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Identifying barriers and opportunities in the deployment of the residential photovoltaic prosumer segment in Chile

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ABSTRACT

Photovoltaic (PV) prosumers can play a significant role in the transition toward sustainable cities. However, the implementation of more effective policies which accelerate the deployment of this market is needed. In this study, after an overview of the residential PV prosumer (RPVP) market's status in Chile, critical parameters that can speed-up the deployment of this segment through policy decisions were identified. Considering the local conditions of each regional capital in Chile, the segment is analyzed with widely-used econometric techniques to evaluate the residential PV systems feasibility empirically. The results show that the Chilean regulatory framework is insufficient for exploiting the potential of the RPVP. Without effective policy instruments, high investment costs and low income per household are the main barriers in the deployment of the segment in this country. Therefore, suitable promotion energy policies, regulatory changes, and financing options can accelerate the deployment without majorly impacting on the national budget. This would let citizens help accelerate decarbonization through a more decentralized and democratic energy transition, gaining socio-economic and socio-environmental benefits, based on solar PV technology.

1. Introduction

Cities are one of the most energy-intensive societal systems responsible for the global greenhouse gas emission and health issues. Around 67 % of the global final energy demand is consumed in cities, accounting for about 75 % of global carbon dioxide emissions (REN21, 2019). According to the World Air Quality Report (IQAir, 2019), about 92 % of the world's population breathes toxic air, most of which is found in cities in less developed countries.

Although advanced technological ways to transform cities into more resilient, sustainable, smart, and healthy places are emerging (Ahad, Paiva, Tripathi, & Feroz, 2020; Ali et al., 2019; Bouzguenda, Alalouch, & Fava, 2019; Ribeiro & Pena Jardim Gonçalves, 2019), there are issues, challenges, and limitations related to political, regulatory, cultural, socio-economic, and environmental aspects (Ahad et al., 2020; Yigitcanlar et al., 2019), which make the transformation of cities a distant prospect. Those barriers seem to be much more difficult to overcome in developing countries. However, solar photovoltaic (PV) is the most affordable, widely-accepted, and fomented technology to increase renewable electricity levels in cities for all end-use energy consumption (REN21, 2019).

According to Keiner, Ram, Barbosa, Bogdanov, and Breyer (2019), PV prosumers (i.e., residential energy consumers who produce electricity through a grid-connected PV system and can sell the excess energy through the grid (Miller & Senadeera, 2017)) could be vital in enabling and accelerating an energy transition. In 2016, rooftop PV

Abbreviations: AE, annual energy production; AOM, annual operation and maintenance cost; CLP, Chilean pesos; DR, annual degradation ratio; EIF, energy-injected factor; EIP, price valued by the energy-injected into the grid; FiT, feed-in tariff; IC, initial investment cost; In, monetary incentive; IRR, internal return rate; LCOE, levelized cost of electricity; NPV, net present value; PE, price of electricity; PI, price index; PV, photovoltaic; PVR, annual return from a PV system; PVP, annual production from a PV system; RPVP, residential PV prosumer; SC, self-consumption; SCEP, price valued by the self-consumed electricity; SCF, self-consumption factor; SPP, simple payback period; SY, specific yield; VAT, value added tax.

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installations had a share of about 25–30 % of global solar PVs installations, according to REN21 (2017). Globally distributed solar PV capacity is forecasted to increase by more than 250 % between 2019–2024, which the prosumer segment is accounting for about 45 % of the total solar PV capacity growth (IEA, 2019). By 2050, this segment would contribute about 21 % of the global electricity generated in the power sector (Breyer et al., 2018). Moreover, it would contribute to the decarbonization of the global economy and the creation of local employment, with consequent environmental, public health, and socio-economic benefits. However, the scenarios vary from country to country, where solar resources, regulatory framework, and policy support are different. Furthermore, these conditions may vary within the same country.

In the case of Chile, a developing country recognized worldwide for its emerging energy market that encourages and promotes the use of sustainable energy (BloombergNEF, 2019), its energy transition is neither decentralized nor democratic (Flores-Fernández, 2020). In other words, its society in general, and citizens are not effectively participating in the energy transition that is happening in Chile. In addition, the country hosts 34 of the 46 most air-polluted Latin American cities (TeleSur, 2019), where the main source of emissions are the form of energy used in homes and transport (Jorquera et al., 2018; Mazzeo et al., 2018; Trewhela et al., 2019).

Chile is also known for its solar energy potential. In addition to the fact the Atacama Desert has the world's highest solar irradiation levels (Rondanelli, Molina, & Falvey, 2015), the solar resource distributed throughout the continental territory of this country is good enough to be harnessed in different ways and applied to reverse the current unsustainable and unhealthy situation of their cities. One of those ways is through PV technology.

In Chile, the residential sector is the main consumer of electricity. In 2017, 34 % of the national electricity demand was consumed by the commercial (12 %), public (4 %), and residential (18 %) sectors (CNE, 2019a). According to Campos et al. (2016), the production from PV prosumers could cover 83 % (national average) of the annual electricity demand in urban areas, but the percentage varies according to the area of the country. In addition, the first simulation of a 100 % renewable energy system for Chile across all sectors showed that, in 2050, PV prosumers would generate 24 % of the total national electricity demand from power and heat sectors (Osorio-Aravena et al., 2020). However, Chile has regulatory barriers in the prosumers segment (Haas et al., 2018) and lacks sufficient policy instruments for promotion (Simsek, Lorca, Urmee, Bahri, & Escobar, 2019). In addition, the residential PV prosumer (RPVP) market is in an incipient stage because there are no clear statistics (Haas et al., 2018). Therefore, the current scenario does not promise such levels of electricity generation from PV prosumers.

According to Couture et al. (2014), there is no PV prosumer revolution due to the lack of enabling policies. Both policymakers and planners need to appreciate how prosumers could become competitors in the electricity market when designing present and future strategies (Parag & Sovacool, 2016). Additionally, in South America, the potential of PV prosumers is under-exploited (Espinoza, Muñoz-Cerón, Aguilera, & de la Casa, 2019). Therefore, this study aimed to identify the key factors involved in the RPVP segment that can be managed through policy decisions. Hence, this work, in addition to providing an updated baseline of the RPVP market in Chile, contributes to the existing literature with a methodological approach for analyzing techno-economic parameters of this segment from a policy-makers perspective. Thus, critical parameters of widely-used econometric techniques that can be managed through policy decisions to support and accelerate the deployment of the RPVP segment are identified. The approach used in this study to analyze the PV prosumer market can be replicated, especially in developing countries.

The research work is structured as follows. Section 2 provides a brief literature review of similar works in the field and studies applied to Chile. Section 3 includes an overview of PV prosumers in Chile, describing the factors influencing the Chilean RPVP market. The methodology, as well as the data and assumptions, are presented in Section 4. Section 5 provides a discussion of the results, and the critical parameters and their variability from the decision-makers perspective are analyzed. Finally, Section 6 contains the conclusions, recommendations, and policy implications.

2. Literature review

Most studies on city level PV systems, applied worldwide, have been addressed from technical and/or economic perspectives. From a purely technical point of view, several approaches to estimating solar rooftop potentials, and designing the optimal size of solar PV systems have been improved and discussed around the world (Gerber, Rix, & Booysen, 2020; Gomez-Gonzalez, Hernandez, Vera, & Jurado, 2020; Nelson & Grubesic, 2020; Roberts, Bruce, & MacGill, 2019; Thebault, Clivillé, Berrah, & Desthieux, 2020; Wijeratne, Yang, Too, & Wakefield, 2019; Zhu, You, Santi, Wong, & Ratti, 2019). From a techno-economic perspective, diverse methodologies have been examined to assess the implementation of small PV systems, from their impact on energy costs in buildings and electricity prices to their profitability (Jiang, Zhou, Lu, & Yang, 2020; Jurasz & Campana, 2019; Sommerfeldt & Madani, 2017a, 2017b).

Furthermore, the techno-economic assessment of different instruments and mechanisms to promote the implementation of grid-connected PV systems in cities (such as subsidies, feed-in tariffs, net-metering, net-billing, and others) have also been addressed worldwide (Ahmad, Tahar, Muhammad-Sukki, Munir, & Rahim, 2015; Huijben, Podoynitsyna, Van Rijn, & Verbong, 2016; Lan, Cheng, Gou, & Yu, 2020; Nikolaidis & Charalambous, 2017; Rathore, Chauhan, & Singh, 2019; Thakur & Chakraborty, 2019). However, the analysis of critical parameters widely used in econometric techniques applied to residential PV prosumer (RPVP), which can be managed by decision-makers, has not been widely discussed in the scientific literature. In fact, some key techno-economic parameters, directly related to the instruments and mechanisms of promotion, can vary significantly between countries, and even within countries, especially in developing ones (Pereira da Silva, Dantas, Pereira, Câmara, & De Castro, 2019).

In Chile, a country with excellent solar resources, small PV systems ($\leq$5 kWp, which can be classified in the RPVP segment) have been evaluated less than other PV system sizes (Campos et al., 2016). According to the existing literature, researchers started studying Chilean residential PV systems less than ten years ago. The focus of the studies mainly refers to the potential for development and economic viability, considering different regulatory frameworks in some cases only.

Araya-Muñoz, Carvajal, Sáez-Carreño, Bensaid, and Soto-Márquez (2014) evaluated the solar potential of the roofs in Valparaíso city. Watts, Valdés, Jara, and Watson (2015) assessed the potential residential PV development applied to 10 cities through a comparative analysis of the effect of net-billing and net-metering schemes. Cáceres, Nasirov, Zhang, and Araya-Letelier (2015) evaluated the economic viability of residential PV systems in Chile's capital, Santiago, considering the effect of dust on panel performance. Alvarado, Troncoso, and Campos (2016) studied the residential solar energy potential in the capital of the Biobio region, Concepción. This study included different technologies (i.e. solar thermal, PV, and hybrid) from a public outreach perspective. Campos et al. (2016) used the same city as a case study and extrapolated the study to all cities with more than 15,000 inhabitants when they analyzed the potential of distributed PV generation (commercial, public, and residential sectors) in urban Chile to determine the annual electricity consumption of each city. Ramírez-Sagner, Mata-Torres, Pino, and Escobar (2017) presented an economic analysis under the current regulatory framework (net-billing) for both residential and commercial PV systems, which was applied to 314 districts covering 13 of the 16 Chilean regions. In addition, Walters, Kaminsky, and Gottschamer (2018) analyzed the factors influencing the adoption of solar PV in the city of

Santiago. Cansino, Moreno, Quintana, and Roman-Collado (2019) addressed a techno-economic evaluation of replacing biomass by residential PV systems in the city of Temuco.

