PONTIFICIA UNIVERSIDAD CATOLICA DE CHILE
ESCUELA DE INGENIERIA

PV INSTALLATION ON BUILDING ROOFTOPS AND FAÇADES IN CHILE: TECHNICAL AND ECONOMIC POTENTIAL

JOAQUÍN ESTEBAN MOLINA

Thesis submitted to the Office of Research and Graduate Studies in partial fulfillment of the requirements for the Degree of Master of Science in Engineering.

Advisor:
DAVID EDUARDO WATTS CASIMIS

Santiago de Chile, Agosto, 2014

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(A mi Madre y Abuela que han sido mi apoyo durante todos mis años de estudio, a mis amigos y profesores que me han enseñado día tras día.)

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RESUMEN

El potencial económico en techos y fachadas para proyectos fotovoltaicos en Chile ha sido estudiado analizando la radiación, generación de electricidad a partir de la instalación fotovoltaica, curvas de consumo eléctrico y tarifas eléctricas de 318 comunas a lo largo de Chile. El estudio considera curvas de generación fotovoltaica para diferentes orientaciones e inclinaciones en techos y fachadas. El sector de Chile con el mayor potencial técnico económico para instalaciones fotovoltaicas se encuentra en la región de atacama, que combina altos niveles de precios eléctricos y altos niveles de radiación. Este estudio indica que Chile es uno de los países privilegiados en Latinoamérica en donde la instalación de proyectos fotovoltaicos en techos es costo-efectivo sin necesidad de políticas de incentivos o subsidios. El período de retorno de inversión para proyectos fotovoltaicos ubicados en techos para un costo de inversión de 2.000 USD/kW varía desde los 7.7 años a más de 20 años. Por el contrario, a los precios actuales los proyectos fotovoltaicos instalados en fachadas no son costo-eficientes en ninguna región, considerando sólo los ingresos por energía generada.

Palabras Claves: (Fotovoltaico, Sistema fotovoltaico en techo, Costo Nivelado de energía, Paridad con la red, Chile, Radiación.)

ABSTRACT

The economic feasibility of rooftop and façade PV projects in Chile has been studied by analyzing solar radiation, PV electricity generation, electricity consumption profiles, and electricity rates from 318 districts throughout Chile. The study considers PV module electricity generation curves with different inclinations and orientations on both rooftops and building façades. The sector of Chile with the highest technical and economic potential for PV installation is located in the Atacama region, which has high-electricity rates and high solar radiation. This study found that Chile is one of the privileged countries in Latin America in which rooftop PV projects are cost-effective without incentive policies and/or subsidies. The payback period for rooftop PV projects with an investment cost of $2.000/kW varied from 7,7 to more than 20 years. Conversely, at current PV prices, Façade PV projects are found to be non-cost-effective in all regions when only their energy value is considered.

Keywords: Photovoltaic; Roof-top PV System; LCOE; Grid Parity; Chile; Radiation

1. PV INSTALLATION ON BUILDING ROOFTOPS AND FAÇADES IN CHILE: TECHNICAL AND ECONOMIC POTENTIAL

1.1. INTRODUCTION

Chile is characterized by an increasing need for cost-effective energy and very high solar irradiation levels. This combined with photovoltaic (PV) technology development worldwide and consistently decreasing PV cost has led to strong interest in implementing PV generation in Chile. In some countries the deployment of PV systems on the ground has led to heated debate on land use. In Italy, for example, installation of PV systems on agricultural soil was forbidden in 2012 (Tudisca, Di-Tripani, Sgroi, Testa, & Squatrito, 2013). Under these circumstances, rooftop PV systems, as a prospective alternative to greenfield PV development, has drawn increasingly more attention. As a result, there has been an increasing need to identify the generation potential of rooftop and façade PV systems, and evaluate the economic benefits that could be obtained for a specific region, city, or country, providing enough information for investors, and supporting material for regulators to develop incentives and appropriate policies.

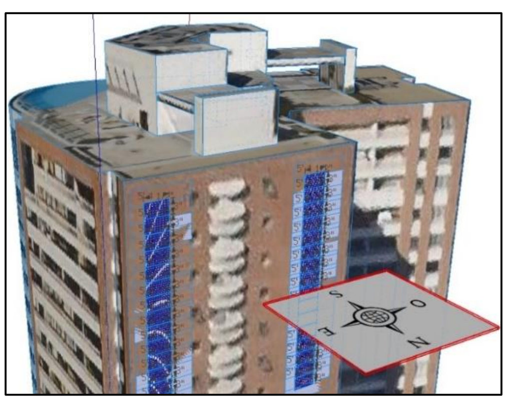

Fig. 1-1: Side facade with PV project installed

Several analyses of rooftop PV systems in European countries have been published. They are often focused on generation potential or investment costs. They provide useful information of the future of the technology in some countries, such as Italy and Germany, among others (Tudisca, Di-Tripani, Sgroi, Testa, & Squatrito, 2013) (Schallenberg-Rodríguez, 2013) (Spertino, Di Leo, & Cocina, 2013). In addition to analyzing the technical components of PV systems (modules, inverters, protections, etc.), the technical and economic analysis PV systems for buildings and façades (see Fig. 1-1) requires information about radiation, electricity tariffs, consumption profiles, incentive policies and construction codes, which may vary by city or county. Specific knowledge of local conditions is crucial.

With the support of the Chilean Construction Chamber (Cámara Chilena de la Construcción, or CChC) and the Chilean Photovoltaic Node[1], an extensive evaluation of different photovoltaic projects over 318 major districts was performed, identifying the most profitable sites for PV development considering the initial investment and local electricity tariffs for different PV projects, including roofs and façades. This paper summarizes the findings of this project.

[1] Organization of main PV developers, government energy officials and universities focused on strengthening the technological networks and the development of distributed PV generation in Chile. source: http://www.cdt.cl/2012/05/CDT-lanza-Nodo-Fotovoltaico/

1.1.1. Methodology and data sources

Technical and economic evaluation of rooftop PV potentials for each of the 318 counties required the following:

1) Having some knowledge of the location, population, housing styles, etc. Housing styles and building number for each county are based on the Chilean CASEN survey (MIDEPLAN, 2014), while population data were obtained from the last national census (2009) (INE, 2012) (Ministerio del Interior, 2014).

2) Obtaining hourly solar irradiation series from the Chilean solar map[2] . For an alternative method to develop this step see (Mellit, Eleuch, Benghanem, Elaoun, & Pavan, 2010).

3) Obtaining local electricity rate structure and tariff values (CHILECTRA, 2009) for each utility in the area (from each company website),

4) Computing solar incident radiation according to the inclination and orientation angles of the system, (and according to the possibilities given by roof angles). The solar irradiation model to compute the incident radiation on the roofs is based on (Duffie & Beckman, 1991) and it was codded in MATLAB.

5) Computing generation from a typical PV project.

6) Obtaining some example electricity consumption profiles.

Since Chile does not have publicly available electricity consumption profiles by customers, a short-term metering campaign was performed to develop representative

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[2] Chilean irradiation data: http://walker.dgf.uchile.cl/Explorador/Solar2/

profiles. Extrapolation to the rest of the year was performed using typical consumption days adjusted by the monthly billing information.

Local electricity consumption profiles were measured for 6 typical clients (a cinema, a residential apartment, an office apartment, a small house, a medium house and a professional institute). In addition 12 different building load profiles were collected using university energy meters, these profiles are assumed to be invariant regardless the city. Depending on solar irradiation, electricity consumption profiles, orientation and availability of area on the building, a PV project was designed and optimized for each building profile type.

7) Comparing building consumption and PV generation for every 5-min period of the year to assess electricity consumption from the grid versus surplus electricity injected into the grid, which sometimes carries different prices.

8) Selecting the proper PV project investment cost.

9) Finally, computing levelized costs of electricity (LCOE), payback periods, and internal rate of returns as economic performance measures of the project.

1.2. CHILEAN SOLAR RESOURCES AND POLICY

PV project economic feasibility on buildings is closely related to the population density of the area and its radiation. Buildings are usually located in densely populated areas, which usually have lower electricity retail rates due to economies of scale perceived by the utilities, reducing a PV projects economic feasibility. Conversely, higher radiation yields more electricity generation and more income for a given PV investment. In general, higher solar radiation in Chile is found in less populated areas (see Fig. 1-2). Solar, financial and other resources are presented through maps by districts similar to (Bergamasco & Asinari, Scalable methodology for the photovoltaic solar energy potential assessment based on available roof surfase area: Application to Piedmont Region (Italy), 2011 b) .

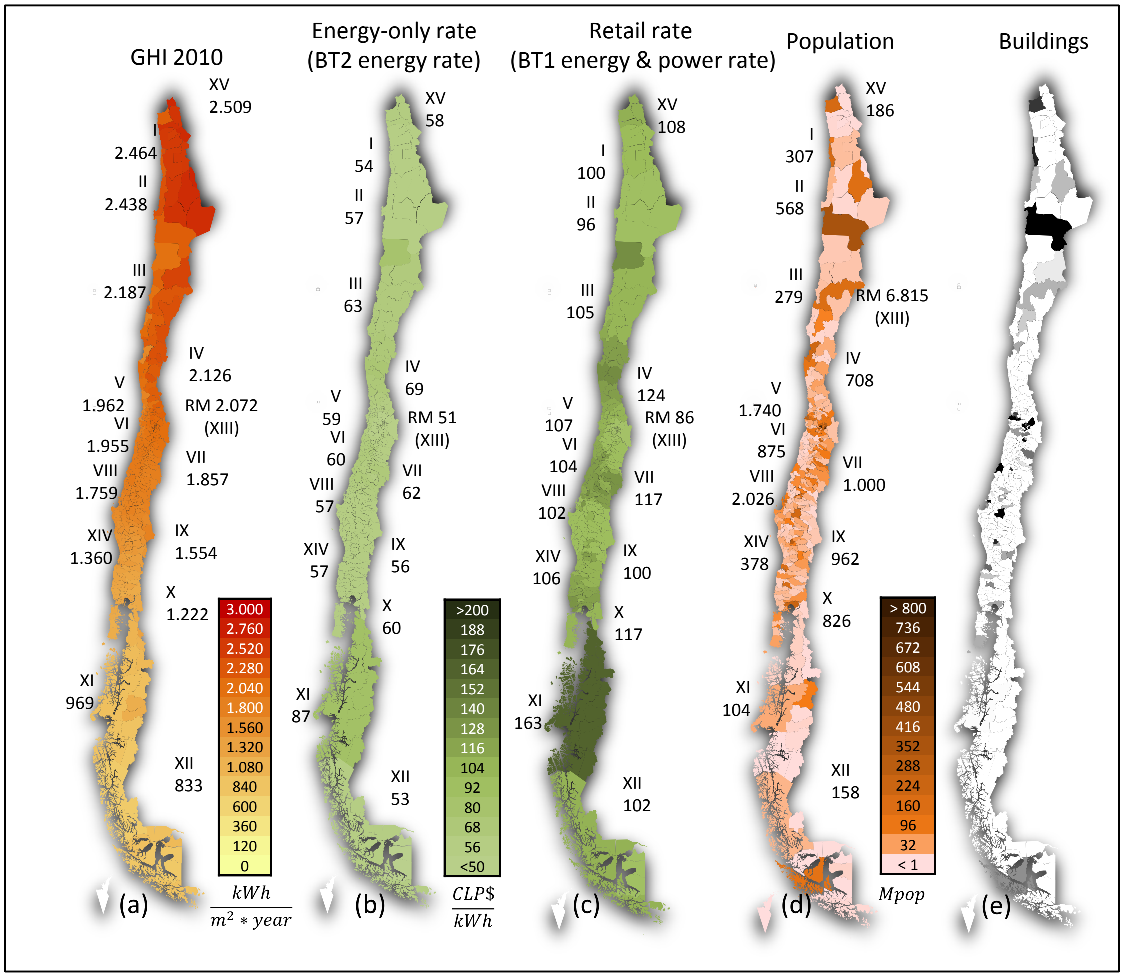


Fig. 1-2: Chilean resources – (a) GHI, (b) energy-only rate, (c) retail rate, (d) population and (e) buildings

1.2.1. Annual radiation by district in Chile

High radiation is crucial for the economic feasibility of PV projects. The solar resource in Chile is quite high in northern areas (one of the world's highest) and decreases towards central and southern Chile, showing a large variability throughout the country (from 730 to 2.676 $\mathrm{kWh}/(\mathrm{m}^2\ \mathrm{yr})$), while for any specific site the annual radiation varies on average less than 7% through the years (Universidad de Chile, s.f.). The annual radiation obtained for year 2010 is shown in Fig. 1-2. Sites with radiation levels over 2.000 $kWh/(m^2\ yr)$ are attractive for PV projects and they are available in over a half of the districts. Solar radiation is highly seasonal, daily averages for Global Horizontal Irradiance (GHI) for each month are presented in Fig. 1-3. During winter months in the southern areas GHI is much smaller than summer ones, while in northern areas the variation in GHI is much more limited.

