industry will be the basis for tackling key barriers, such as the Atacama Module—whose development was just confirmed. Funding for the *Plataforma Solar de Atacama*, however, is not currently in sight.

The detected regulatory barriers are comprised of difficulties in attaining the environmental permits, land concessions and connections to the power grid. The challenges in the environmental permits involve delays and indirectly, speculation. It is not clear whether the delays are being addressed. The speculation, nevertheless, was handled in terms of a regulatory change that now expires the environmental permit, if the project is not started within five years. Problems related to land concessions are not being addressed beyond the growing quantity of public land tendered. Finally, the issues of grid connection for small PV systems are being addressed regarding a revised regulatory framework of the net-billing scheme. For large solar power plants, major changes in regulation are still required, unless projects are developed in private installations, e.g. mining operations.

Regarding information barriers, a lack of trained human capital and social awareness are detected in the context of all solar technologies. Ayllu Solar aims to solve the first two deficiencies by involving locals in developing and deploying solar solutions for the Atacama during the next five years. However, further training institutes and programs, and technology transfers with international actors, as transversal solutions for forming human capital in the solar area, are required across the whole country.

Solar technologies can play a key role towards the successful achievement of Chile's long-term clean energy goals. For this, immediate actions for overcoming the identified barriers are required. These actions should be part of a set of alignments embedded in the long-term energy roadmap. Further, the proposed solutions need to be evaluated in quantitative terms to develop a clear cost-benefit evaluation and prioritization, as well as understanding their interactions. Their implementation may require changes in regulation. If addressed in a timely matter, we can realize Chile's potential of becoming the solar energy state of South America; thus, setting the clock for a sunrise.

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