However, most of these previous works were conducted before Law 20928 (BCN, 2016), the tariff equity law that modified the residential tariff across the country, was in place, which changed some of the analyzed factors. This means that some of the parameters that were employed and assumed as input values of those studies are different today. Thus, the electricity prices for a residential tariff, as well as the price that values the energy injected into the grid, have changed throughout the country. Furthermore, the initial investment cost of a PV project has also varied across the country (see Section 3.2.3). Moreover, the residential sector is the only regulated client without any incentive and financing options (until September 2019) in the Chilean electricity market. In addition, as in the literature outside Chile, those previous studies have not analyzed how some key parameters managed by decision-makers could affect the RPVP market.

Therefore, this work, besides providing an updated baseline of the RPVP market in Chile, contributes to the existing literature with a methodological approach for identifying and discussing critical parameters of widely-used econometric techniques that can be managed through policy decisions, in order to support and accelerate the deployment of the RPVP segment. This segment can play an essential role in the decarbonization of the energy sector at the city level (Keiner et al., 2019). Additionally, this would imply environmental, public health, and socio-economic benefits (REN21, 2019).

3. Background on PV prosumers in the Chile's context

3.1. The Chilean PV prosumers' market

In Chile, PV technology dominates the prosumer market. Ever since the net-billing scheme came into effect via Law 20571 (BCN, 2012) in 2014, grid-connected systems have increased exponentially (see Fig. 1). In four years, 4378 of them were installed, of which 4373 were PV systems (CNE, 2019b). The remaining five systems consist of one biomass power plant, a gas-based combined heat and power plant, and three small hydropower plants. Further, the total installed capacity of the PV prosumers at the end of 2018 reached 24.2 MWp, which represented 99.3 % of the prosumer market (CNE, 2019b).

By the end of 2018, 3759 of the total grid-connected PV systems existing had an installed capacity of ≤5 kWp. They can be classified as under the RPVP segment. In this prosumer segment, 61.4 % of the systems are ≤1 kWp (see Fig. 2). More than 1700 PV systems of this size were installed under a program of reconstruction between 2017 and 2018 after a natural disaster occurred in the Atacama (AT) region in 2015 (ME, 2017). Thus, under this particular situation, about 45 % of the current RPVP market in Chile has an investment cost that was entirely financed by the government.

Fig. 3 shows the distribution of PV installations for each region of Chile until the end of 2018 by matching north-south allocations from left to right. PV systems ≤5 kWp represents RPVPs, and those >5−100 kWp, public and commercial PV prosumers. Fig. 3 shows that AP and TA regions have fewer RPVPs than almost the rest of the region, although these regions have good solar conditions. Regions with higher population levels and grosser domestic product (GDP) show the greatest number of PV systems, although there is not a direct correlation. In any case, the total number of residential PV systems is more than six times that of the public and commercial together.

However, small PV systems (≤5 kWp) have been assessed less than other PV system sizes in Chile (Campos et al., 2016), and the RPVP market is in an incipient stage because there are no clear statistics (Haas et al., 2018).

3.2. Influential factors in the Chilean RPVP market

This section describes the factors that directly influence the PV prosumer market in Chile, which were identified based on previous studies mentioned before. The factors include the solar conditions of a particular place, the regulatory framework, electricity prices, investment costs, socio-economic aspects, promotion policies, the financing options, and the electricity consumption and self-consumption levels.

3.2.1. Solar resource conditions

Chile has significant differences in solar irradiation levels across the 4337 km of its continental territory. The northern areas have global horizontal irradiation (GHI) that exceeds 2500 kW h/m^2-year, as illustrated in Fig. 4. This zone has the highest solar conditions around the world (Rondanelli et al., 2015). Nevertheless, at the other extreme of the country, the minimum GHI is about 900 kW h/m^2-year.

Although Chile has only an average width of about 200 km, its irradiation levels also vary from the Andes Mountain to the coast (Zurita et al., 2018). This situation can be appreciated in Fig. 4, where areas near the coast (left side) have less solar radiation than other areas (right side). Moreover, most of the regional capitals are allocated over coastal zones, which are employed in this study. Copiapó city (27.37 °S) has the highest total GHI, while Punta Arenas city (53.15 °S) has the lowest: 2259 kW h/m^2-year and 1106 kW h/m^2-year, respectively. The capital of Chile (Santiago, 33.44 °S) has comparable irradiation values with the south of Spain, as is the case of Almeria, with 1858 kW h/m^2-year (ESMAP, SOLARGIS, WB, & IFC, 2019). To know the solar condition of the rest of the locations under analysis, refer to Table 1 in Section 4.2.1.

Despite the solar radiation differences throughout Chile, the most unfavorable regional capitals have higher GHI than some cities in Germany, which is one of the countries with the highest RPVP penetration rates. The Chilean territory extends from 17.5 °S to 56.0 °S, which is equivalent in the northern hemisphere to Nouakchott (Mauritania) and Copenhagen (Denmark). Puerto Montt (41.47 °S) and Coyhaique

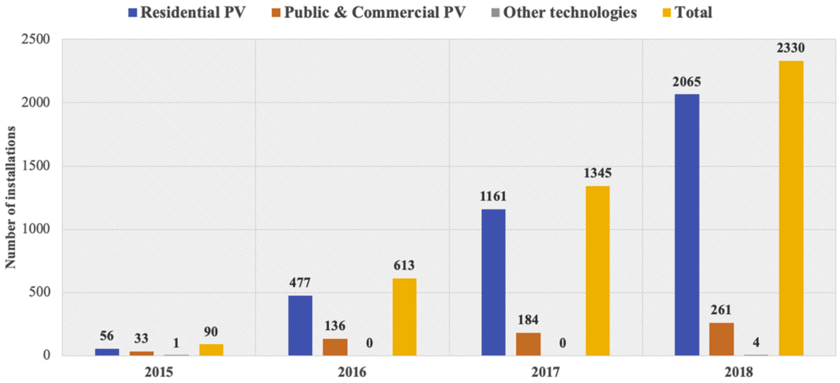


Fig. 1. Prosumer systems installations from 2015 to 2018. Data is obtained from Chile's Ministry of Energy (CNE, 2019b).

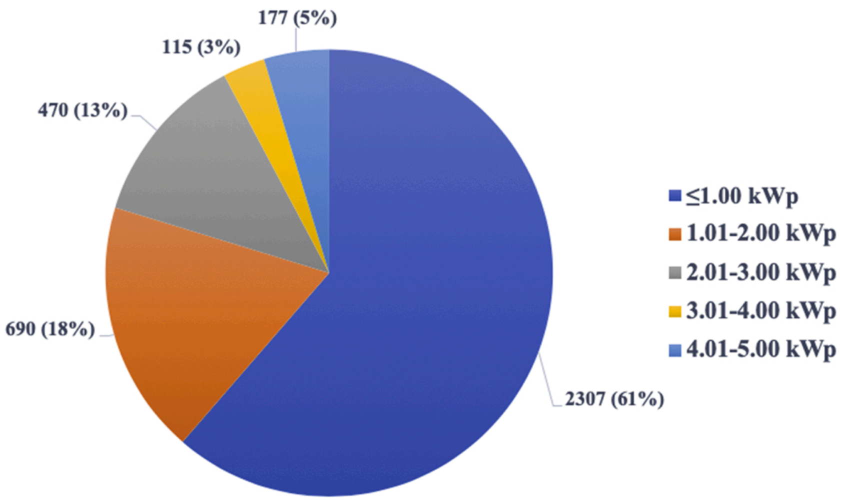
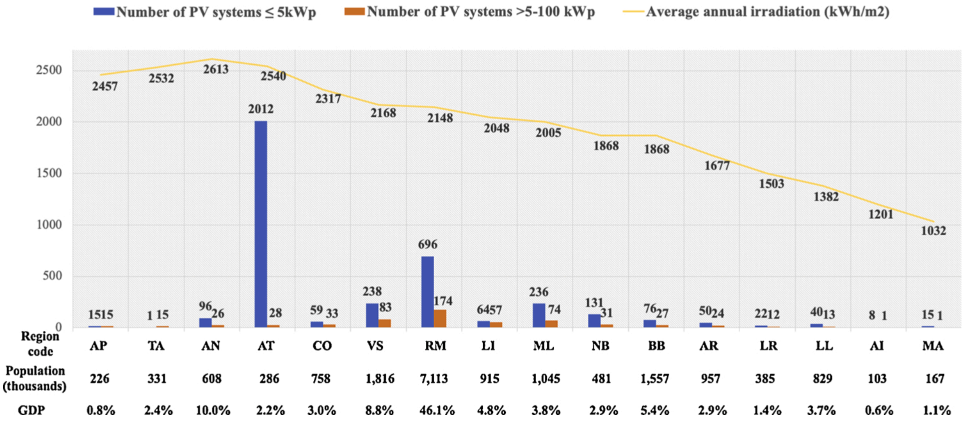


Fig. 2. Residential PV prosumers installations by capacity range. Data is obtained from Chile's Ministry of Energy (CNE, 2019b).



Region code	AP	TA	AN	AT	CO	VS	RM	LI	ML	NB	BB	AR	LR	LL	AI	MA
Population (thousands)	226	331	608	286	758	1,816	7,113	915	1,045	481	1,557	957	385	829	103	167
GDP	0.8%	2.4%	10.0%	2.2%	3.0%	8.8%	46.1%	4.8%	3.8%	2.9%	5.4%	2.9%	1.4%	3.7%	0.6%	1.1%

Fig. 3. The number of residential (≤5 kWp), public, and commercial PV prosumers (>5–100 kWp) until the end of 2018 (CNE, 2019b), and average annual irradiation (Ascencio-Vásquez, Osorio-Aravena, Brecl, Muñoz-Cerón, & Topic, 2020) by region. Code regions defined in ISO 3166-2:CL. Population is obtained from the Chilean National Statistics Institute (INE, 2017). GDP is obtained from Banco Central de Chile (BC, 2018).