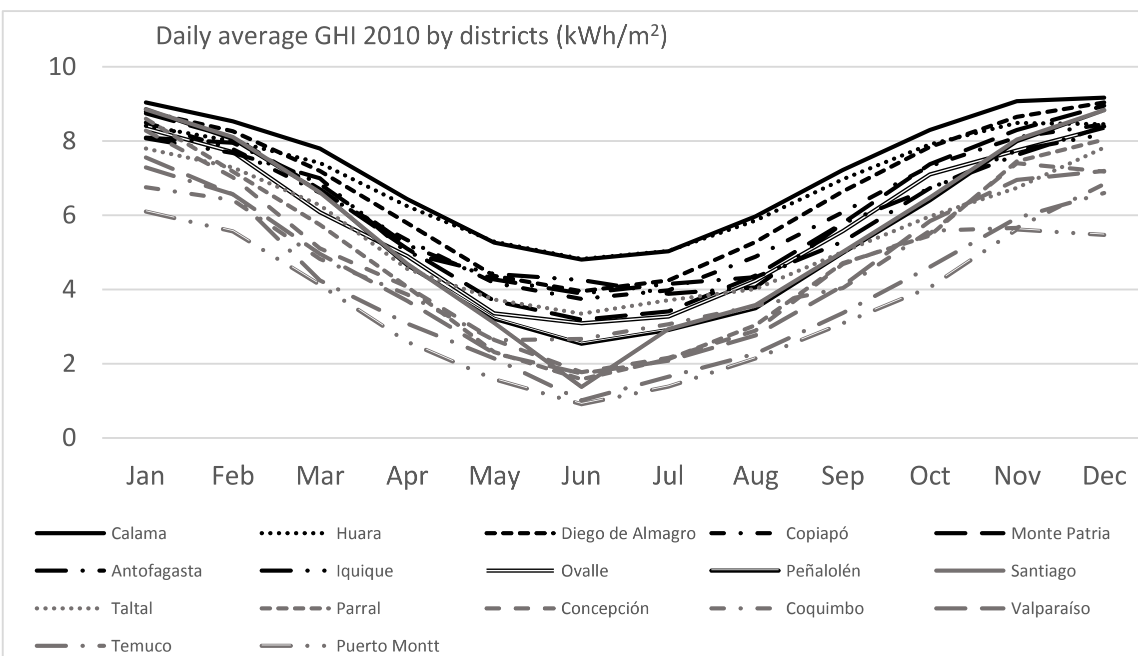


Fig. 1-3: Daily average GHI monthly 2010 in Chile by districts

1.2.2. Population, population density and buildings by region

Chile's population is concentrated in the central part of the country, mainly in the Metropolitan Region -referred also as "Región Metropolitana de Santiago" (RM) or XIII. This small region holds the capital city, Santiago, with 40% of the country's population and an average density of 14.200 hab/km^2. Similarly, buildings are concentrated in central Chile, leaving less than 2.000 buildings in the region with the highest GHI, Atacama.

The most favored areas by radiation within the country are in the regions XV, I, II, III, and in the northern part of the IV region. However, the population over this area is limited to only 10% of the country's population with an average density of 15 hab/km^2 among the five regions. A summary table with statistics for radiation, population, population density and buildings for Chilean districts is presented in TABLE 1.

TABLE 1: RADIATION (2010), POPULATION (2009)/BUILDINGS, POPULATION DENSITY FOR DISTRICTS AT ALL REGIONS OF CHILE (Universidad de Chile, s.f.), (INE, 2012)

Region		GHI (kWh/m^2)			M Population / Buildings	Pop. Density		
		Min	$\bar{I}$	Max		Min	$\overline{PD}$	Max
XV	Arica	2.213	2.509	2.676	186,1/ 1.081	0,2	10	38
I	Tarapacá	2.210	2.464	2.646	307,4/ 1.453	0,3	33	143
II	Antofagasta	2.012	2.438	2.690	568,4/ 4.450	0,1	3	12
III	Atacama	1.801	2.187	2.432	278,5/ 1.965	0,7	3	10
IV	Coquimbo	1.697	2.126	2.360	708,4/ 5.661	0,9	25	144
V	Valparaíso	1.685	1.962	2.206	1.739,9/ 13.024	5,5	241	2.399
XIII	Santiago (RM)	1.926	2.072	2.152	6.814,6/ 37.307	2,9	4.774	14.200
VI	B. O'Higgins	1.856	1.955	2.045	874,8/ 7.045	7,2	100	933
VII	Maule	1.780	1.857	1.921	999,7/ 10.457	6,4	65	1.032
VIII	Biobío	1.550	1.759	1.863	2.027/ 15.053	2	184	1.860
IX	La Araucanía	1.417	1.554	1.778	962,1/ 7.290	2,9	47	644
XIV	Los Ríos	1.282	1.360	1.448	378,2/ 2.233	5,5	26	156

X	Los Lagos	1.071	1.222	1.324	825,8/ 4.920	0,6	30	170
XI	Aysén	772	969	1.177	103,7/ 477	0	1	8
XII	Magallanes	730	833	979	158,1/ 477	0	1	7
	Country	730	1.818	2.690	16.931.9/112.893	0	369	14.200

1.2.3. Chilean electricity rates

Chile has different electricity tariffs schemes for low voltage (<400V) consumers, labeled as BT1, BT2, BT3 and BT4. The variation is explained by the connection capacity (and its overcurrent protection), the metering technology and peak power treatment (peak power can be measured or contracted and limited by overcurrent protections).

Residential consumers have a simple energy-only meter and a retail rate (BT1) high enough to finance both its energy consumptions (E) and its power demand (P). Above 10kW, different industrial and commercial customers (BT2, BT3 and BT4 tariffs) have separate charges for E and P, according to the peak load pricing theory. Through this formula, the energy consumption tariff (E) is targeted to finance mainly the generation sector, while the power demand charge (P) is targeted to finance the distribution and transmission infrastructure. Unlike Italy or Germany, Chile currently applies no incentive policy for solar power, but electricity prices are high enough (from 2 to 4 times higher than in Midwestern US) to make solar power competitive.

Electricity tariffs differ in different areas, and the retail tariff (BT1) – chiefly for residential customers – is cheaper when networks have higher density, given that lower investments are required to serve several nearby houses with the same power lines. For larger consumers (BT2, BT3 and BT4) population density does not affect the energy tariff as infrastructure is charged separately (P is splitted from the E charge). BT3 and BT4 tariffs share the same energy tariff as BT2 clients. In all cases the tariff provides key information for investors to find the best places to locate or promote PV generation. Electricity rates are presented in Fig. 1-2 and TABLE 2 sorted by its value.

TABLE 2: NON-RESIDENTIAL ENERGY RATES (BT2) FOR DISTRICTS BY REGION. AVERAGE, MAX, MIN IN $USD AND $CLP. (ORDERED BY RATE) VAT INCLUDED

Region	Region name	Average Energy Price ($\bar{P}$) ($\$USD^*/MWh$)		($\$CLP/kWh$)	
		$\overline{BT2}$	$\overline{BT1}$	$\overline{BT2}$	$\overline{BT1}$
XI	Aysén	172	322	87	163
IV	Coquimbo	137	246	69	124
III	Atacama	125	207	63	105
VII	Maule	123	232	62	118
X	Los Lagos	118	231	60	117
VI	Gral. B. O'Higgins	118	206	60	104
V	Valparaíso	117	211	59	107
XV	Arica y Parinacota	115	214	58	108
VIII	Biobío	113	201	57	102
XIV	Los Ríos	112	210	57	106
II	Antofagasta	112	190	57	96
IX	La Araucanía	112	198	56	100
I	Tarapacá	106	198	54	100
XII	Magallanes y Antártica	104	201	53	102
XIII	**Metropolitana de Santiago**	100	170	51	86

Electricity rates are higher in regions XI, IV, III, but region XI is in the south and has high levels of cloudiness, rain, and thus a very low GHI. Conversely, regions IV and III have a very high solar radiation combined with high electricity tariffs. Regions I, II and XV in the north have a great GHI but electricity rates are not that high. It's worth highlighting that the capital city, Santiago, is very densely populated and has the lowest electricity rates in the country; therefore, 40% of the population is facing very limited incentive to engage in PV projects.

1.3. ROOFTOP PV PROJECTS AND ENERGY CAPTURED AS FUNCTION OF MOUNTING ANGLES

Building rooftops are often flat, but equipment installed on the top of the building (escalators, water storage and ventilation systems, etc.) may limit the available area for PV. This PV area is even more limited when partial shadows from these objects and from neighboring objects, such as other buildings and trees are considered. Fig. 1-5 shows the PV potential area of an example 2-story building with a PV array optimally installed on a flat rooftop in Peñalolén district, in the Metropolitan Region. Depending on the orientation of the building, the optimal PV project may vary. Fig. 1-5a) shows a 11,5 kWp PV project with 46 panels of 250 Wp each, mounted on 67 m^2 of rooftop surface, with a 74,7 m^2 PV area, azimuth = 180° (North) and 27° tilt. In this case, 171.4 MWh/yr incident radiation produce 23,5 MWh/yr electricity. Similarly, Fig. 1-5b) shows a 10,3 kWp PV project with 41 panels of 250 Wp each, mounted on 60 m^2 of rooftop surface, with a 66,6 m^2 PV area, azimuth = 180° (North) and 27° tilt. Incident radiation of 152,8 MWh/yr produces 23,5 MWh/yr electricity.

Since Chile latitude ranges from 17° to 56°, optimal PV inclination is far from horizontal and most PV systems face a radiation gain (w.r.t. GHI) by its optimal orientation and tilt. Electricity generation varies with the change of radiation captured during a specific period of time: by the day, season or year. A proper choice for these angles is needed to maximize the total radiation captured or the value of energy produced.

The Azimuth (orientation angle, γ) and inclination or slope (tilt angle, β) of the panel are the two free parameters/angles of fixed PV modules. The orientation w.r.t. to the south is measured clockwise by the Azimuth (γ) from 0° to 360°. Unlike other countries, in the northern hemisphere where the optimal orientation is south (Mondol, Yohanis, & Norton, The impact of array inclination and orientation on the performance of a grid-connected photovoltaic system, 2007), the maximum radiation in Chile can be captured by pointing north (Pino, Bustamante, Escobar, & Pino, 2012), this is Azimuth γ=180. The tilt angle refers to the angle measured from the horizontal to the surface where the plane is located and is defined between 0° (the horizontal plane parallel surfaces) and 90° (vertical surfaces).

For Chile, the average optimum tilt angle is 27° and varies depending on the location within the country from 16° in the north to 30° in the south. The optimal orientation ranges are from 145° to 192°, depending on the characteristics of the location (weather, mountains, etc.).

The incident radiation decreases as mounting angles depart from optimal. For Peñalolén, with changes of tilt between 10° to 30° and orientation between 140 and 220° incident radiation range drops from the optimum in less than 5% (contour 95%, see Fig. 1-4).

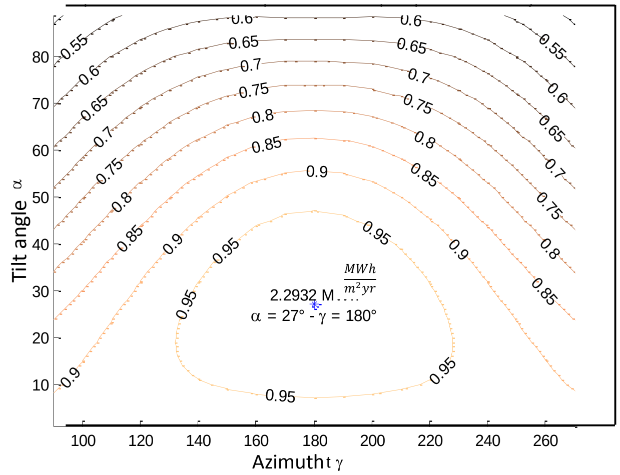


Fig. 1-4: Ratio of incident radiation received to maximum at optimal mounting: from tilt angle 0° (horizontal) to 90° (vertical) and orientation from 90° (East) to 270° (west) compared to the maximum radiation received ($\alpha = 27° \ \gamma = 180°$) in Peñalolén District

Locating PV modules on flat **horizontal** rooftops allows saving on mounting structures, but limits the opportunity for optimal orientation of the PV modules. Furthermore, mounting PV modules horizontally is not a good choice, because the modules are likely to accumulate excess dirt or mud, reducing energy capture. A tilt angle of 5º and above is often used for nearly horizontal mounting.

1.3.1. Captured radiation and energy production in different façade orientations

Considering the geographic characteristics of Chile and the tendency of high-rise building in high-density area, Façade-mounted PV requires careful consideration in order to understand the potential of PV generation for this style of mounting. Most high-rise buildings have four main walls and one main rooftop. The available space in walls is mostly unoccupied and serves to separate the interior space from the exterior environment;

some windows are polarized to reject energy from the sun. Polarized windows and walls have the potential for radiation capture which could be used for photovoltaic generation (see Fig. 1-1).

In the southern hemisphere, the orientation of the façade to the North captures more radiation per kWp installed, followed by east and west, while south is the worst orientation for PV generation (see Fig. 1-6 a). Fig. 1-6b shows the captured isolation by a 10kW PV panel at various orientations as an example relative to the horizontal. The generation on the horizontal plane is presented as 100% (16,65 MWh per year). To the north, generation is 65,3% (10,88MWh), 53,94 and 53,89% to east and west respectively (8,98 and 8,98 MWh) and to the south is only 24,08% (4,01 MWh). This is further explained considering rooftop configuration in (Bergamasco & Asinari, Scalable methodology for the photovoltaic solar energy potential assessment based on available roof surfase area: Application to Piedmont Region (Italy), 2011) (Karteris, Theodoridou, Mallinis, & Papadopoulos, 2014) (Bergamasco & Asinari, Scalable methodology for the photovoltaic solar energy potential assessment based on available roof surface area: Further improvements by ortho-image analysis and application to Turin (Italy), 2011 a).

Fig. 1-6: (a) Comparison of radiation captured by 1 kWp PV panels on different façade

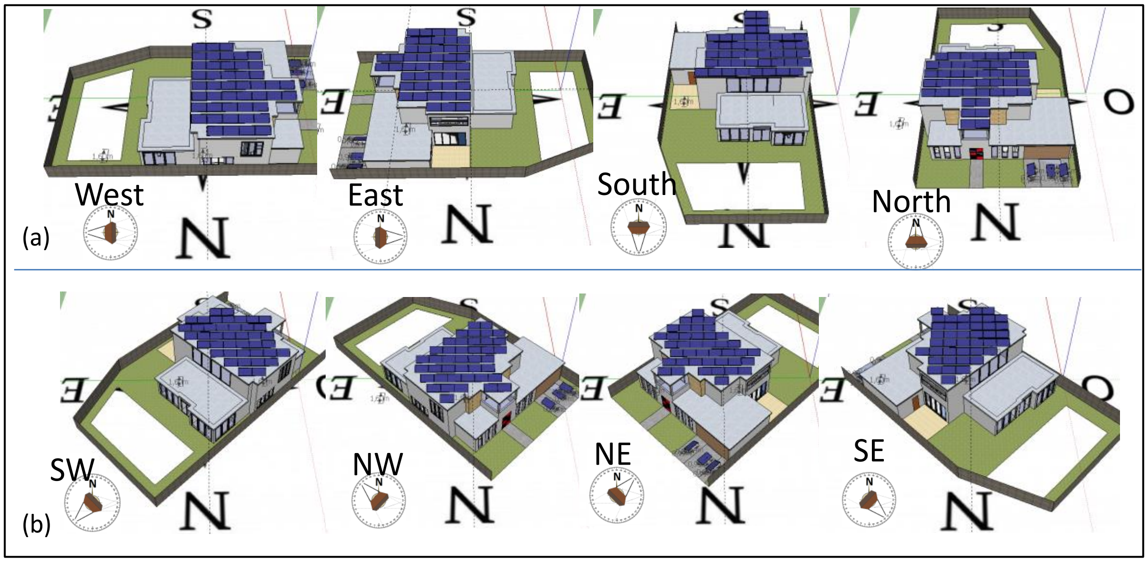
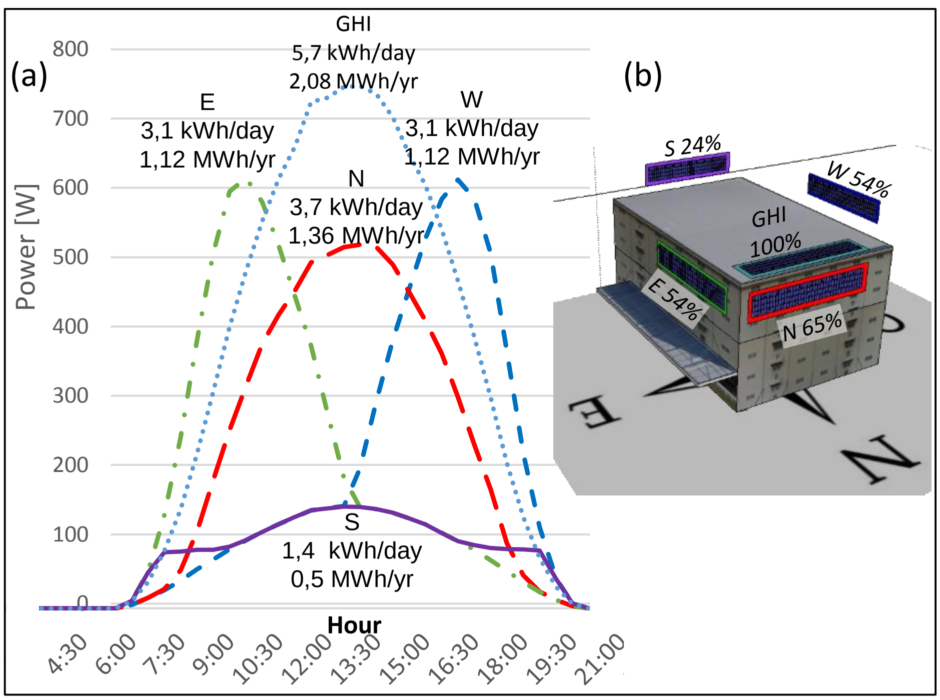


Fig. 1-5: Optimal PV mounting in flat rooftops in Santiago: a) orientation at N, S, W, E and b) SW, NW, NE and SE



orientations in Peñalolén. (b) 10 kWp PV panels mounted on different façade orientations in a building

.

The east and west orientation have similar total annual generation, however, they have very different generation curves because the east has the greatest amount of generation during the morning and negligible generation during the afternoon, while the west has virtually no generation during the morning and peaks in the afternoon (see Fig. 1-6 a). Thus, the west façade may provide better returns under a time-of-use tariff, because Chileans face the highest electricity consumption and prices in the late afternoon.

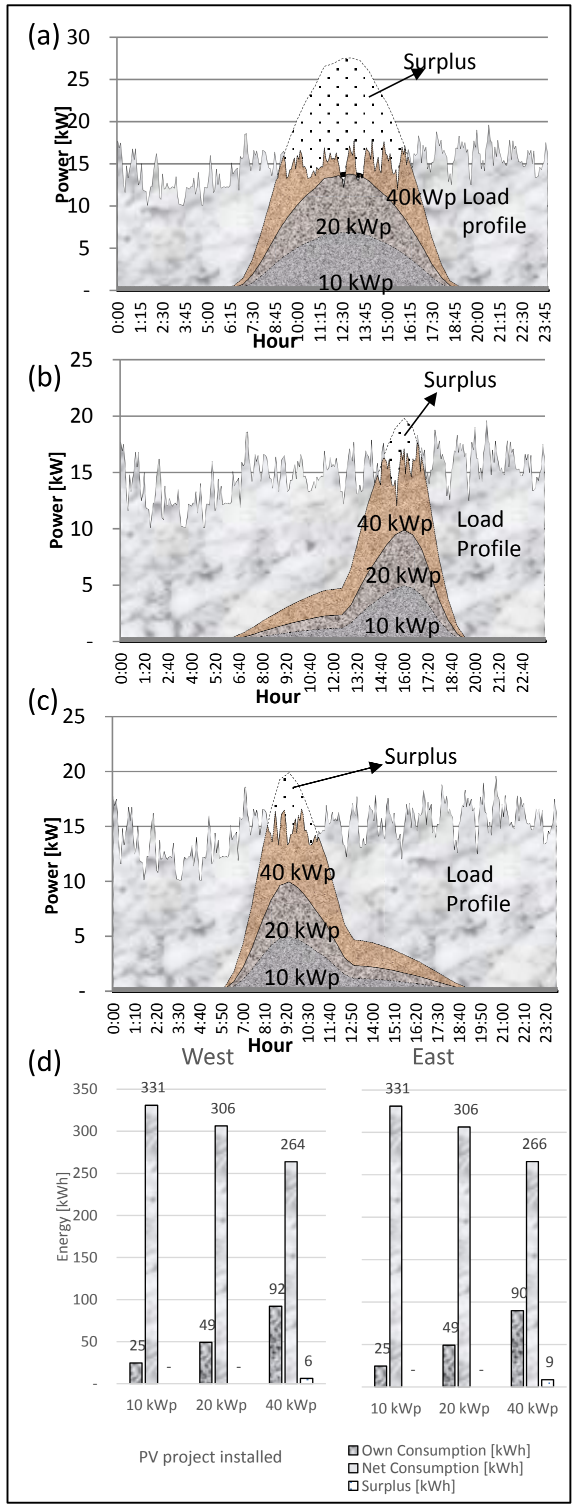


Fig. 1-7: (a) Horizontal PV panel: comparison of load consumption and photovoltaic generation (b) West oriented PV panel: Comparison of load consumption and photovoltaic generation (c) East oriented PV panel: comparison of load consumption and photovoltaic generation (d) Daily Generation and consumption by east and west orientations

The interaction between generation and consumption during the day depends on the orientation of the wall where the PV modules (see Fig. 1-7) are located. The maximum generation intervals for PV panels are those intervals of day when PV panels are directly facing the sun. Horizontally oriented generation has a peak at noon (Fig. 1-7 a), panels facing west maximize their generation during the afternoon (Fig. 1-7 b) and panels facing east have peak generation during the morning (Fig. 1-7 c). East-facing and west-facing panels produce similar amounts of energy, but at different times of the day (Fig. 1-7 d).

1.4. RESULTS: CALCULATION OF ECONOMIC INDICATORS

Seventeen districts were selected to represent the differences through the country according to four characteristics: proximity to the sea, differences between energy prices in the centralized grid system (SIC) and the "Norte Grande" system (SING), high radiation, and population. LCOE, payback, grid-parity investment cost and IRR are calculated and presented in colored maps (see Fig. 1-8). Despite of some criticism to payback as an economic indicator for PV installations (Perez, Burtis, Hoff, Swanson, & Herig, 2004), it was calculated due to its spread use.

1.4.1. Levelized cost of electricity (LCOE) for PV projects

The levelized cost of electricity (LCOE) is an economic assessment of the cost of the energy generated from a system and it represents the price at which electricity must be generated to break even over the lifetime of a specific project, including all costs over the project lifetime.

PV project investment cost was initially based on several invoices and price quotes, but since prices have been dropping consistently a range of prices was adopted from 2.000 to 3.000 $USD/kW (Fig. 1-8a and Fig. 1-8b); these represent the lowest cost found and a more typical price, respectively. PV price local projections are near 2.000 $USD/kW for the next few years.

The time horizon used for evaluation is 20 years, and the discount rate utilized is 10%. However, the full study incorporates also 6% for more residential investors, 14% for energy investors.

While rooftop PV installation cost is simple to define (the cost of the PV project), the cost of installing PV panels on façade is more difficult to assess, because it requires

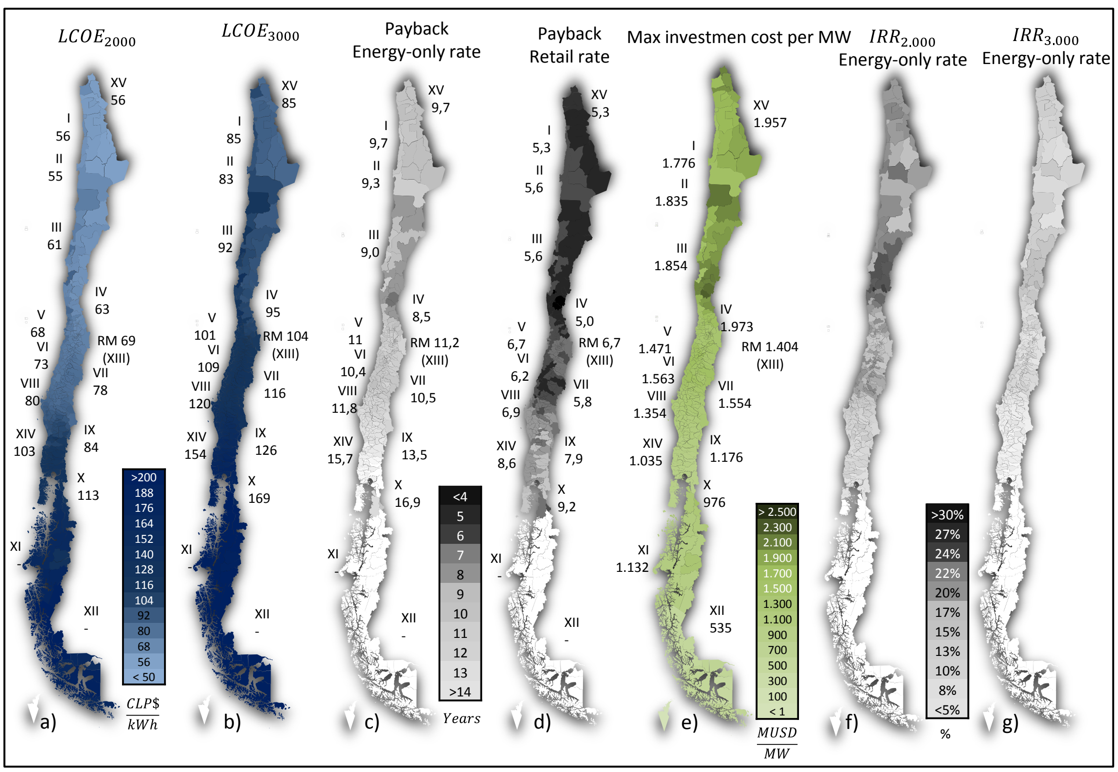


Fig. 1-8: PV project economic analysis 2.000 and 3.000 $USD/kW – a,b) LCOE, c,d)payback, e) grid-parity investment cost per MW and f,g) IRR

considering the cost associated with the integration with the building walls or windows (which is an additional cost to the building, due to PV, as opposed to a stand alone cost as PV is for rooftops). For evaluation purposes, the actual cost can be estimated as the cost of building walls/windows with the PV generator minus the cost of building walls/windows without PV generator. This is the incremental cost due to PV installations.