(45.58 °S) have better solar conditions than the German cities of Freiburg and Munich (both near 1200 kW h/m^2-year). The same discussion can be applied to Punta Arenas (53.15 °S), which is the southern regional capital in Chile, as compared to Kassel (1045 kW h/m^2-year) (ESMAP, SOLARGIS, WB, & IFC, 2019). Therefore, from the solar resource perspective, it does not represent a barrier in the deployment of the RPVP market across Chile. However, although Chile has a good solar condition in almost all its territory, the RPVP segment has been evaluated less than other PV system sizes (Campos et al., 2016).

3.2.2. *Regulatory framework and electricity prices*

The RPVP segment is at the end of the business chain of the Chilean electricity market. This market has historically been composed of three industries: generation, transmission, and distribution. The first is considered as an open market, and the others, natural monopolies (CNE, n.d.). Only generation companies can trade electricity in the spot market, which was designed based on private competition by marginal energy prices. Both transmission and distribution companies have their rates regulated. Regarding distribution operators, the energy end-users, as regulated customers, can participate in the market as prosumers. There are three segments: commercial, public, and residential. The RPVP segment is affected by two Chilean electricity market factors: energy prices and distributed generation regulation.

Residential clients have a regulated tariff, but the price varies throughout Chile. Those differences occur because each distribution company has to buy the electricity at a nodal price, which is directly dependent on the type of primary energy source used in every power generation plant near the purchase point. The distribution company, then, sells electricity to its regulated clients at a tariff that is the sum of the nodal price plus the added value of the distribution. Moreover, in some cases, a charge for the use of the trunk transmission system is added. That added value corresponds to an average cost that incorporates all the investment and operation costs of a model or theoretical distribution company operating in the country (CNE, n.d.). Until September 2017, residential tariff differences in Chile could reach 70 %. From October 2017, given Law 20928 (BCN, 2016), which brought the residential tariff equity law into effect, the maximum difference possible between residential tariffs across the country were required to be 10 % of the national average. The situation changed the RPVP scenario in Chile, of which the literature has no studies.

Distributed generation regulation creates variations in the values of energy injected into the grid across Chile. Law 20571 (BCN, 2012), known as the "Distributed Generation Law," was created to promote the electricity self-consumption of regulated customers. Essentially, this law caters to the injection and sale of energy surplus from regulated clients at a regulated price. The electricity is measured and valued separately from electricity purchased from the grid (IEA, 2018b). Initially, every individual customer with a grid-connected system of up to 100 kW of capacity could benefit from this law. Today, given the modification introduced in 2018 through Law 21118 (BCN, 2018), in addition to

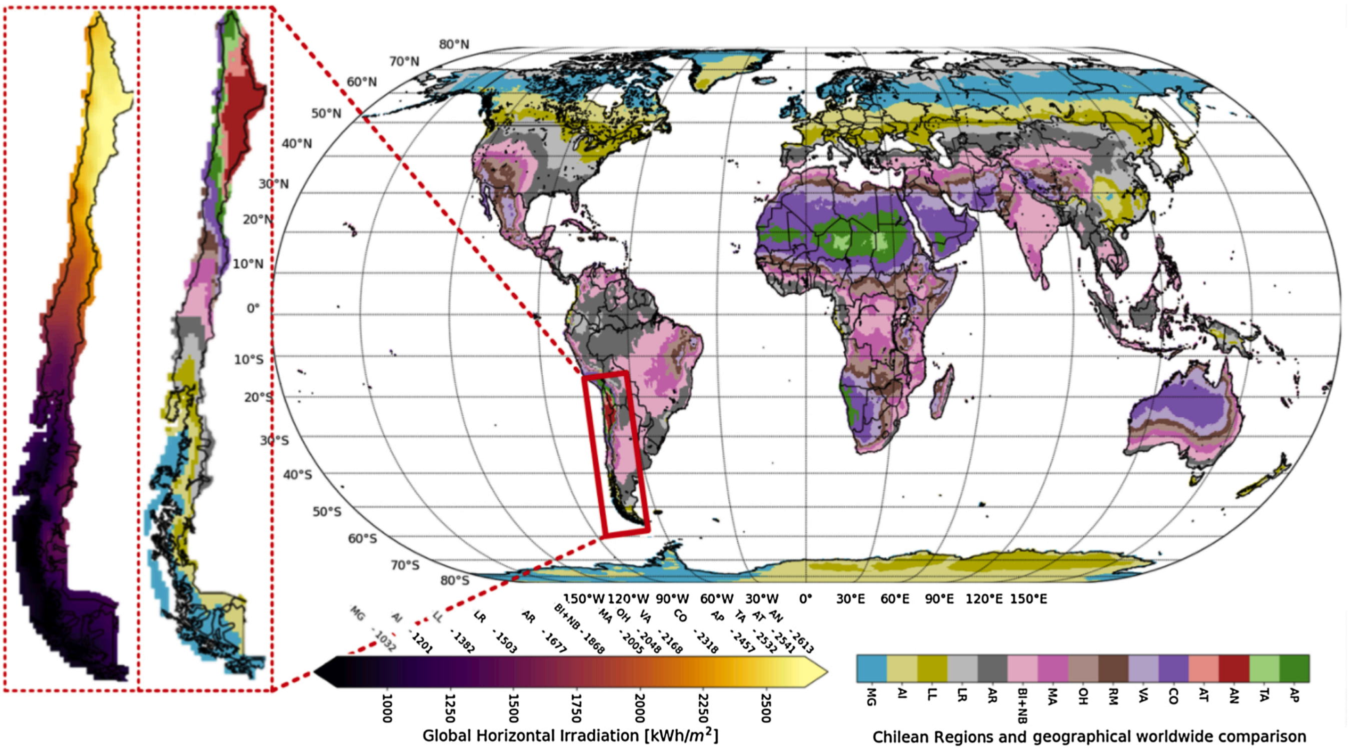


Fig. 4. Solar irradiation in Chile and worldwide comparison of the solar resource per Chilean region in terms of annual global horizontal irradiation (Ascencio-Vásquez et al., 2020). Name regions defined in ISO 3166-2:CL.

extending the limit of installed capacity up to 300 kW, the new law allows for the development of projects with single or several owners. Thanks to the Distributed Generation Law, residential clients have now become prosumers with contracts of up to 10 kW of capacity, which is the upper limit for a residential tariff. This tariff varies in each city, as does the value of self-consumption, due to the price assumed for each kWh saved through self-generated electricity by a grid-connected system. The energy injected into the distribution network also varies. This variation occurs because the regulation is a net-billing scheme. That is, energy injections are valued at the price for which the distribution companies bought the electricity from the transmission companies.

As Fig. 5 shows, the value of the energy injected into the grid is approximately 44 % to 56 % less than the residential tariff; that is, energy sales for an RPVP are valued at, on average, 50 % less than the kWh saved by self-consumption in Chile. The result is a variation in the profitability of a residential PV project throughout this country and an unequal potential deployment. This deployment can increase in zones with less solar resources and higher initial investment costs.

However, the new situation under the residential tariff equity law, which changed the scenario of the RPVP market across Chile, has not been studied in the scientific literature applied to this country. Furthermore, it has not been analyzed how a regulatory change –from net-belling to net-metering–, which can be managed by decision-makers, could affect the RPVP market.

3.2.3. Investment costs

Investment costs in the Chilean PV prosumers market differ by installed capacity and segment. Since 2016, Chile's Ministry of Energy (ME) and Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) have conducted a project to obtain a yearly price index (*PI*) of grid-connected PV systems marketed in Chile. The *PI* considers the costs for the concept's design, equipment, and installation in USD/kWp for turnkey projects without value-added tax (*VAT*), which is set to 19 % in Chile. Fig. 6 (left) shows the investment cost differences between four installed capacity ranges, as reported by ME, and GIZ (2018). There, an important dispersion, as a system decreases in size, is observed, thereby

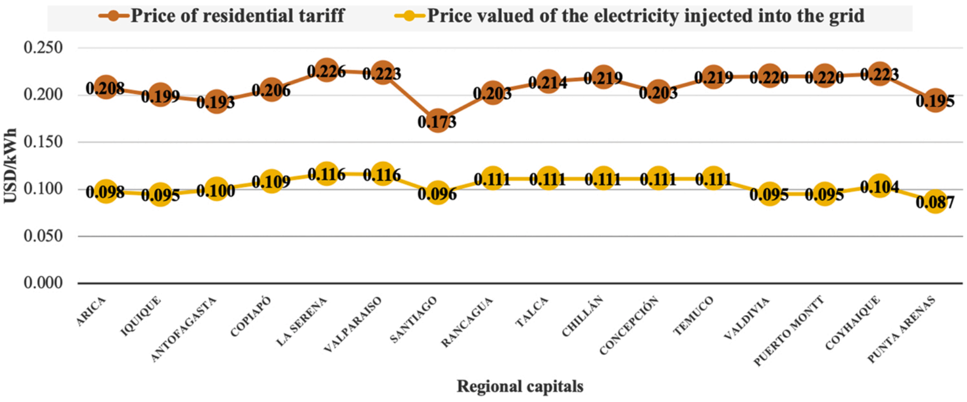


Fig. 5. Electricity prices in the sample cities. Data is obtained from each distribution company operating in every city.

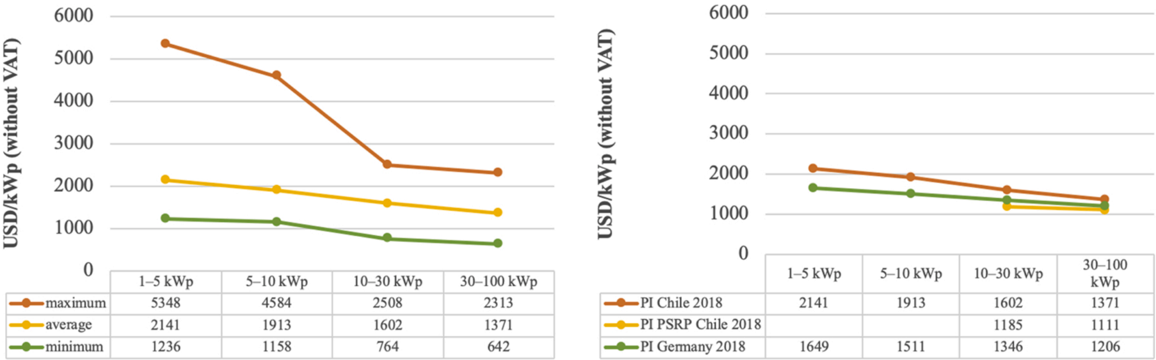


Fig. 6. Investment costs for different installed capacity ranges in Chile (left) and *PI* comparison between Chile, public solar roofs program (PSRP) of Chile, and Germany, for different installed capacity range (right). Data is obtained from ME and GIZ (2018).

reaching a 77 % difference in the 1–5 kWp range. In addition, it is possible to make two observations from the right side of Fig. 6. First, the Chilean *PI* is higher than that of Germany, and the difference increases while the range decreases. The second observation comes from the public solar roof program (PSRP, a governmental program to support the total investment cost of the installation of grid-connected PV systems on public buildings), where the *PI* in Chile is lower than that of Germany. This observation is mainly due to the public tenders considered in this program, which induces the bidder companies to reduce the investment cost of a PV project to be eligible for its construction (ME, & GIZ, 2017). In any case, as a PV system of the residential segment is principally in the 1–5 kWp installation range, the RPVP segment has to pay the higher investment costs of the Chilean PV prosumer market.

Although the RPVP segment has had a decrease in its initial investment costs, they are higher than those found at the international level (Haas et al., 2018). Fig. 7 shows that the national *PI* of PV systems between 1–5 kWp in Chile has fallen between 2016 and 2018, and the price of these grid-connected PV systems in Chile is, on average, 22 % cheaper than in 2016. However, in comparison with a mature market, such as that of Germany, the 2018 *PI* is still 23 % more expensive in Chile.

An investment cost projection of residential PV systems for Chile is also shown in Fig. 7. According to this projection (ME, 2018), the 2018 *PI* of a residential PV system would be reduced by about 30 % and 51 % by 2025 and 2035, respectively. The investment cost projected for 2025 would, currently, be paid by an RPVP in a case of a subsidy (or incentive) to the initial investment cost of 30 %.

Moreover, investment costs for the residential prosumer segment vary throughout Chile. Fig. 8 exposes the regional *PI* for the 1–5 kWp range of installations, as of 2017. When comparing the *PI* by region, it is notable that there is up to a 60 % difference between the lowest and highest *PI*. According to the ME, and GIZ (2017) report, whether a correlation between *PI* and the distance to the center of the country exists is not clear (RM region); and, where there are greater population and GDP, there are more PV systems (refer to Fig. 3). However, only the RPVP segment cannot recover the *VAT*. Therefore, the real investment costs for the citizens are 19 % higher than the data shown in Fig. 8.

Nevertheless, in addition to the fact that previous studies applied to Chile have not considered the range of difference in the investment cost across the country shown in Fig. 8, how a subsidy (or incentive) could affect the RPVP market, which can be managed by decision-makers, has not been discussed.

3.2.4. *Socio-economic*

An important factor in the RPVP segment is the purchasing power of the families. According to the Chilean National Statistics Institute (INE, 2018), the average monthly national income per home was 1715 USD in 2017. Only five regions in this country have an average monthly income per home higher than the national average (see Fig. 9), and 68 % of the homes have a lower income than the national average (INE, 2018). Nevertheless, according to the Long-term Energy Planning Report (ME, 2018), of the 1,124,978 homes that are technically apt to implement a PV system of 2 kWp, 35 % of them have the socio-economic aptitude to secure a loan from a bank, which means that owners live at home, the income of families is greater than 1500 USD, and at least one of the inhabitants is a professional with a university degree. Therefore, the potential size of the RPVP market is strongly dependent on the home's purchasing power and strongly reliant on the socio-economic level of the family that inhabits them (ME, 2018). In fact, this socio-economic aspect is not included in the widely-used econometric techniques to empirically evaluate the residential PV system projects, and there is a lack of financing options for the prosumer segment in Chile as well.

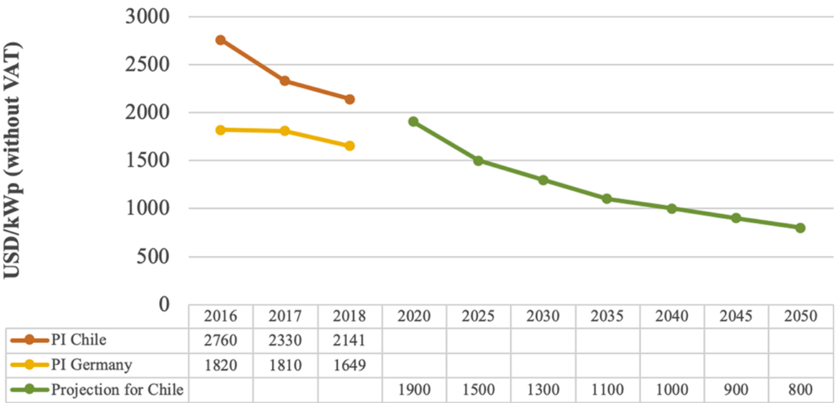


Fig. 7. Price Index (*PI*) comparison of PV systems, 1–5 kWp installed capacity between Chile and Germany from 2016 to 2018, and a projection of investment costs for Chile. Data is obtained from ME, and GIZ (2017, [ME and GIZ, 2018]2018) and ME (2018).

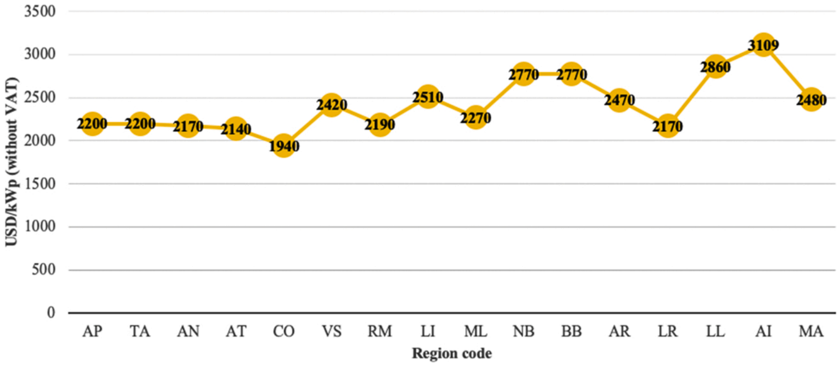


Fig. 8. The 2017 price index of 1–5 kWp range PV systems by region in Chile. Data is obtained from ME, and GIZ (2017). Name regions defined in ISO 3166-2:CL.

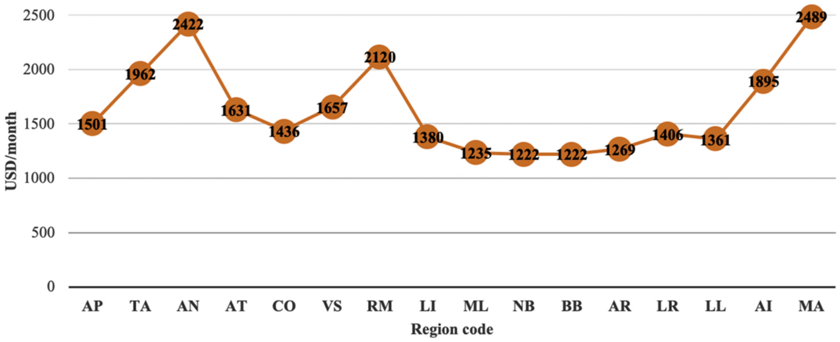


Fig. 9. The 2017 average monthly income per home by region in Chile. Data is obtained from INE (2018). Name regions defined in ISO 3166-2:CL.

3.2.5. *Promotion and financing*

When a market is incipient, promotion policies to invest in a project and financing options are key elements, particularly when the projects include renewable energy sources; these are the base actions that must be taken to fight against climate change (Simsek et al., 2019). Renewable energy sources can help in the decarbonization of the energy sector, and, regarding prosumers, they can also help decentralize the market, incorporating the citizens in the equation. In addition to the regulation scheme, other key elements of support from energy policy instruments employed globally in the deployment of renewable energy projects are fiscal investment and public finance (Benitez, 2012; Elizondo Azuela & Barroso, 2012; IRENA, 2012; Thapar, Sharma, & Verma, 2016). Tradable green certificates, tax incentives, tax credits, support for investment, and a feed-in tariff (FiT) are common mechanisms used by governments to encourage renewable energy investments (Abolhosseini & Heshmati, 2014; Burns & Kang, 2012; Matisoff & Johnson, 2017; Thapar et al., 2016). Moreover, specific loan schemes from banks could exist that allow for investing in a renewable energy project. There are also business models such as that of the Energy Service Company (ESCO). However, according to Simsek et al. (2019), Chile has been successful in promoting renewable electricity with only non-conventional renewable energy targets as a mandatory quota at utility-scale.

Although the development of renewable energy utilities in Chile has been without any fiscal incentives or FiT (Zurita et al., 2018), the prosumer segments have had some supports, albeit unequally and occasionally. Regarding a public segment, the PSRP (ME, 2015) is a specific financial instrument for governmental buildings; they can also access other fiscal financing sources through national and sub-national budgets. The commercial segment has financing options, such as contracts with the ESCO model (ME, 2016) and special promotion programs regarding the productivity from governmental entities, some of which can vary by region (ME, 2020). The segments even have the purchasing power to secure loans from banks. The only support for the residential segment was conducted in the Atacama region as a subsidy to the reconstruction of houses after a natural disaster (mentioned in Section 3.1).