1.4.2. Effect of the size of the project

The inverter and protections of the project are sized with the maximum generation of the PV modules. Mounting hardware, wiring and monitoring devices, as well as AC and DC over-current and over-voltage protection are also included as part of the projects. An optimized option for inverter sizing is presented in Mondol et al. (2006) (Mondol, Yohanis, & Norton, Optimal sizing of array and inverter for grid-connected photovoltaic systems, 2006). For façade PV project, the inverter should not be rated for capacity of PV modules, as incident energy and electricity generation are much lower. Optimal inverter ratios, the ratio between PV panel capacity (DC) and Inverter capacity (AC), are similar to the inverse of the percentage of radiation captured by the PV panels presented in Fig. 1-6. This means it is possible to install more than double the PV panel capacity than the inverter capacity when they are mounted East or West.

1.4.3. Comparing LCOE for PC projects with electricity rates

The revenues obtained from PV generation are equal to the amount of energy sold valued at a rate similar to non-residential rate (BT2) of the district where the project is located.

Economically profitable installation costs for façade-mounted PV panels facing each direction are calculated.

Considering the prices has gone down quickly over the past few years, 2.000 $USD/kW is a reasonable expectation as it´s happening in other European places (G.J.H.M. van Sark, Peter Muizebelt, Vries, & Rijk, 2014). With that investment cost and with optimal inclination and orientation on flat roofs, only some districts of the third region of Chile have levelized costs of electricity generation less than the retail rate paid to the utility.

Facilities on the east and west façade would require investment costs as low as 1.000 USD/kW to achieve the levelized cost parity with the energy rate (BT2). The north facing façade requires investment costs lower than 1.300 USD/kW to achieve parity with the cost of the grid. In turn, installation facade facing south gets generates very little and is not recommended for solar installations in Chile.

A 2.000 USD/kW PV project installed in Chile achieves a levelized cost of electricity lower than non-residential rates (BT2) in some districts of I, III and IV region, as shown in Fig. 1-9. This cost parity is expected to happen in some European countries by year 2025. Levelized cost is higher than BT1 rates in districts of XI and XII regions and in the others districts levelized cost are between BT1 and BT2 rates. That means that almost in every place in the north and middle of Chile, house owners can install photovoltaic profitable PV projects (with positive return on investments). Even some buildings with BT2 rates from some places of northern Chile can get high revenues without any subsidy or policy (see example in Table 3 and results Fig. 1-10).

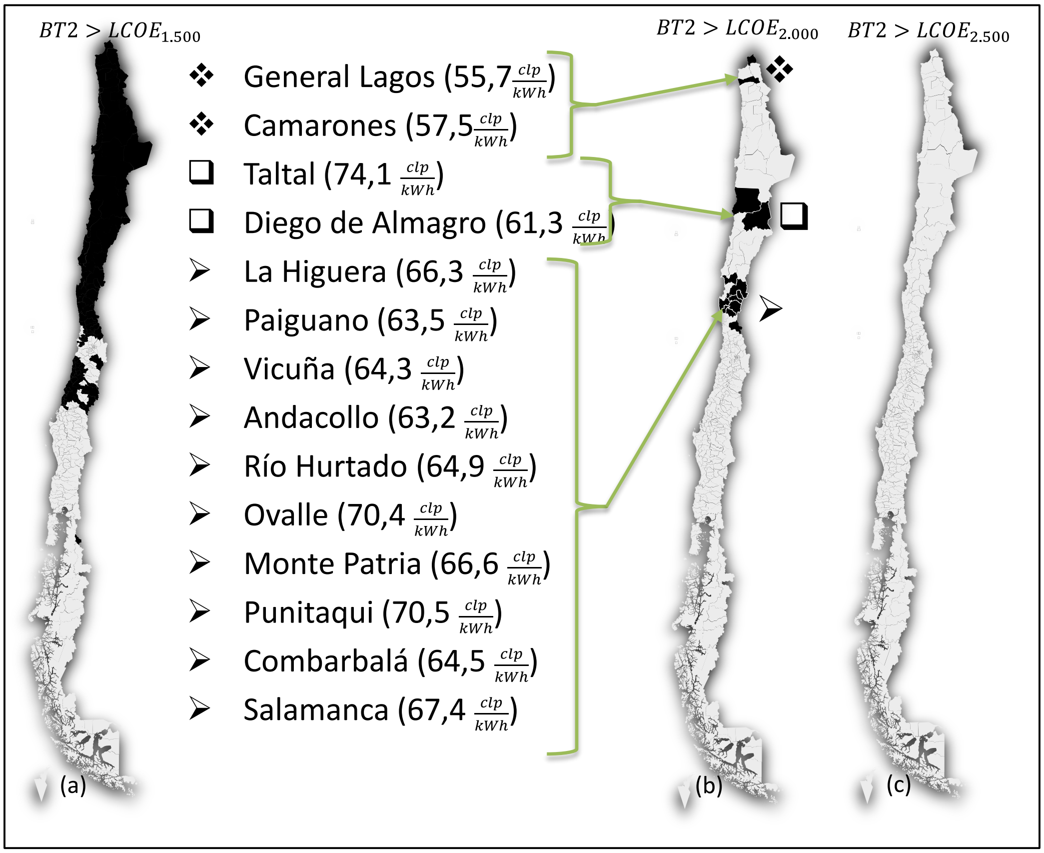


Fig. 1-9: Districts whose levelized cost is lower than energy rate BT2 for investment of 2.000 $USD/kW and 10% discount rate (district name; $LCOE_{2.000}$)

TABLE 3: LOCATION, LCOE AND RATES EXAMPLE FOR UNDERSTANDING FIG. 1-10

Location Region Number Region Name	**Energy Rate (BT2 rate)**	**LCOE 2,000 $USD/kW**	**Retail rate (BT1 rate)**
Santiago XIII/RM	51	72	86

In 2013, several PV project investments exceed 2.300 $\$USD/kW$ without considering maintenance. However, considering that prices of solar panels have declined sharply over the last years, using costs close to 2.000 USD/kW and lower for photovoltaic systems is a reasonable expectation.

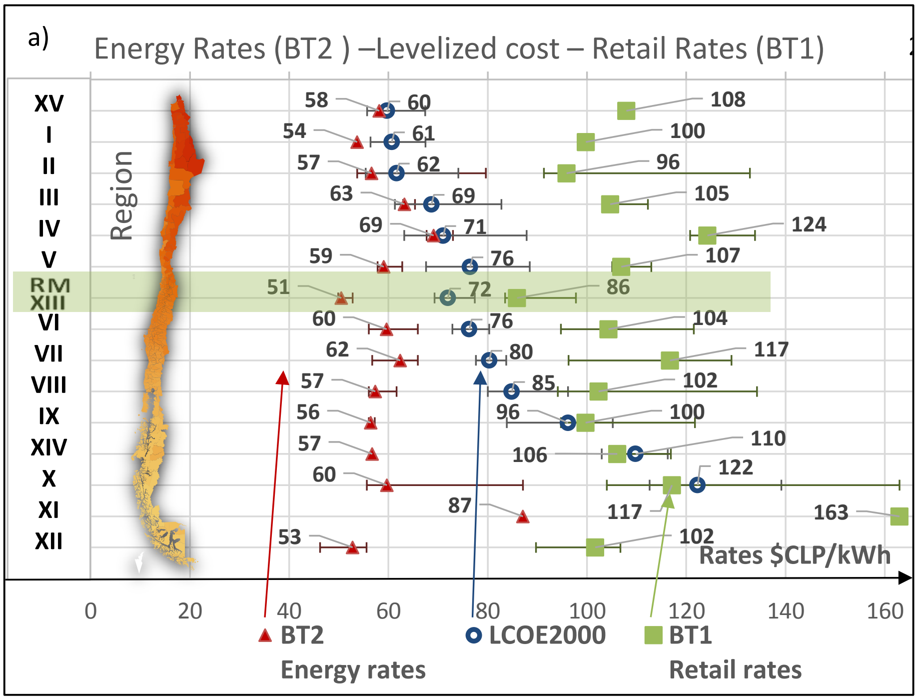


Fig. 1-10: Comparison between non-residential rates (BT2 energy rates), levelized cost with 2.000 $USD/kW investment, residential rates (BT1 retail rates) and non-residential rates (BT2) in Chile by region

1.4.4. Payback of PV projects

According to payback period calculated for those 17 districts in Chile, with an initial investment of 2.000 $\$USD/kW$, considering flat installation, the minimum payback time required is 7,7 years in Monte Patria and the maximum is 17,2 years in Puerto Montt. Installation on the north, east or west facades presents payback periods more than 44% longer, returning the investment after the life expectancy of the solar projects (see Fig. 1-8, Table 5 and Table 4), therefore the project is not economically feasible.

TABLE 4: ANNUAL GENERATION, NON-RESIDENTIAL RATES AND LEVELIZED COST CONSIDERING 2.000 \$USD/KWP INITIAL INVERSION, 15,4% EFFICIENCY PANNELS, DISCOUNT RATE OF 10%, 1% OF ANNUAL GENERATION DECAY, 1% COST IN ANNUAL MAINTENANCE

District		Annual generation kWh/kWp					BT2 $\frac{\$CLP}{kWh}$	Levelized cost 2.000 $\$USD/kW$				
		West	North	East	GHI	I. Opt. Ang.		West	North	East	GHI	I. Opt. Ang.
I	Huara	1.013	1.042	1.013	2.015	2.112	53,7	135,6	131,8	135,6	68,2	65,0
I	Iquique	905	880	910	1.768	1.823	53,7	151,8	156,0	150,9	77,7	75,3
II	Calama	1.075	1.141	1.070	2.106	2.238	53,7	127,8	120,4	128,3	65,2	61,4
II	Antofagasta	892	967	967	1.768	1.862	53,7	154,0	142,0	142,0	77,7	73,8
II	Taltal	934	921	772	1.610	1.714	79,6	147,1	149,1	177,8	85,3	80,1
III	D. Almagro	1.012	1.141	987	1.946	2.102	62,9	135,7	120,4	139,2	70,6	65,3
III	Copiapó	1.004	1.105	840	1.822	1.991	62,9	136,8	124,3	163,4	75,4	69,0
IV	Coquimbo	882	869	646	1.358	1.489	67,7	155,8	158,1	212,5	101,2	92,3
IV	Ovalle	958	1.074	814	1.694	1.866	73	143,3	127,8	168,8	81,1	73,6
IV	M. Patria	966	1.134	903	1.791	1.970	73	142,1	121,2	152,1	76,7	69,7
V	Valparaíso	796	807	699	1.353	1.434	59,1	172,6	170,2	196,5	101,5	95,8
RM	Santiago	885	1.024	884	1.642	1.789	49,9	155,2	134,2	155,4	83,6	76,8
RM	Peñalolén	898	1.087	897	1.665	1.839	49,9	152,9	126,3	153,1	82,5	74,7
VII	Parral	825	964	779	1.463	1.609	65,9	166,4	142,4	176,2	93,9	85,4
VIII	Concepción	797	993	787	1.425	1.590	56,4	172,3	138,3	174,5	96,4	86,4
IX	Temuco	704	806	644	1.182	1.290	57,3	195,2	170,4	213,4	116,2	106,4
X	P. Montt	625	741	597	1.034	1.132	56,8	219,7	185,3	230,2	132,9	121,3

In addition, 205 districts can recover their PV investment in 10 and 12 years, 38 districts in less than 10 years and 75 districts in more than 12 years (see Fig. 1-11).

The payback period for PV projects is presented in 17 districts for each orientation and optimum angle, the latter is available on horizontal surfaces. The levelized cost of electricity is lower than the BT2 electricity rate in Monte Patria, located in Region IV, because of the amount of radiation and high retail rate of energy.

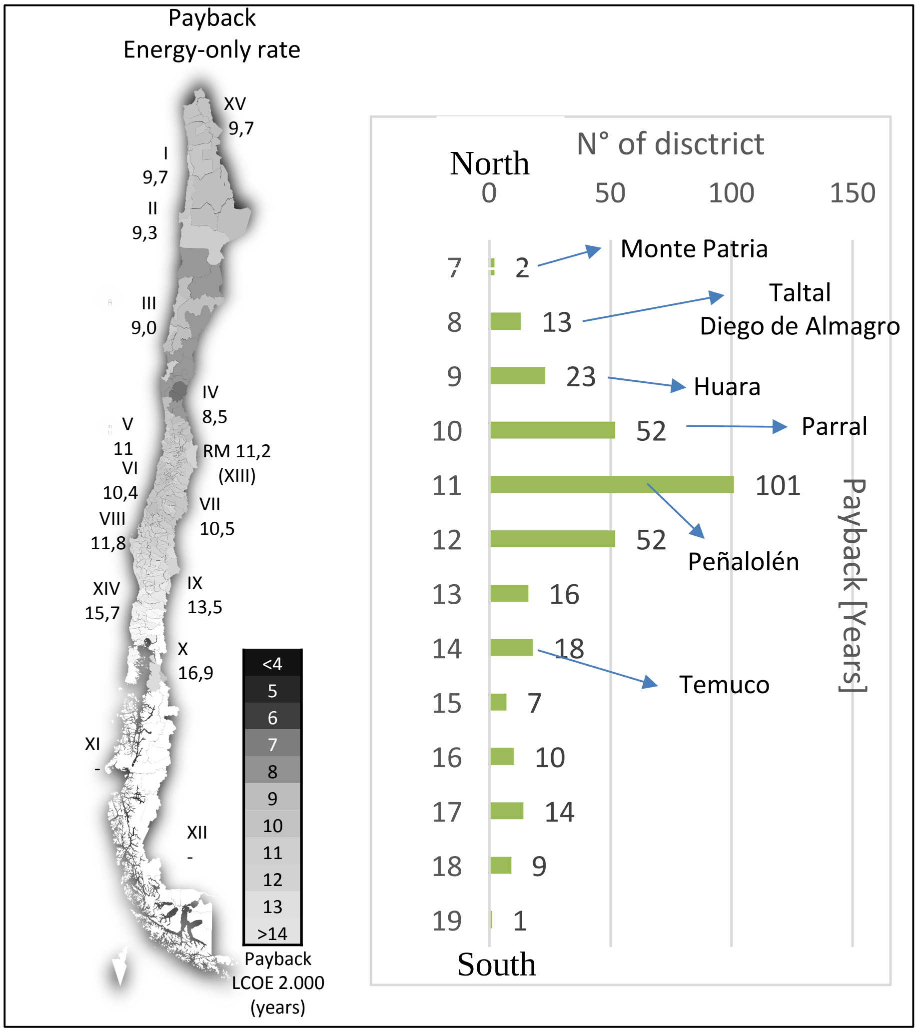


Fig. 1-11: Payback histogram -project 2,000 $USD/kW considering energy only rates (BT2 energy rates)

TABLE 5: RADIATION, NON-RESIDENTIAL RATES AND PAYBACK PERIOD (BT2 ENERGY RATE) CONSIDERING: 2.000 $USD/KWP INITIAL INVERSION, 15,4% EFFICIENCY PANELS, WITHOUT DECAY IN ANNUAL GENERATION

Districts		Captured Radiation kWh/m2					BT2	Payback Period				
		West	North	East	GHI	Opt. Ang.	$\frac{\$CLP}{kWh}$	West	North	East	GHI	Opt. Ang.
I	Huara	1.266	1.303	1.266	2.519	2.640	53,7	18,6	18,1	18,6	9,3	8,9
I	Iquique	1.131	1.101	1.137	2.210	2.279	53,7	20,8	21,4	20,7	10,6	10,3
II	Calama	1.343	1.426	1.338	2.632	2.798	53,7	17,5	16,5	17,6	8,9	8,4
II	Antofagasta	1.115	1.209	1.209	2.210	2.327	53,7	21,1	19,5	19,5	10,6	10,1
II	Taltal	1.167	1.151	966	2.012	2.143	79,6	13,6	13,8	16,4	7,9	7,4
III	D. Almagro	1.265	1.426	1.234	2.432	2.628	62,9	15,9	14,1	16,3	8,3	7,6
III	Copiapó	1.255	1.381	1.050	2.277	2.489	62,9	16,0	14,5	19,1	8,8	8,1
IV	Coquimbo	1.102	1.086	808	1.697	1.861	67,7	16,9	17,2	23,1	11,0	10,0
IV	Ovalle	1.198	1.343	1.017	2.118	2.332	73	14,4	12,9	17,0	8,2	7,4
IV	M. Patria	1.208	1.417	1.128	2.239	2.463	73	14,3	12,2	15,3	7,7	7,0
V	Valparaíso	995	1.009	874	1.691	1.792	59,1	21,5	21,2	24,5	12,6	11,9
RM	Santiago	1.106	1.280	1.105	2.053	2.236	49,9	22,9	19,8	22,9	12,3	11,3
RM	Peñalolén	1.123	1.359	1.122	2.081	2.299	49,9	22,6	18,6	22,6	12,2	11,0
VII	Parral	1.032	1.205	974	1.829	2.011	65,9	18,6	15,9	19,7	10,5	9,5
VIII	Concepción	996	1.242	984	1.781	1.987	56,4	22,5	18,0	22,8	12,6	11,3
IX	Temuco	879	1.008	805	1.478	1.613	57,3	25,1	21,9	27,4	14,9	13,7
X	P. Montt	781	927	746	1.292	1.415	56,8	28,5	24,0	29,8	17,2	15,7

1.5. CONCLUSIONS

Roof-mounted and façade-mounted PV systems for electricity generation in residential and commercial buildings have been promoted worldwide as an important concept for sustainable cities. Considering different radiations and rates, mounting position, optimum and feasible mounting direction, and inclination of PV panels in various regions of the country and the optimal configuration of the projects, the economic profitability of PV-on-building projects was evaluated, with detailed information for 318 districts presented on colored maps and 17 representative districts presented on tables.

PV-on-building project profitability is closely related to the population density, solar radiation in the area, and the rates of the area. With the current rate policy in Chile, by 2014 Chile's most economically feasible area for PV installation is in region III, where high electricity rates and high solar radiation levels co-exist. This set of circumstances makes Chile the only country in Latin America that makes rooftop PV projects economically feasible without incentives.

The average optimum inclination angle for PV panels in Chile is 27° and varies from 16° to 30° depending on the area of the country. The optimal orientation ranges are from 145° to 192°, depending on the characteristics of the location. On roofs with a slope, the photovoltaic modules are installed in parallel to the slope. The radiation captured for a tilt from 10° to 30° and orientation between 140 and 220° range leads to radiation capture departing from the optimum by less than 5%.

Chilean PV projects investment costs have achieved 2.000 $\$USD/kW$, much lower than in the US, and a cost low enough to make this technology competitive.

Façade-mounted PV projects facing north (the best orientation for facade), requires an even lower investment cost to be profitable (less than 1.300 $\$USD/kW$). This means PV costs need to keep going down in order to be feasible in building façades and only projects where the PV modules constituent a part of the building wall or window, so that the cost of materials is considered part of the present structure, would be feasible.

Payback period can be as low as 7.7 years (in Monte Patria oriented skyward installation, parallel to the surface) and as large as 17.2 years (in Puerto Montt for an installation of the same characteristics). Façade installations north side, east and west presents more than 44% extra longer payback period, going beyond the limit of average life expectancy of solar projects (20 years).

Very high electricity prices, very high radiation levels, as well as very low PV investments costs are turning Chile into a photovoltaic paradise, even without subsidies.

2. RESIDENTIAL PV ROOFTOP INSTALLATION IN CHILE: TECHNICAL AND ECONOMIC POTENTIAL

2.1. INTRODUCTION

Chile is characterized by an increasing need for cost-effective energy and very high solar irradiation levels. This combined with photovoltaic (PV) technology development worldwide and consistently decreasing PV cost has led to strong interest in implementing PV generation in Chile. In some countries the deployment of PV systems on the ground has led to heated debate on land use. In Italy, for example, installation of PV systems on agricultural soil was forbidden in 2012 (Tudisca, Di-Tripani, Sgroi, Testa, & Squatrito, 2013). Under these circumstances, rooftop PV systems, as a prospective alternative to greenfield PV development, has drawn increasingly more attention. As a result, there has been an increasing need to identify the generation potential of rooftop PV systems, and evaluate the economic benefits that could be obtained for a specific region, city, or country, providing enough information for investors, and supporting material for regulators to develop incentives and appropriate policies.

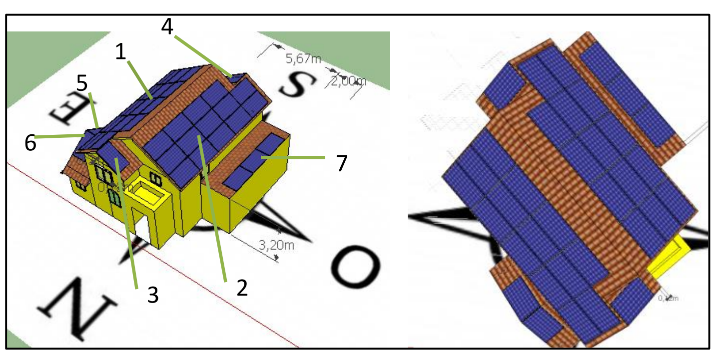


Fig. 2.1-1: Rooftop PV project examples

Several analyses of rooftop PV systems in European countries have been published. They are often focused on generation potential or investment costs. They provide useful information of the future of the technology in some countries, such as Italy and Germany, among others (Tudisca, Di-Tripani, Sgroi, Testa, & Squatrito, 2013) (Schallenberg-Rodríguez, 2013) (Spertino, Di Leo, & Cocina, 2013). In addition to analyzing the technical components of PV systems (modules, inverters, protections, etc.), the technical and economic analysis PV systems for rooftops (see Fig. 2.1-1) requires information about radiation, electricity tariffs, consumption profiles, incentive policies and construction codes, which may vary by city or county. Specific knowledge of local conditions is crucial.

With the support of the Chilean Construction Chamber (*Cámara Chilena de la Construcción, or* CChC) and the Chilean Photovoltaic Node[3], an extensive evaluation of different photovoltaic projects over 318 major districts was performed, identifying the most profitable sites for PV development considering the initial investment and local electricity tariffs for different PV projects, including tilted and horizontal roofs. This paper summarizes the findings of this project.

[3] Organization of main PV developers, government energy officials and universities focused on strengthening the technological networks and the development of distributed PV generation in Chile. Source: http://www.cdt.cl/2012/05/CDT-lanza-Nodo-Fotovoltaico/

2.1.1. Methodology and data sources

Technical and economic evaluation of rooftop PV potentials for each of the 318 counties required the following:

1) Having some knowledge of the location, population, housing styles, etc. Housing styles and the quantity of houses for each county are based on the Chilean CASEN survey (MIDEPLAN, 2014), while population data were obtained from the last national census (2009) (INE, 2012) (Ministerio del Interior, 2014).

2) Obtaining hourly solar irradiation series from the Chilean solar map[4]. For an alternative method to develop this step see Mellit et al. (2010) (Mellit, Eleuch, Benghanem, Elaoun, & Pavan, 2010).

3) Obtaining local electricity rate structure and tariff values (CHILECTRA, 2009) for each utility in the area (from each company website),

4) Computing solar incident radiation according to the inclination and orientation angles of the system, (and according to the possibilities given by roof angles). The solar irradiation model to compute the incident radiation on the roofs is based on Duffie and Beckman (Duffie & Beckman, 1991) and it was codded in MATLAB.

5) Computing generation from a typical PV project.

6) Obtaining examples of electricity consumption profiles.

Since Chile does not have publicly available electricity consumption profiles by customer, a short-term metering campaign was performed to develop representative

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[4] Chilean irradiation data: http://walker.dgf.uchile.cl/Explorador/Solar2/

profiles. Extrapolation to the rest of the year was performed using typical consumption days adjusted by the monthly billing information.

Local electricity consumption profiles were measured for 2 typical clients (a residential apartment and a medium house). In addition 12 different building load profiles were collected using university energy meters, these profiles are assumed to be invariant regardless the city. Depending on solar irradiation, electricity consumption profiles, orientation and availability of area on the rooftop, a PV project was designed and optimized for each building profile type.