In summary, only the residential sector in Chile has no investment support, financing programs, fiscal credits, or loan options to become a prosumer, at least as of September 2019. In October 2019, the first financing option, called “Green Credit”, was launched by a bank for the residential sector (ME, 2019). However, this type of credit has not been discussed in the scientific literature applied to Chile.

3.2.6. *Self-consumption and electricity consumption*

According to López Prol and Steininger (2017), the percentage of self-consumed electricity is one of the most critical parameters for the evaluation of the profitability of a small grid-connected PV project. This situation occurs principally under a net-billing scheme because the self-consumed electricity is evaluated as a monetary return. Moreover, the self-consumption level is directly dependent on the load profile of the prosumer and the PV installed capacity relative to consumption during the year.

In Chile, residential clients consumed 18 % of the national electricity consumption in 2017 and 16 % more electricity than commercial and public sectors combined (CNE, 2019a). It means that residential segment is the main consumer among regulated clients.

Residential consumption levels and profiles in Chile vary by regions, seasons, and houses with different socio-economic levels (CDT, 2010). Therefore, the self-consumption level can also vary. The regional monthly average electricity consumption of the residential sector throughout Chile fluctuates between 132 kW h and 209 kW h (CNE, 2018). Nonetheless, the residential load profile has not been studied in detail across this country. Hence, there is uncertainty regarding the exact self-consumption levels in this sector.

However, the tendency observed in developing countries, especially in Latin America, shows that residential consumption is increasing (IEA, 2018a). Regarding Chile, the Long-term Energy Planning Report (ME,

2018) evaluated a scenario where residential consumption can increase from 15 % in 2015 to 20 % by 2046. In any case, given a regulatory change to the net-metering scheme, the self-consumption level would lose importance in the assessment of PV system profitability. Nevertheless, this has not been discussed in the scientific literature applied to Chile.

4. Methodology and data

This study was conducted in three stages. In the first stage, data on the initial investment cost of an RPVP system and electricity prices, both associated with the year 2018, were collected for each country's region and each region's capital, respectively. Thus, the RPVP market in 2018 was considered as the baseline case (which comprised a net-billing scheme as a regulatory framework) without incentives or financing options.

In the second stage, with the data of the RPVP market in 2018 as a baseline case for each of the 16 regional capitals of Chile, widely-used metrics were applied (i.e. simple payback period, internal rate of return, and levelized cost of energy) to empirically evaluate a PV project under different assumptions and scenarios. The economic assessment identified the parameters that caused greater variability in the economic metrics; they are essential in the detection of both barriers and opportunities in the deployment of PV systems.

In the third stage, the parameters identified were used to analyze the dependence of their variability. The dependence of the critical factors was allocated based on the following analysis elements: natural phenomenon, promotion policy, market conditions, financing options, and consumption profile. The analysis emphasized the parameters that are managed from a regulatory and policy perspective because of decision-makers' abilities to modify them. Based on the dependence identified for some key parameters, ideas were then suggested that would apply to future policymaking and research. This was conducted to reveal possible ways regulation and policies could positively affect the deployment of the RPVP segment throughout the country.

4.1. Economic metrics

The economic evaluation of a PV project by the metrics applied in this study is described in the following subsections.

4.1.1. Simple payback period (SPP)

The *SPP*, which represent the amount of time taken to recover the cost of an investment, was calculated based on Eq. (1), according to Chang and Starcher (2019):

$$SPP = \frac{IC - In}{AE * PE - AOM} , \tag{1}$$

where *SPP* is the payback period in years, *IC* is the initial cost of installation in USD/kWp, *In* represents the value of a monetary incentive to cover portions of *IC*, *AE* is the annual energy production in kWh/kWp-year, *PE* is the price of electricity in USD/kWh, and *AOM* is the annual operation and maintenance cost in USD/kWp-year.

Table 3 presents the input data for the initial cost (*IC*) in Section 4.2.2. Regarding incentive (*In*), since this parameter is nonexistent in Chile for RPVPs, two alternatives were assumed for comparison with the base case; that is, 30 % and 50 % *IC*. The 30 % *IC* was assumed as it is the common incentive that the commercial segment can choose under current financing mechanisms. Regarding the 50 % *IC*, it was assumed as a conservative option in comparison with the public segment, which has a 100 % incentive under the public solar roof program (PSRP). Moreover, the incentives of 30 % and 50 % mean reaching the same investment costs forecasted for 2025 and 2035, respectively. Furthermore, due to the difference between irradiation levels and electricity prices across the country, Eqs. (2) and (3) were used to calculate *AE*EP* of Eq. (1). The assumed value for *AOM* is described in Section 4.2.2.

$$AE * PE = SY * (SCEP * SCF + EIP * EIF) , \tag{2}$$

$$EIF = 1 - SCF , \tag{3}$$

where *SY* is the specific yield on each city in kWh/kWp-year; *SCEP* is the residential tariff in USD/kWh, which is also the price valued by the self-consumed electricity; *SCF* is a self-consumption factor expressed as a percentage; *EIP* is the price valued by the energy injected into the grid in USD/kWh; and *EIF* is an energy-injected factor expressed as a percentage.

Section 4.2.1 shows the specific yield (*SY*) values. Section 4.2.3 shows *SCEP* and *EIP* as the price of the residential tariff and price valued for energy injection into the grid, respectively. For each incentive assumption, the self-consumption factor was considered as 30 %, 50 %, and 70 % for comparison with the base case. Meanwhile, the payback period was calculated under the net-metering scheme, which means $SCEP = EIP$.

4.1.2. Profitability

The internal rate return (*IRR*) metric is used to assess the profitability of a residential PV project. It was conducted based on the annual cash flow method. Eqs. (4)–(6) represent the mathematical procedure to obtain the net present value (*NPV*), considering the annual difference between returns and expenses during the lifetime of the PV system. The values of the energy savings (or self-consumed) and the energy injected into the grid were used as the returns, and operation and maintenance costs, expenses. The *IRR* was then obtained to estimate the profitability of a potential investment based on Eq. (7). By definition, when the *NPV* of a project is zero, the project's *IRR* is equal to its discount rate (Burns & Kang, 2012; Bustos, Toledo, Contreras, & Fuentes, 2016). Hence, if the *IRR* is greater than the annual discount rate (*r*), the project is profitable.

$$NPV = -IC + \sum_{t=1}^{T} \frac{PVR_t - AOM_t}{(1+r)^t} , \tag{4}$$

$$PVR_t = PVP_t * (SCEP * SCF + EIP * EIF) \ \forall(t) \in 1..T, \tag{5}$$

$$PVP_t = SY * (1 - DR * t) \ \forall(t) \in 1..T , \tag{6}$$

$$\sum_{t=1}^{T} \frac{PVR_t - AOM_t}{(1+IRR)^t} - IC = 0 , \tag{7}$$

where *NPV* is the net present value in USD; *IC* is the initial cost of installation in USD/kWp; *T* represents the economic horizon of analysis in years; PVR_t is the annual return from a PV system in USD; PVP_t is the annual production from a PV system in kWh/year; *SY* is the specific yield on each city in kWh/kWp-year; *DR* is the annual degradation ratio in %/year; *SCEP* represent the price valued by the self-consumed electricity in USD/kWh; *SCF* is a self-consumption factor expressed as a percentage; *EIP* is the price valued by the energy injected into the grid in USD/kWh; *EIF* is an energy-injected factor expressed as a percentage; AOM_t is the annual operation and maintenance cost in USD/kWp-year; *r* is the annual discount rate of the financial exercise expressed as a percentage; and *IRR* the internal rate return expressed as a percentage.

Section 4.2 shows the values for *SY*, *PI*, AOM_t, *SCEP*, and *EIP*. Moreover, $T = 25$ years as the lifetime of the system and $r = 5$ % as the annual discount rate has been assumed to analyze small-scale PV projects in Chile (Ramírez-Sagner et al., 2017). However, $r = 6.24$ % was also analyzed since it is the annual discount rate of the first financing option for the RPVP segment in this country (ME, 2019). Moreover, the same degradation ratio ($DR = 0.5$ %/year) used by Ramírez-Sagner et al. (2017) has been considered.

The profitability assessment was carried out under three scenarios. The first was for the base case (current market date under the net-billing scheme), assuming 30 %, 50 %, and 70 % of the self-consumption factor. The second considered a net-metering scheme, which implies a regulatory modification. The third, including the incentive of 30 % for the initial investment under both net-billing and net-metering mechanisms, was a promotion policy scenario.

4.1.3. Levelized cost of electricity (LCOE)

The *LCOE* indicates the unit energy cost over the lifetime of a project, including investment, operating, and financing costs. This metric compares the costs of energy projects. It was calculated according to Ramírez-Sagner et al. (2017) using Eq. (8), which is an adaptation from Massachusetts Institute of Technology (MIT, 2015) and Darling, You, Veselka, and Velosa (2011):

$$LCOE = \frac{IC + \sum_{t=1}^{T} \frac{AOM_t}{(1+r)^t}}{\sum_{t=1}^{T} \frac{SY*(1-DR*t)}{(1+r)^t}}, \tag{8}$$

where *LCOE* is the levelized cost of electricity in USD/MWh; *IC* is the initial cost of installation in USD/kWp; *T* represents the economic horizon of analysis in years; AOM_t is the annual operation and maintenance cost in USD/kWp-year; *r* the annual discount rate of the financial exercise expressed as a percentage; *SY* is the specific yield on each city in kWh/kWp-year; and *DR* is the annual degradation ratio in %/year.

Section 4.2 reveals the values for *IC*, AOM_t, and *SY*. Regarding the economic exercise, $T = 25$ years, $r = 5$ %, $r = 6.24$ %, and $DR = 0.5$ %/year were assumed and described in the previous section. Here, an *IC* of 30 % less than current values was also assumed, which implies the investment costs that will be had by 2025.

4.2. Input data

4.2.1. Solar irradiation and generation assumptions

Table 1 shows the latitude, longitude, solar annual irradiation, and yield for the locations under study. Yields were obtained through simulations carried out with Chile's Solar Energy Explorer open tool; the theoretical basis was published by Molina, Falvey, and Rondanelli (2017). In addition to the coordinates of each place, which is the first input to the tool, the assumptions used for the PV parameters to run the simulations are shown in Table 2.