7) Comparing building consumption and PV generation for every 5-min period of the year to assess electricity consumption from the grid versus surplus electricity injected into the grid, which sometimes carries different prices.

8) Selecting the proper PV project investment cost.

9) Finally, computing levelized costs of electricity (LCOE), payback periods, and internal rate of returns as economic performance measures of the project.

2.2. CHILEAN SOLAR RESOURCES AND POLICY

PV installation potential depends on the radiation, energy tariff and population. Northern Chile has levels of radiation that exceeds 2.500$kWh/(m^2\ \ yr)$, higher than the maximum annually captured radiation by countries with high PV development projects as Germany and Spain (1.200 y 1.850 $kWh/(m^2\ \ yr)$ respectively).

Highly populated areas have more houses, leading to lower costs for distribution service (economies of scale leading to lower rates). High levels of radiation are found in northern Chile, but the North has less than 10% of the total national population. Rates, radiation and other resources are presented by district similar to the material presented in (Bergamasco et. al, 2011) (Bergamasco & Asinari, Scalable methodology for the photovoltaic solar energy potential assessment based on available roof surfase area: Application to Piedmont Region (Italy), 2011) .

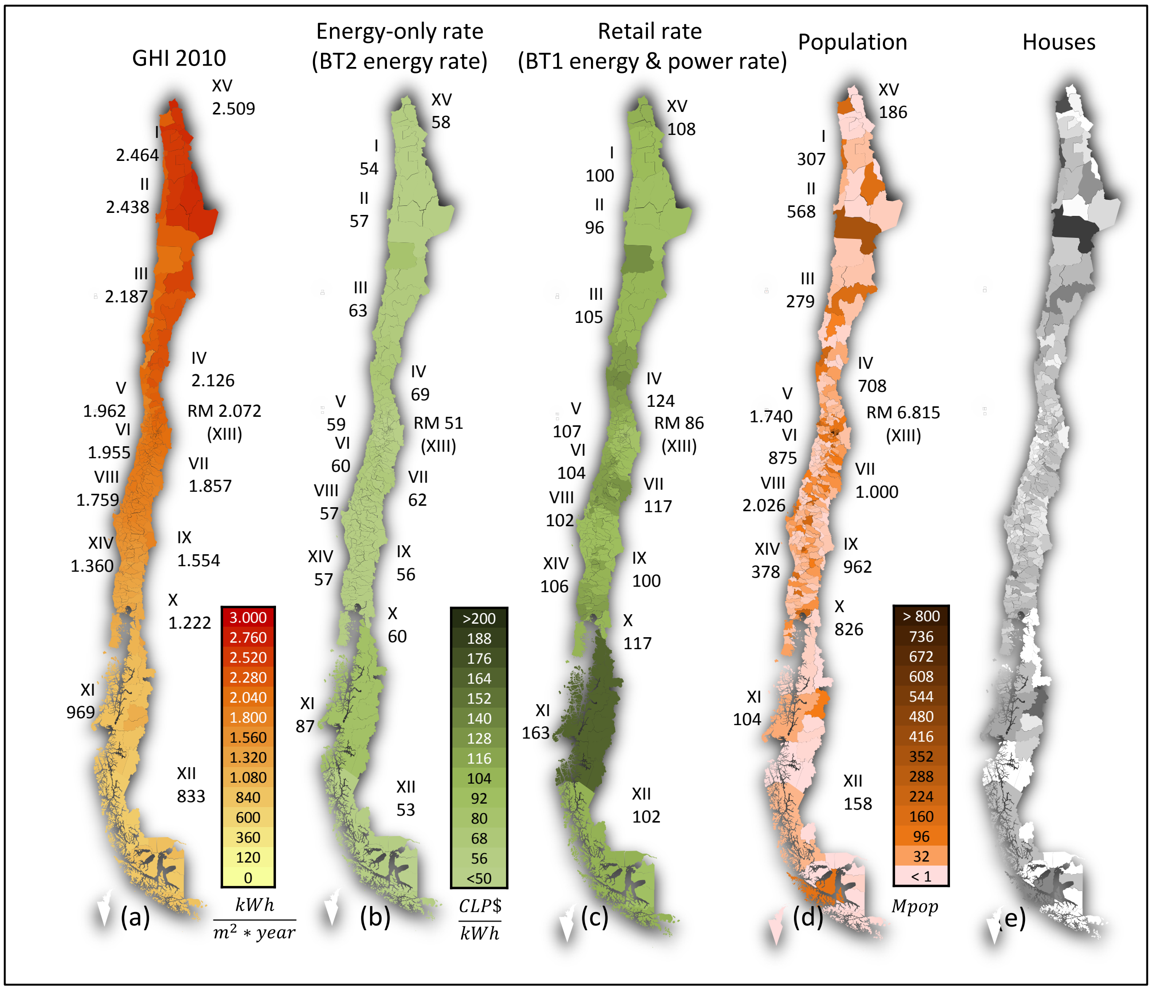

Fig. 2.2-1: Chilean resources - (a) GHI, (b) energy-only rate, (c) retail rate, (d) population, (e) Houses

2.2.1. Annual radiation by districts in Chile

The economic feasibility of PV projects requires high levels of solar radiation. The solar resource in northern Chile has a maximum of 2.676 $\mathrm{kWh/(m^2\ yr)}$), one of the highest radiation levels worldwide. Radiation varies throughout the country, the radiation levels decrease towards the south to less than 730 $\mathrm{kWh/(m^2\ yr)}$ (see Table 1 with the average radiation by region for year 2010). The variation across years for the same place is less than 7% (Universidad de Chile, s.f.). Annual radiation obtained during 2010 is shown in Fig. 2.2-1 (a). Regions in the north of the metropolitan area have an radiation average of over 2.000 $\mathrm{kWh/(m^2\ yr)}$, levels that in European countries are attractive for photovoltaic projects.

Solar radiation depends significantly on seasons; the maximum radiation is captured in summer and the minimum in winter, with differences of more than 50% of monthly captured radiation. The variation in radiation between seasons is sharper in the south than in the north of the country. The average daily radiation per month and region is presented in Table 1.

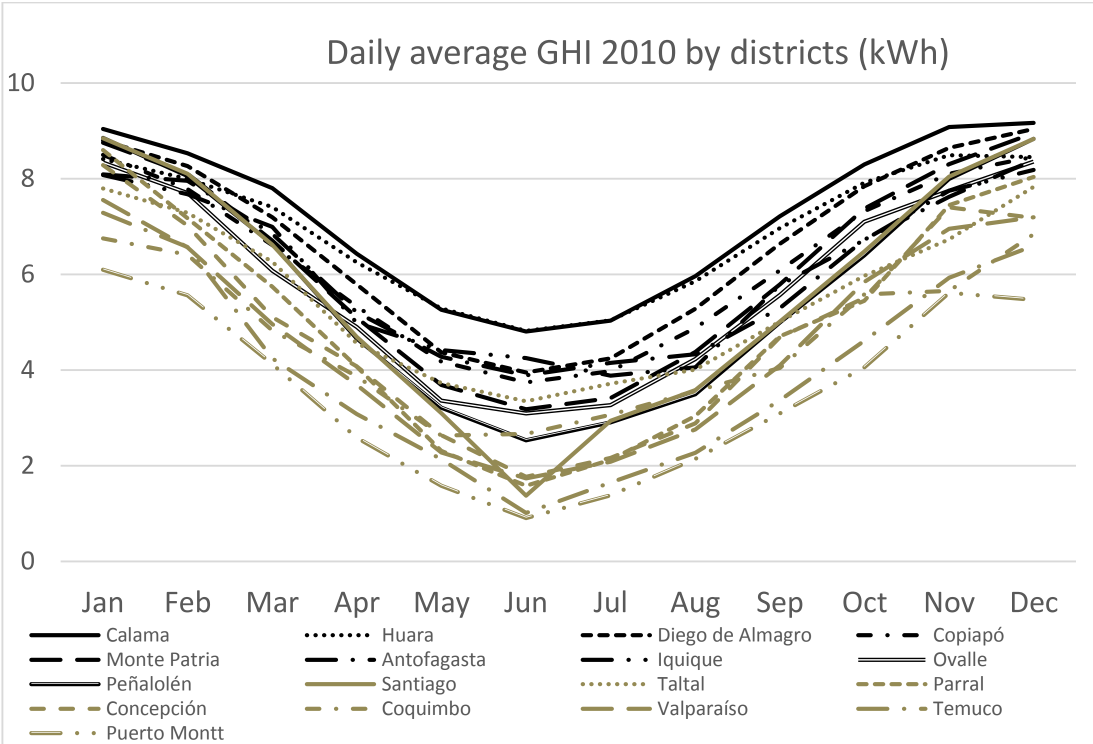

Fig. 2.2-2: Daily average GHI monthly 2010 in Chile by districts

2.2.2. Population, population density and houses by region

Most of Chileans are located in the Metropolitan Region (RM or XIII region) located in the center of the country. This small region contains 40% of the population with an average population density of 14.200 hab/km^2. The amount of roofs in the XIII (RM) region is much higher than districts in the north, however have up to 20% less annual radiation. The most favored area by radiation are regions XV, I, II, III, and IV at the North. However, these regions have less than 10% of the total population with an average population density of 15 hab/km^2. A summary of the population, density of population and homes is presented in Table 1.

TABLE 6: RADIATION, POPULATION, POPULATION DENSITY FOR DISTRICTS AT ALL REGIONS OF CHILE (Universidad de Chile, s.f.), (INE, s.f.)

Region		GHI (kWh/m^2)			M Population /M home inhab.[5]	Pop. Density		
		Min	$\bar{I}$	Max		Min	$\overline{PD}$	Max
XV	Arica y	2.213	2.509	2.676	186,1/164,4	0,2	10	38
I	Tarapacá	2.210	2.464	2.646	307,4/283	0,3	33	143
II	Antofagasta	2.012	2.438	2.690	568,4/178,1	0,1	3	12
III	Atacama	1.801	2.187	2.432	278,5/90,1	0,7	3	10
IV	Coquimbo	1.697	2.126	2.360	708,4/238	0,9	25	144
V	Valparaíso	1.685	1.962	2.206	1.739,9/524,8	5,5	241	2.399
XIII	Santiago (RM)	1.926	2.072	2.152	6.814,6/5.831,1	2,9	4.774	14.200
VI	B. O'Higgins	1.856	1.955	2.045	874,8/809,9	7,2	100	933
VII	Maule	1.780	1.857	1.921	999,7/952,2	6,4	65	1.032
VIII	Biobío	1.550	1.759	1.863	2.027/1.900,7	2	184	1.860
IX	La Araucanía	1.417	1.554	1.778	962,1/ 922,1	2,9	47	644
XIV	Los Ríos	1.282	1.360	1.448	378,2/ 119,5	5,5	26	156
X	Los Lagos	1.071	1.222	1.324	825,8/ 790,4	0,6	30	170
XI	Aysén	772	969	1.177	103,7/ 950,9	0	1	8
XII	Magallanes	730	833	979	158,1/ 142,5	0	1	7
	Country	730	1.818	2.690	16.931,9/15.342,9	0	369	14.200

2.2.3. Chilean electricity rates and policy

Chile has different electricity tariffs schemes for low voltage (<400V) consumers, labeled as BT1, BT2, BT3 and BT4. The variation is explained by the connection capacity (and its overcurrent protection), the metering technology and peak power treatment (peak power can be measured or contracted and limited by overcurrent protections).

Residential consumers have a simple energy-only meter and a retail rate (BT1) high enough to finance both its energy consumptions (E) and its power demand (P). Above

[5] Considering inhabitants with homes (in thousands). CASEN 2011

10kW, different industrial and commercial customers (BT2, BT3 and BT4 tariffs) have separate charges for E and P, according to the peak load pricing theory (see Fig. 2.2-3). Through this formula, the energy consumption tariff (E) is targeted to finance mainly the generation sector, while the power demand charge (P) is targeted to finance the distribution and transmission infrastructure. Unlike Italy or Germany, Chile currently applies no incentive policy for solar power, but electricity prices are high enough (from 2 to 4 times higher than in Midwestern US) to make solar power competitive.

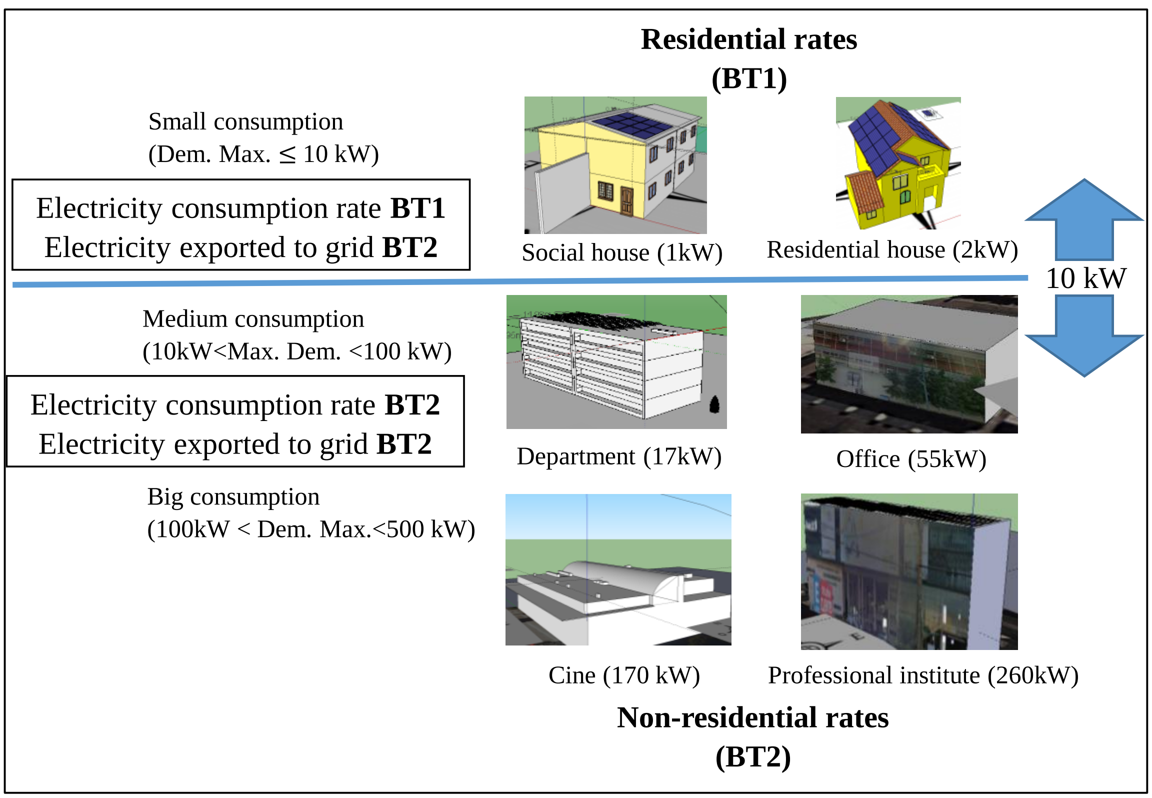

Fig. 2.2-3: Energy-only and residential rates

Electricity tariffs differ in different areas, and the retail tariff (BT1) – chiefly for residential customers – is cheaper when networks have higher density, given that lower investments are required to serve several nearby houses with the same power lines. For larger consumers (BT2, BT3 and BT4) population density does not affect the energy tariff as infrastructure is charged separately (P is split from the E charge). BT3 and BT4 tariffs share the same energy tariff as BT2 clients. In all cases the tariff provides key information for investors to find the best places to locate or promote PV generation. Electricity rates are presented in Table 7 and sorted by value.

TABLE 7: NON-RESIDENTIAL ENERGY RATES (BT2) AND RESIDENTIAL RATES (BT1) FOR DISTRICTS BY REGION. AVERAGE, MAX, MIN IN $USD AND $CLP. (ORDERED BY RATE) VAT INCLUDED

Reg.	Region name	Average Energy Price ($\bar{P}$) Dollar ($\frac{\$USD^*}{MWh}$)		CLP ($\frac{\$CLP}{kWh}$)		Energy Ratio $\frac{Capacity + Energy}{Energy}$
		$\overline{BT2}$	$\overline{BT1}$	$\overline{BT2}$	$\overline{BT1}$	
XV	Arica y Parinacota	115	214	58	108	1.86
I	Tarapacá	106	198	54	100	1.85
II	Antofagasta	112	190	57	96	1.68
III	Atacama	125	207	63	105	1.67
IV	Coquimbo	137	246	69	124	1.80
V	Valparaíso	117	211	59	107	1.81
XIII	Metropolitana de Santiago	100	170	51	86	1.69
VI	Gral. B. O'Higgins	118	206	60	104	1.73
VII	Maule	123	232	62	117	1.90
VIII	Biobío	113	201	57	102	1.79
IX	La Araucanía	112	198	56	100	1.79
XIV	Los Ríos	112	210	57	106	1.86
X	Los Lagos	118	231	60	117	1.95
XI	Aysén	172	322	87	163	1.87
XII	Magallanes y Antártica	104	201	53	102	1.92

Electricity rates are higher in the XI, IV and III regions, but region XI is in the south and has high levels of cloudiness, rain, and thus a very low GHI. Conversely, regions IV and

III have a very high solar radiation combined with high electricity tariffs. Regions I, II and XV in the north have a great GHI but electricity rates are not as high. It’s worth highlighting that the capital city, Santiago, is very densely populated and has the lowest electricity rates in the country; therefore, 40% of the population is facing very limited incentive to engage in PV projects.

2.3. ROOFTOP PV PROJECTS AND ENERGY CAPTURED AS FUNCTION OF MOUNTING ANGLES

The installation of photovoltaic modules on the surface of a house can be done in pitched roofs, flat roofs or facades (see Fig. 2.3-1 a,b,c). The installation of PV modules on pitched roofs tend to be located parallel to the roof surface to minimize installation costs, the same applies with modules located on facades. Horizontal PV modules prevent easy water drainage and increase the amount of dust and dirt accumulation, therefore reducing their productivity. Modules installed on horizontal surfaces include a structure to provide tilt and orientation to avoid the decrease in productivity. Tilt and orientation angle (see Fig. 2.3-1 d, e) directly affects the amount of radiation captured during the year. The economic potential of the installation of PV panels is increased for tilt and orientation angles that maximize the incident radiation.

2.3.1. Effect of the orientation and tilt angle on the total incident radiation

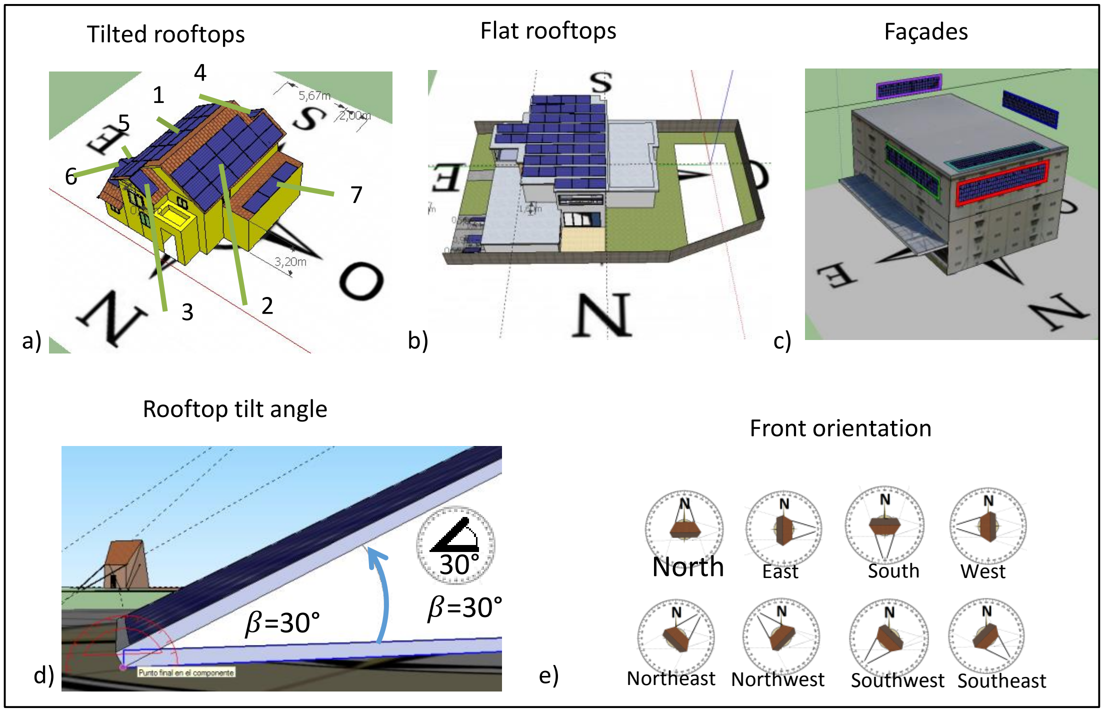

Fig. 2.3-1: Tilted roof, horizontal roof and facade mounting PV projects

The roof tilt angles of the houses depend on each country´s regulations. Regulation defines minimum and maximum according to technical and social requirements. Concerning technical requirements, PV mounting angles must be sufficient to drain the water from rainfall and resist the force of the wind. With respect to social needs, there are certain neighborhoods who want to share similar aesthetic or wish to limit the amount of shade produced on neighboring territories. Chilean standard provides minimum to guarantee rainwater drain and a maximum not exceeding a certain angle from the edges of the territory. The maximum and minimum depend on the rules of each district. Because of rainfall, roofs of households in the South have a higher mandatory tilt than in the north.

Due to the wide range of possible angles to use in each district, a sample of roof angles is required to establish the predominant slope. For the particular case of Peñalolén located in the Metropolitan Region of Chile (District code # 13122), a sampling of the main districts is performed (see Fig. 2.3-2). The most commonly used inclination for roofs in Peñalolén varies between 20° and 40° (see Fig. 2.3-3).

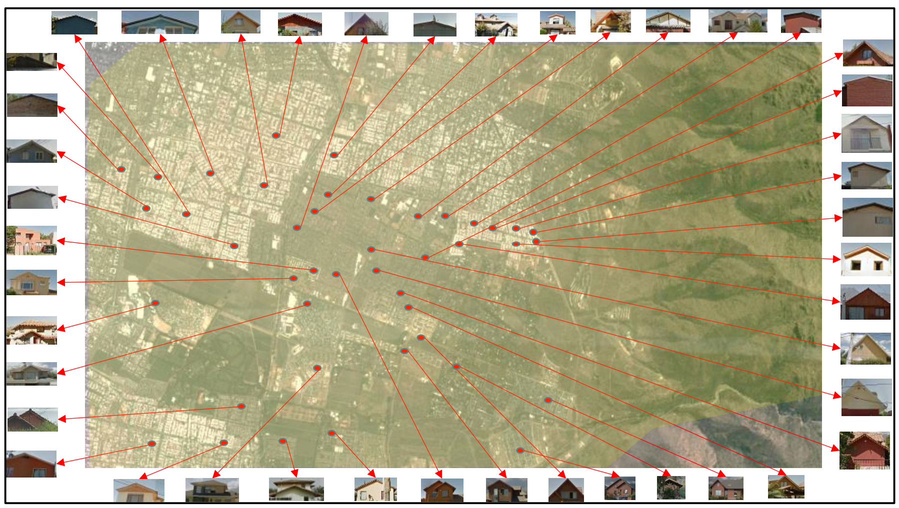

Fig. 2.3-2: Sampling different residential neighborhoods roof slopes in Peñalolén

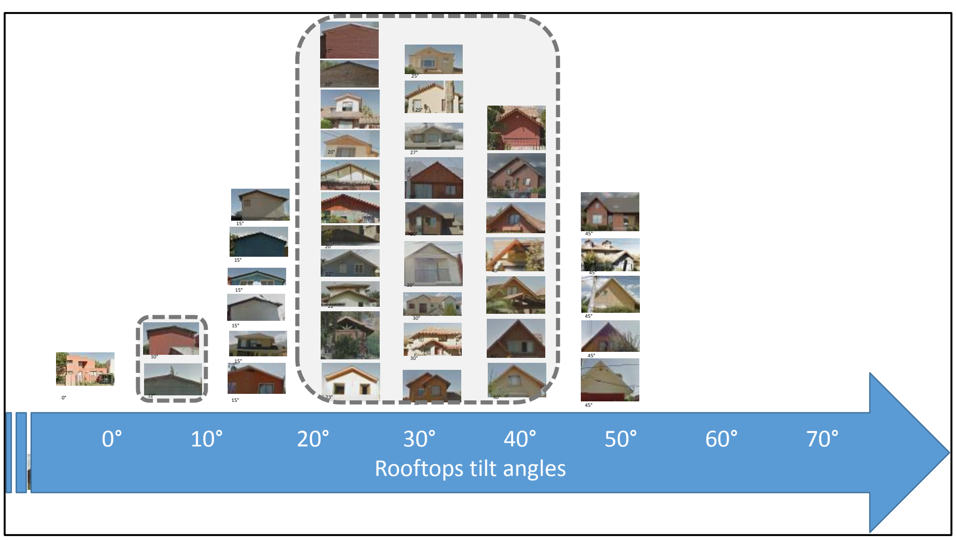

Fig. 2.3-3: Observed roof slopes in Peñalolén (District code # 13122)

The orientation of the construction of houses is varied and depends on the access road. Two identical houses can have very different PV installation potential for different orientations. The particular case of houses with flat roof, orientation influences only in the number of structures that can be assembled according to the geometry of the surface.