Table 2
Parameters assumed to simulate a PV system with *Chile's Solar Energy Explorer*[a] open tool.

Parameters	Assumption
Installed capacity	1.0 kWp
Module's temperature coefficient	−0.45 %/°C
Configuration	Tilted fix
Mounting	Roof mount
Tilt and azimuth	Optimal angles
Inverter capacity	1 kW
Inverter efficiency	96 %
PV system losses factor	14 %

[a] http://www.minenergia.cl/exploradorsolar/.

4.2.2. Costs

Installation costs used in our study come from the report provided by ME, and GIZ (2018). They are a price index (*PI*) in USD/kWp, which is a regional average of grid-connected PV systems between 1–5 kWp without batteries (turnkey project). As the available values were for the year 2017, they were adjusted to consider the 9 % reduction in the *PI* in 2018, which was mentioned in the same report. Additionally, these

Table 3
The installation cost of PV systems between 1–5 kWp by region and their differences throughout the country in 2018. Name regions defined in ISO 3166-2:CL.

Name region	Price Index (*PI*) of installation USD/kWp	Difference with the lower *PI* %
AP	2382	13.4
TA	2382	13.4
AN	2350	11.9
AT	2317	10.3
CO	2101	0.0
VS	2621	24.7
RM	2372	12.9
LI	2718	29.4
ML	2458	17.0
NB	3000	42.8
BB	3000	42.8
AR	2675	27.3
LR	2350	11.9
LL	3097	47.4
AI	3367	60.3
MA	2686	27.8
Average	2617	
Max	3367	
Min	2101	

Table 1
Coordinates and solar conditions for every city and their differences throughout the country. Name regions defined in ISO 3166-2:CL.

Name region	Regional capital names	Latitude °	Longitude °	Solar irradiation kWh/m^2-year	Specific yield (*SY*) kWh/kWp-year	Difference with the highest *SY* %
AP	Arica	−18.48	−70.30	2084	1529	−9.6
TA	Iquique	−20.23	−70.14	2040	1473	−12.9
AN	Antofagasta	−23.65	−70.39	2194	1623	−4.1
AT	Copiapó	−27.37	−70.32	2259	1691	0.0
CO	La Serena	−29.90	−71.25	1705	1324	−21.7
VS	Valparaiso	−33.05	−71.61	1759	1367	−19.2
RM	Santiago	−33.44	−70.65	1858	1413	−16.5
LI	Rancagua	−34.17	−70.73	1953	1489	−11.9
ML	Talca	−35.42	−71.65	1865	1439	−14.9
NB	Chillán	−36.61	−72.10	1825	1429	−15.5
BB	Concepción	−36.82	−73.04	1723	1370	−19.0
AR	Temuco	−38.74	−72.61	1580	1269	−25.0
LR	Valdivia	−39.83	−73.23	1529	1233	−27.1
LL	Puerto Montt	−41.47	−72.95	1336	1120	−33.8
AI	Coyhaique	−45.58	−72.05	1361	1189	−29.7
MA	Punta Arenas	−53.15	−70.91	1106	1036	−38.8
	Max			2259	1691	
	Min			1106	1036	

values include *VAT* (19 %) because the residential sector does not have the right to tax recovery. Table 3 shows the final numbers for the initial investment in a residential PV system.

Due to the non-existence of more accurate values for the operation and maintenance (*AOM*) of small-scale grid-connected PV systems, we adopt that of Ramírez-Sagner et al. (2017): 10 USD/kWp-year.

4.2.3. Energy prices

Table 4 shows the electricity prices: the residential rate for the purchase of energy from the grid and the value assigned for injection into the grid. These values are the average annual prices of the year 2018, obtained from the website of each retail company that operates as an electricity distributor in the cities covered by the study. The exchange rate is the average annual dollar value observed in 2018 in Chile (1 USD = 640.29 CLP).

5. Results and discussion

This section presents the results of the economic assessment by metrics and the analysis of the critical parameters that affect the variability of these metrics in the residential PV prosumer (RPVP) market across Chile. The econometric techniques employed include the *SPP*, *IRR*, and *LCOE*; the results are described in Sections 5.1, 5.2, and 5.3, respectively. As the metric results are presented, and key parameters are detected, the identified barriers in the deployment of the RPVP segment are highlighted. Section 5.4 analyses the critical parameters, emphasizing the discussion about which of them are managed from a policy perspective. Moreover, suggestions for opportunities to accelerate the RPVP deployment in Chile are presented.

5.1. The effect of incentive on the simple payback period (SPP)

Table 5 provides an overall view of the effect of incentives (*In*) on the *SPP*. This metric is presented by city, considering 0 %, 30 %, and 50 % *In* of *IC* (initial investment cost). For each *In* percentage, the *SPP* was estimated at 30 %, 50 %, and 70 % of the self-consumption (*SC*) level for both net-billing (top line) and net-metering (bottom line) schemes.

Under the net-billing scheme and 0 % *In*, which represents the current state of the RPVP market in Chile, all places have an *SPP* greater than seven years for each *SC* level assumed. For the net-metering scheme and 0 % *In*, only one city (Copiapó, which is located in the central north of the country) has a *SPP* of less than seven years. Under the net-billing scheme and 30 % *In*, the results show that two and five cities have a *SPP* of less than seven years at 50 % and 70 % *SC* levels, respectively. By contrast, 10 of the 16 cities recover the investment in less than seven years under the net-metering scheme and 30 % *In*. The best scenario is 50 % *In*, where, on the one hand, every city has a *SPP* of less than seven years regarding net-metering. On the other hand, regarding net-billing and 50 % *In*, eight, four, and three of the locations have a *SPP* of more than seven years for 30 %, 50 %, and 70 % *SC*, respectively. However, this last scenario of 50 % *In* is less likely to occur in practice, and even seven years is much more than a family would expect to recover an investment.

Table 4
Electricity prices by city and differences between prices throughout the country.

Regional capital names	Price of residential tariff USD/kWh	Difference with the lower residential price %	Price valued for injection into the grid USD/kWh	Difference with the highest injection price %
Arica	0.208	20.7	0.098	−16.14
Iquique	0.199	15.6	0.095	−18.84
Antofagasta	0.193	11.9	0.100	−14.50
Copiapó	0.206	19.5	0.109	−6.71
La Serena	0.226	31.1	0.116	0.00
Valparaiso	0.223	29.4	0.116	−0.18
Santiago	0.173	0.0	0.096	−17.53
Rancagua	0.203	17.6	0.111	−4.36
Talca	0.214	24.2	0.111	−4.36
Chillán	0.219	26.7	0.111	−4.36
Concepción	0.203	17.7	0.111	−4.36
Temuco	0.219	27.1	0.111	−4.36
Valdivia	0.220	27.3	0.095	−18.07
Puerto Montt	0.220	27.3	0.095	−18.07
Coyhaique	0.223	29.2	0.104	−11.03
Punta Arenas	0.195	12.7	0.087	−25.31
Average	0.209		0.104	
Max	0.226		0.116	
Min	0.173		0.087	

The *SPP* is naturally higher in the south of the country due to lower irradiation levels. It is also because these locations have a higher investment cost. Beyond the *SPP*'s dependence on energy prices and irradiation levels (where the last one is unmanageable), the initial investment (*IC*) is a critical parameter. Therefore, having a high *IC* without incentive seems to be one of the most significant barriers in the deployment of the RPVP segment in Chile. Moreover, the *SPP* results show that net-metering is a much more favorable scheme for the investment recovering than a net-billing framework. This situation reveals the importance of the type of regulatory scheme in this metric.

5.2. Profitability of the RPVP segment in Chile

For an investment to make sense from the economic perspective, the internal rate return (*IRR*) should be greater or at least equal to the annual discount rate. In this profitability assessment, annual discount rates of 5 % and 6.24 % were assumed. The first one has been widely used to analyze small-scale PV projects in previous studies on Chile, and the second one is the annual discount rate of the first financing option for the Chilean residential sector.

Table 6 presents the *IRR* results calculated for three scenarios to evaluate the minimum profitability of a residential PV project. For the baseline case (scenario 1 in Table 6) with a 30 % self-consumption factor (*SCF*), five and two cities have *IRR* values higher than 5 % and 6.24 %, respectively. For 50 % *SCF*, the number of cities rises to 11 and 7. Similarly, for 70 % *SCF*, every city from Valdivia to the north can potentially investment in a PV project. However, 50 % *SCF* and below seems to be more realistic.

The *IRR* values, in case of a regulatory change (from net-billing to the net-metering scheme), would favor investment in almost every Chilean city. Table 6 (scenario 2) shows that even the southern cities have an *IRR* higher than 5 % (Punta Arenas would be the only exception). This is because they have higher residential tariffs. Moreover, under a net-metering framework, the return is independent of the energy self-consumed. In the same case (scenario 2), only the three southern cities have an IRR lower than 6.24 %. This result is mainly due to high investment costs and low irradiation levels.

As is logical in locations with better solar resources, *IRR* achieves values that are double 5 % in scenario 2. The places with more than 1500 kW h/kWp-year can achieve an *IRR* of more than 10 %. However, in La Serena, which has a yield of 1324 kW h/kWp-year, the *IRR* is over 12 %. This situation is because the city has the lowest *IC* and highest electricity prices among the cities covered by the study, which is the best combination under a net-metering framework. The combination of low *IC* and high electricity prices can also occur in places with a yield of less than 1250 kW h/kWp-year, which is the case of Valdivia. In this city, with 1233 kW h/kWp-year, its *IRR* reaches 9.6 % in a net-metering scheme.

The *IRR* results under promotion policies are presented as scenarios 3a and 3b in Table 6. Those scenarios comprise an *In*, which is 30 % of the initial investment cost for both regulatory mechanisms and net-billing and net-metering, respectively. In scenario 3a, regarding 30 % *SCF*, the three southern cities have an *IRR* of less than 5 % and 6.24 %. Regarding the rest of the locations, the *IRR* is greater than the annual discounted rates. For the same scenario, from 50 % *SC*, almost every city

Table 5
Simple payback period (*SPP*) by city (in years) for different percentages of incentive and self-consumption (*SC*) levels: top-line net-billing scheme and bottom line net-metering scheme.

City	0 % *Incentive*			30 % *Incentive*			50 % *Incentive*		
	30 % *SC*	50 % *SC*	70 % *SC*	30 % *SC*	50 % *SC*	70 % *SC*	30 % *SC*	50 % *SC*	70 % *SC*
Arica	12.5 7.7	10.6	9.2	8.8 5.4	7.4	6.5	6.3 3.9	5.3	4.6
Iquique	13.6 8.4	11.5	10.0	9.5 5.9	8.1	7.0	6.8 4.2	5.8	5.0
Antofagasta	11.9 7.7	10.3	9.1	8.3 5.4	7.2	6.4	6.0 3.9	5.2	4.6
Copiapó	10.4 6.8	9.0	8.0	7.3 4.8	6.3	5.6	5.2 3.4	4.5	4.0
La Serena	11.2 7.3	9.7	8.5	7.8 5.1	6.8	6.0	5.6 3.6	4.8	4.3
Valparaiso	13.6 8.9	11.8	10.4	9.5 6.2	8.3	7.3	6.8 4.4	5.9	5.2
Santiago	15.0 10.1	13.2	11.8	10.5 7.1	9.2	8.2	7.5 5.1	6.6	5.9
Rancagua	13.8 9.3	12.1	10.8	9.7 6.5	8.5	7.6	6.9 4.7	6.1	5.4
Talca	12.6 8.2	11.0	9.7	8.8 5.8	7.7	6.8	6.3 4.1	5.5	4.8
Chillán	15.4 9.9	13.3	11.7	10.8 6.9	9.3	8.2	7.7 5.0	6.6	5.8
Concepción	16.6 11.2	14.6	13.0	11.6 7.8	10.2	9.1	8.3 5.6	7.3	6.5
Temuco	15.5 10.0	13.4	11.8	10.9 7.0	9.4	8.2	7.8 5.0	6.7	5.9
Valdivia	15.3 9.0	12.8	10.9	10.7 6.3	8.9	7.7	7.6 4.5	6.4	5.5
Puerto Montt	22.3 13.1	18.6	15.9	15.6 9.2	13.0	11.2	11.2 6.6	9.3	8.0
Coyhaique	21.6 13.2	18.3	15.8	15.1 9.2	12.8	11.1	10.8 6.6	9.1	7.9
Punta Arenas	23.7 14.0	19.8	17.0	16.6 9.8	13.8	11.9	11.8 7.0	9.9	8.5
Max	23.7 14.0	19.8	17.0	16.6 9.8	13.8	11.9	11.8 7.0	9.9	8.5
Min	10.4 6.8	9.0	8.0	7.3 4.8	6.3	5.6	5.2 3.4	4.5	4.0

Table 6
Internal rate return (*IRR*) by city for different scenarios.

City	Scenario 1[a]			Scenario 2[b]	Scenario 3a[c]			Scenario 3b[d]
	SCF 30%	*SCF* 50%	*SCF* 70%	Net-metering	*SCF* 30%	*SCF* 50%	*SCF* 70%	*In* 30% and net-metering
Arica	5.7	7.5	9.2	11.7	9.9	12.2	14.5	17.7
Iquique	4.9	6.6	8.2	10.5	8.9	11.1	13.1	16.1
Antofagasta	6.2	7.9	9.4	11.7	10.6	12.7	14.7	17.6
Copiapó	7.8	9.5	11.2	13.6	12.6	14.8	17.0	20.2
La Serena	6.9	8.6	10.3	12.6	11.5	13.7	15.8	18.9
Valparaiso	4.8	6.3	7.8	9.8	8.9	10.7	12.5	15.2
Santiago	3.9	5.1	6.4	8.1	7.7	9.2	10.8	13.0
Rancagua	4.7	6.0	7.3	9.2	8.7	10.4	12.0	14.4
Talca	5.6	7.2	8.7	10.8	9.8	11.8	13.7	16.5
Chillán	3.6	5.1	6.4	8.4	7.4	9.2	10.9	13.3
Concepción	2.9	4.1	5.3	6.9	6.5	8.0	9.4	11.5
Temuco	3.5	5.0	6.4	8.3	7.3	9.1	10.8	13.2
Valdivia	3.7	5.5	7.2	9.6	7.4	9.7	11.8	14.9
Puerto Montt	0.4	1.9	3.3	5.2	3.5	5.3	7.0	9.3
Coyhaique	0.6	2.1	3.4	5.2	3.8	5.5	7.0	9.3
Punta Arenas	−0.1	1.4	2.7	4.5	2.9	4.6	6.2	8.5
Max	7.8	9.5	11.2	13.6	12.6	14.8	17.0	20.2
Min	−0.1	1.4	2.7	4.5	2.9	4.6	6.2	8.5

[a] Scenario 1 – Current market, net-billing scheme and three different self-consumption levels (SCF).
[b] Scenario 2 – Regulatory modification, net-metering scheme.
[c] Scenario 3a – Promotion policies, incentive of 30 % for the initial investment under net-billing scheme and three different self-consumption levels (SCF).
[d] Scenario 3b – Promotion policies, incentive (In) of 30 % for the initial investment under net-metering scheme.

is in a favorable situation to invest in a residential PV project. Here, 12 of 16 places have an *IRR* of over 9 %, nearing Copiapó city at 15 % in the more favorable situation. Logically, under scenario 3b, a PV project would be profitable everywhere in Chile, even in places with lower irradiation levels. This situation would be the effect of a 30 % incentive to the initial investment plus net-metering framework.

In summary, the results reveal that the irradiation levels, investment cost, the annual discount rate, and the regulatory scheme are all critical parameters in the profitability assessment of a residential PV project. When the regulatory scheme is a net-billing framework, the self-consumption levels become a key parameter.

5.3. Levelized cost of electricity (LCOE) across Chile

Fig. 10 shows the *LCOE* results by city and the respective residential tariffs, where *LCOE* differences between the cities can be observed. Indeed, Copiapó and Coyhaique present extreme cases with two-fold differences.

Lower *LCOE* values were found in the northern regions because these locations have the highest irradiation levels in the country combined with lower initial investment costs. In contrast, higher *LCOE* values in southern cities are due to their low irradiation levels and high *IC*. Notably, the solar resource and *IC* significantly affect this metric.

Comparing two different annual discount rates (r), where $r = 5$ % and $r = 6.24$ % (blue and orange lines in Fig. 10, respectively), the $LCOE_{(r\,=\,5\,\%)}$ is about 11 % less than the $LCOE_{(r\,=\,6.24\,\%)}$ in each city. The range of the *LCOE* values is 108–220 USD/MWh and 122–247 USD/MWh for $r = 5$ % and $r = 6.24$ %, respectively. The national average *LCOE* values are 153 USD/MWh and 172 USD/MWh for $r = 5$ % and $r = 6.24$ %, respectively. These results reveal the impact of the annual discount rate on this metric, which is another critical parameter in the economic assessment of residential PV projects.

Nevertheless, as Fig. 10 shows, $LCOE_{(r\,=\,5\,\%)}$ and $LCOE_{(r\,=\,6.24\,\%)}$ are already less than the price of the residential tariff for most of the country. It means that grid parity has been reached in most of the cities. Punta Arenas is the only exception for the case where $r = 5$ %, and the three southern cities are the exception for the case where $r = 6.24$ %.

Although the *LCOE* values seem to be good enough to invest in residential PV projects for most of the country, the deployment is yet to start. According to ME (2018), 1.13 million homes have a favorable condition to install a 2 KWp PV system. Nonetheless, almost 3000 PV systems with that capacity or less are already installed across Chile, which is less than 0.3 % of the total. Some of the reasons could be attributed to high *SPPs* and low *IRRs* (refer to Section 5.1 and 5.2, respectively), which is a consequence of the current market conditions, specifically a net billing scheme as a regulatory framework and high investment costs without incentives or financing options.

The yellow line (in Fig. 10) shows the $LCOE_{(r\,=5\,\%)}$ expected by 2025, which is based on the investment cost projection reporting by ME (2018). The *LCOE* values could be immediately obtained across the country by two different means. One of them is to keep the current investment costs but would require an annual discount rate of 1.7 %. The second would have an incentive of 30 % on the current *ICs* to match the *ICs* projected by 2025.

These changes could be obtained by promotion policies and financing options, respectively. Even so, they might be unrealistic because a financing option with $r = 1.7$ % is much less than a bank would expect as an annual discount rate in Chile. The “Green Credit” recently launched has $r = 6.24$ %. Finally, an incentive under a promotion policy would imply using a huge amount of money from the national budget to cover the whole country.

5.4. Analysis of the critical parameters of the economic metrics

Although in general terms the econometric results agree with previous studies (Campos et al., 2016; Ramírez-Sagner et al., 2017; Watts et al., 2015), these results differ in absolute terms. This difference has two main reasons. The previous studies were conducted before the Tariff Equity Law came into effect. Thus, residential electricity prices are different today throughout the country and they could have certain influence on the consumption profiles of residential users, although up to date, there is no tangible evidence of such behavior in the country. The other reason is they used similar investment costs for each location. Therefore, our results represent an update on the current RPVP market across Chile.

Nevertheless, the critical parameters obtained with the econometrics are in total concordance with the highlights of previous studies. These key parameters include irradiation levels, investment costs, annual discount rate, electricity prices, regulatory scheme (net-billing or net-metering), and self-consumption levels. The variability of these factors depends on the different influential elements or a mix of them. These include natural phenomena, promotion policy, market conditions, financing options, and consumption profile. However, as decision-makers cannot handle all factors, the analysis emphasizes the dependence element that can be managed by policy-decision and can influence the critical parameters.

Table 7 shows that the critical parameters that can be directly managed by policy-decision are the *IC* and regulatory schemes. In addition, promotion policies could have an indirect influence on the discount rate. This parameter is fixed accordingly to the weighted average cost of capital (WACC), which is related to the financing scheme applied to an investment. In the case that these promotion policies are applied to the financing options, the WACC could be reduced, and therefore the value of the annual discount rate could be reduced. Therefore, it has been included in Table 7 that promotion policies not only influence investment costs and financing options, but also the annual discount rate.

Similar to the existing support programs for public and commercial sectors in this country (refer to Section 3.2.5), the residential sector could be stimulated through government instruments. Above all,

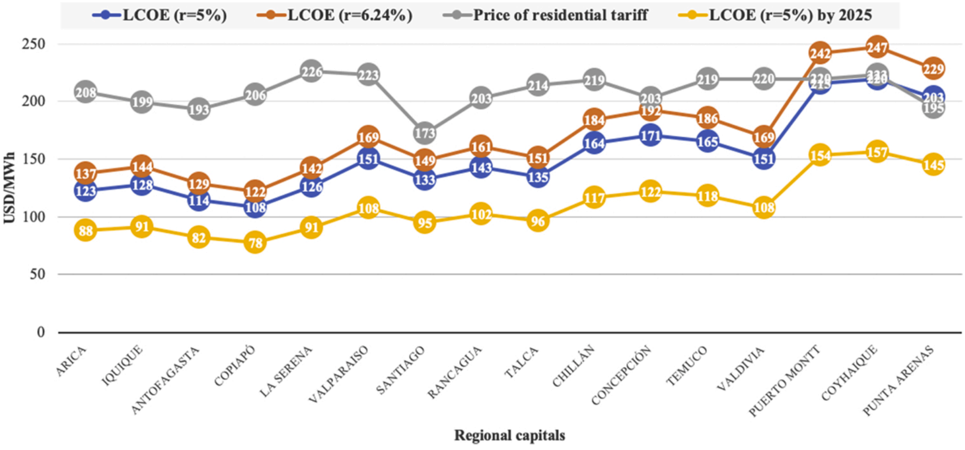


Fig. 10. Levelized cost of electricity (*LCOE*) and electricity prices across the country.

Table 7
Critical parameters and its dependencies: X represent the dependence of a key parameter with its respective influential elements, and the green marks highlight those that can be managed by policy-decision.

Key Parameters	Dependence elements				
	Natural phenomenon	Promotion policies	Market condition	Financing options	Consumption profile
Irradiation levels	X				
Investment costs		🟩 X	X	🟩 X	
Annual discount rate		🟩 X	X	🟩 X	
Electricity prices			X		X
Regulatory scheme		🟩 X			
Self-consumption					X

because the main obstacle is the level of income of a family in Chile, which means that their capacity to secure a loan is low. According to ME (2018), about 1 % of homes in 2016 in Chile complied with requests to install a PV system of 2 kWp (where, in addition to technical characteristics, socio-economic factors considered include an owner living at his house; a minimum income level; and, at least, one professional per family to obtain a bank loan). Without those socio-economic restrictions, the percentage of suitable homes increases to 20 %, which would translate to close to 1.13 million RPVPs (ME, 2018). Nevertheless, only about 3760 residential PV systems have currently been installed. Moreover, the government financed almost half of them under a special situation (as mentioned in Section 3.1).

In addition, deciding on the annual discount rate should be a part of the energy policy, through the promotion of financial schemes that reduce the weighted average cost of capital. However, this has not been the case in Chile. Establishing an annual discount rate for the RPVP segment lower than 5 % would increment the profitability of a small PV project for residential customers throughout the country. This would enhance the current financing option scenario for the RPVP segment, which is based on an annual discount rate of 6.24 %. This would also increase the opportunity to the citizens to obtain financing as well as to be part of the electricity market and contribute to the decarbonization of the power sector.

Furthermore, the regulatory framework can also be modified by policy decisions. The results of this study show that the net-billing scheme seems to be insufficient for the deployment of the RPVP segment in Chile, even in the north of the country that has the highest irradiation levels. Therefore, under a regulatory change from the current scheme to a net-metering framework, the scenario for the RPVP segment would improve. Moreover, net-metering and a bonus for energy injection into the grid, as conducted in some developed countries, can result in a *FiT* mechanism that produces a real deployment in this segment.

As many studies on developed countries have shown (Beermann & Tews, 2017; Burns & Kang, 2012; Candas, Siala, & Hamacher, 2019; Hsu, 2018; La Monaca & Ryan, 2017; Lee, Hong, & Koo, 2016; Matisoff & Johnson, 2017; Ossenbrink, 2017; Ramírez, Honrubia-Escribano, Gómez-Lázaro, & Pham, 2017; Yamamoto, 2017), the role of the government through promotional policies is key to the deployment of decentralized PV technology, particularly on a residential scale. Moreover, it can come from a policy decision. Additionally, the deployment of small PV systems in Chile needs established guarantee funds for loans (Haas et al., 2018). Hence, without policy support, Chile will not achieve a high penetration of the residential PV system across the country, even in locations with better solar conditions. This means that the benefits from the residential PV systems for the sustainable energy transition, hence for the cities and society, are being lost.

Therefore, to accelerate the deployment of residential PV systems in Chile, the following measures are suggested:

- Conduct a regulatory change to the net-metering scheme.
- Implement incentive and financing options, at least, for families with less income and in locations with yield levels less than 1300 kWh/kWp-year.
- Establish a standardized annual discount rate lower than 5 % for financing options.

Moreover, to understand the contribution of the RPVP segment in a more decentralized and clean energy system and take advantage of their socio-economic and environmental benefits, future research can consider the following:

- Estimate job creation at a local level and the potential reduction of air pollution at city level from the residential PV systems across Chile.
- Study the technical limitations of the distribution grids and the impact of battery and electric vehicles in scenarios with high penetration of the residential PV systems.

6. Conclusions, recommendations, and policy implication

Due to the significant role that decentralized solar technology can play in the future energy system, this study has explored the residential PV prosumer (RPVP) market in Chile by examining its regional capitals. This market is currently under a net-billing scheme as a regulatory framework without any incentives or support. Therefore, to identify parameters that can be managed with policy decisions and to understand their influence in the deployment of this segment, the study used three common econometric techniques to evaluate a PV project: simple payback period (*SPP*), internal rate return (*IRR*), and levelized cost of electricity (*LCOE*). Thus, several scenarios were assumed that comprise incentive to investment, different self-consumption levels, and an alternative regulatory scheme (net-metering). The methodological approach used in this work, which, up to the author's knowledge, has not been addressed in the scientific literature, can be applied to any city, especially in developing countries, to assess grid-connected PV systems from both a decision-maker's and an economic perspective.

The solar resource, investment costs, annual discount rate, electricity prices, regulatory schemes, and self-consumption levels are critical parameters in the economic evaluation of a residential PV system. However, family income is also a key factor that is not considered within the economic assessment of the widely used metrics. Actually, 68 % of the households in Chile have a lower income than the national average (1750 USD), and the national average income per household is 33 % lower than the average investment cost to install one kWp of a residential PV system in Chile. The purchasing power of the Chilean's families seems to be the main obstacle for the deployment of the RPVP segment. In fact, of the 1.13 million homes that are technically apt to install a 2 KWp PV system, there is only about 0.3 % of that total of houses that already installed a PV system across Chile.

In Chile, in addition to the enormous variations in solar radiation levels between the north and the south (2259−1106 kW h/m^2-year among the analyzed cities), there are investment cost differences that reach 60 %. Moreover, there are variations of 29 % and 25 % in residential energy prices and in the value paid for the electricity injected into the grid, respectively. On the other hand, 99 % of the homes in 2016 are in an unfavorable position to install a 2 kWp PV system due to the lack of minimum technical infrastructure, but mainly because of the impossibility of obtaining a loan from a bank. (ME, 2018). These factors, which includes a net-billing scheme as a regulatory framework and the lack of incentives or financing options, mean that the deployment of the RPVP segment in Chile is far from taking off, despite the presence of a grid-parity in almost the entire country. High investment costs and low income per home have been the main barriers in the deployment of the RPVP segment in Chile.

Investment costs, regulatory frameworks, and annual discount rates, through the promotion of financing schemes that influence in the WACC, are parameters that can be managed by government decisions. Investment costs can be reduced for citizens by promotion policies and incentives through financing programs, similar to those currently existing for public and commercial segments in Chile. Nevertheless, the value of energy injection into the grid can be shifted with a regulatory adjustment. This means that the current regulatory framework needs to be changed from a net-billing to a net-metering scheme, in order to achieve a more favorable scenario for the deployment of the RPVP segment. In addition, an annual discount rate lower than 5 % could be standardized for the whole country.

In order to relieve the high upfront costs for the installation of this type of system, an incentive of 30 % for the initial investment (which matches the projected investment cost by 2025), and considering the application of a net-metering scheme and an annual discount rate of 5 %, SPP would be between 4.8–9.8 years and IRR values would range between 8.5–20.2 % alongside Chile. Moreover, with an incentive of 30 % for the initial investment or an annual discount rate of 1.7 %, LCOE could be the same that by 2025.

All these regulatory changes could become an opportunity to advance in the contribution that the RPVP segment could give for achieving sustainable cities.

In this sense, on the one hand, it is recommended to estimate jobs creation and the potential reduction of air pollution at the city level from the high penetration of residential PV systems throughout Chile. On the other hand, an analysis of the financing option resulting in a standardized annual discount rate and any direct incentives to investment for families with less income and in (at least) locations with less than 1300 $\mathrm{kWh/m^2}$-year is also recommended. These suggestions are based on the following three reasons:

- A regulatory framework modification and funding schemes which influence in setting a standardized annual discount rate would not imply using money from the country's public budget.
- Incentive and financing options have been implemented in countries with less solar conditions, such as Germany, and therefore could, be applied to the southern part of Chile.
- Incentive policies remain vital to the deployment of residential solar PV systems in some developed countries (Lee et al., 2016).

Thus, policies that promote distributed energy resources can provide solutions for citizens (Simsek et al., 2019) and the environment. The role of promotion policies and some regulatory changes are essential to deploy the RPVP segment without having a major impact on the national budget. With better energy promotion policies and a regulatory framework, which can be managed by policy decision, homes could receive additional income during certain periods of the year. National policies and regulations with implications for cities can encourage their residents to support the energy transition (REN21, 2019). Citizens can then become actors in their own energy distribution market, participating in and contributing to the decarbonization of the power sector. In other words, families could significantly contribute to decarbonization through a more decentralized and democratic energy transition based on solar PV technology.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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