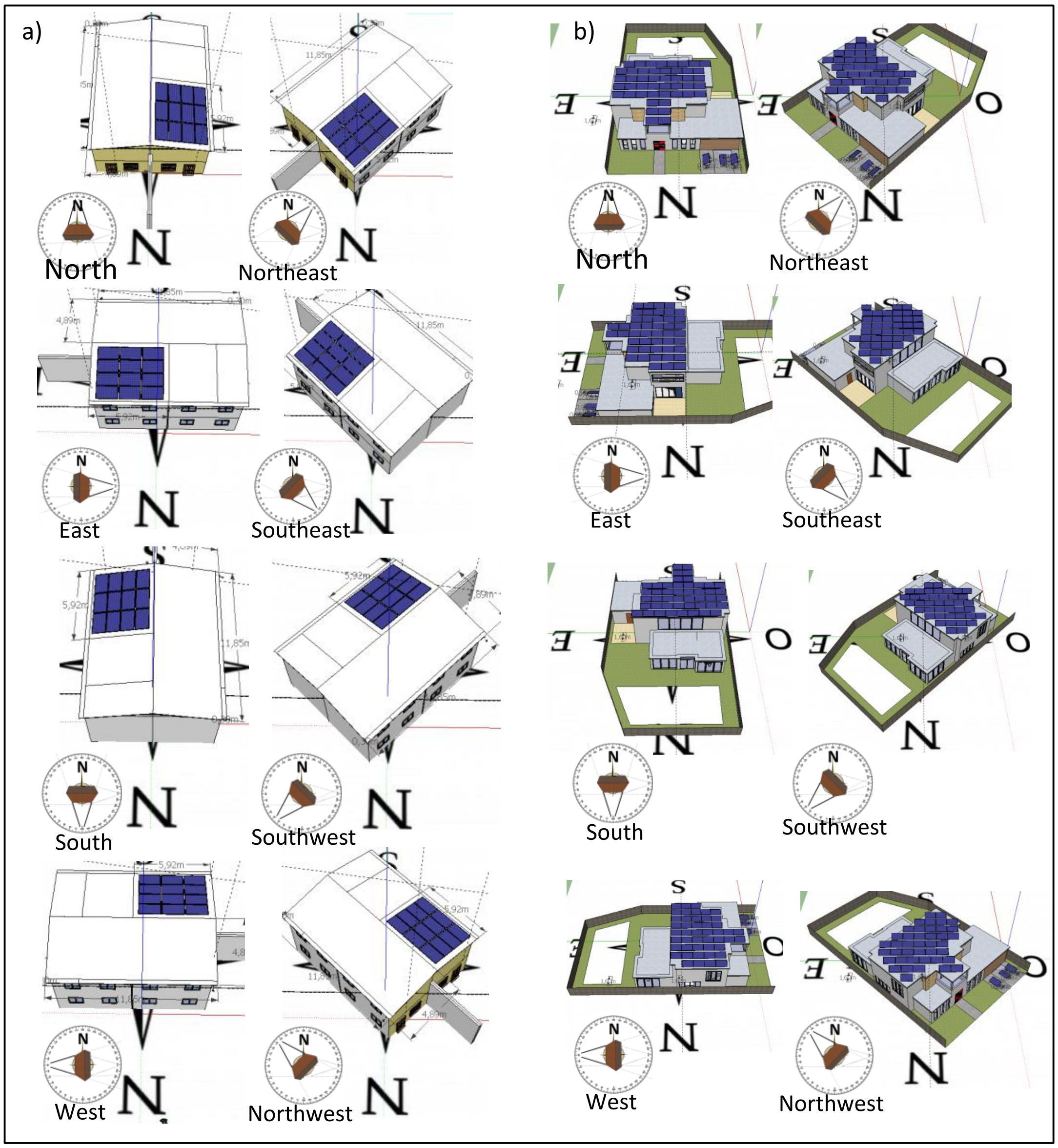

Fig. 2.3-4: different house orientation

Optimum PV panels orientation and inclination angles that maximize photovoltaic generation depend on the geographic location. For example for Peñalolén district, maximum capture radiation occurs for a north facing (asimuth 180°) and tilt 27°. The 5% contour of maximum incident radiation consists of a +-15° range centered on the optimum tilt and between 130 and 210° orientation. In the case of Peñalolen, the orientation and inclination of the roof to maximize the incident radiation is between 12° and 32° (see Fig. 2.3-5).

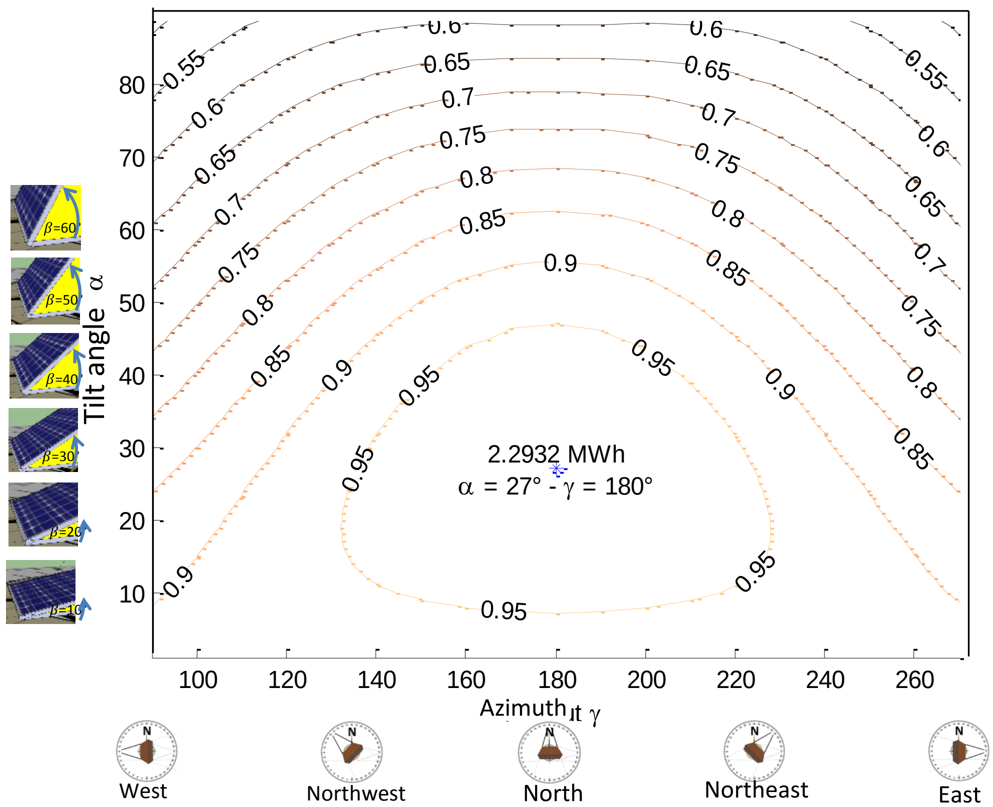

Fig. 2.3-5: Ratio of radiation received to maximum: from tilt angle 0° (horizontal) to 90° (vertical) and orientation from 90° (East) to 270° (west) compared to the maximum radiation received (α=27° γ=180°)

2.3.2. PV modules installed on tilted roofs

For homes with no continuous rooftops, each roof segment can be considered as a separate project. In the 7 segments roof case shown in Fig. 2.1-1, 1x1,6 m^2 modules can only cover at most 62.4% of the total area available, due to the separation edge and the geometry of the roof. Each segment is considered for evaluation in each district, according to those projects whose orientation allows PV generation (see Table 4).

TABLE 8: MAXIMUM SURFACE USED FOR EACH SEGMENT OF AVAILABLE ROOF CONSIDERING FRONT AT NORTH

Orientation γ / Tilt β	Total roof area [m^2]	Used roof area [m^2/%]	Panels [250 Wp]	Total Wp
1 East/270°	30,69	22,7/74%	14	3.500
2 West/90°	30,84	22,7/73%	14	3.500
3 West/90°	3,30	1,6/49%	1	250
4 East/ 270°	3,35	1,6/49%	1	250
5 South/360°	5,34	1,6/30%	1	250
6 North/180°	5,34	1,6/30%	1	250
7 Flat/360°	12,26	4,9/40%	3	750
Total	91,12	56,8/62,4%	35	8.750

PV projects of 2 kWp, 1 kWp y 0.5 kWp are analyzed on the tilted roofs with north orientation and a slope of 30°. Consider the respective inverter system according to the installed peak power (see Fig. 2.3-6). The inverters are connected to an electrical panel with current and voltage protection, and then connected to the local consumption and finally to the meter. The meter connects the home's electrical system to the grid.

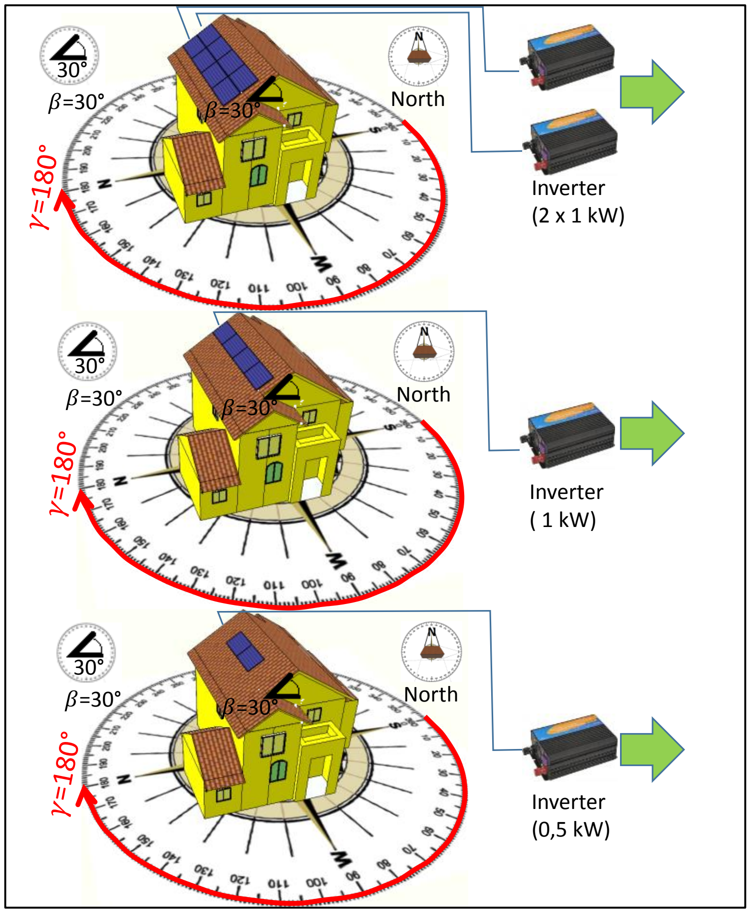

Fig. 2.3-6: PV projects: PV panels and inverter

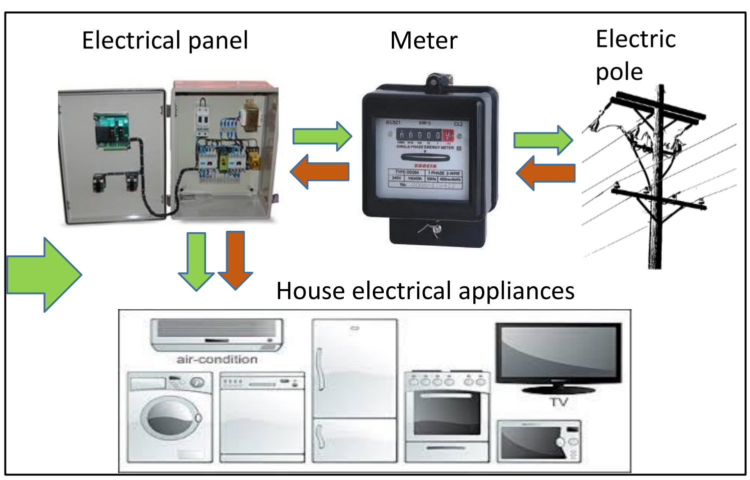

Fig. 2.3-7: Protection, meter, load and connection to the grid

2.3.3. PV generation and consumption

The injection of PV generation to the network corresponds to the surplus between local generation and local consumption. The orientation of the PV module influences the power generation curve. North-east facing photovoltaic generation functions mainly during the morning and facing north-west in the afternoon (See Fig. 2.3-8).

A consumer load curve with pronounced use during the evening is illustrated in Fig. 2.3-8. In this case, the self-consumption is higher for a west facing orientation compared to east orientation. The results presented consider the three projects illustrated in Fig. 2.3-6 de 0,5, 1 and 2 kWp. The orientation of the PV panels is particularly important when generation is larger or comparable with the amounts of consumption.

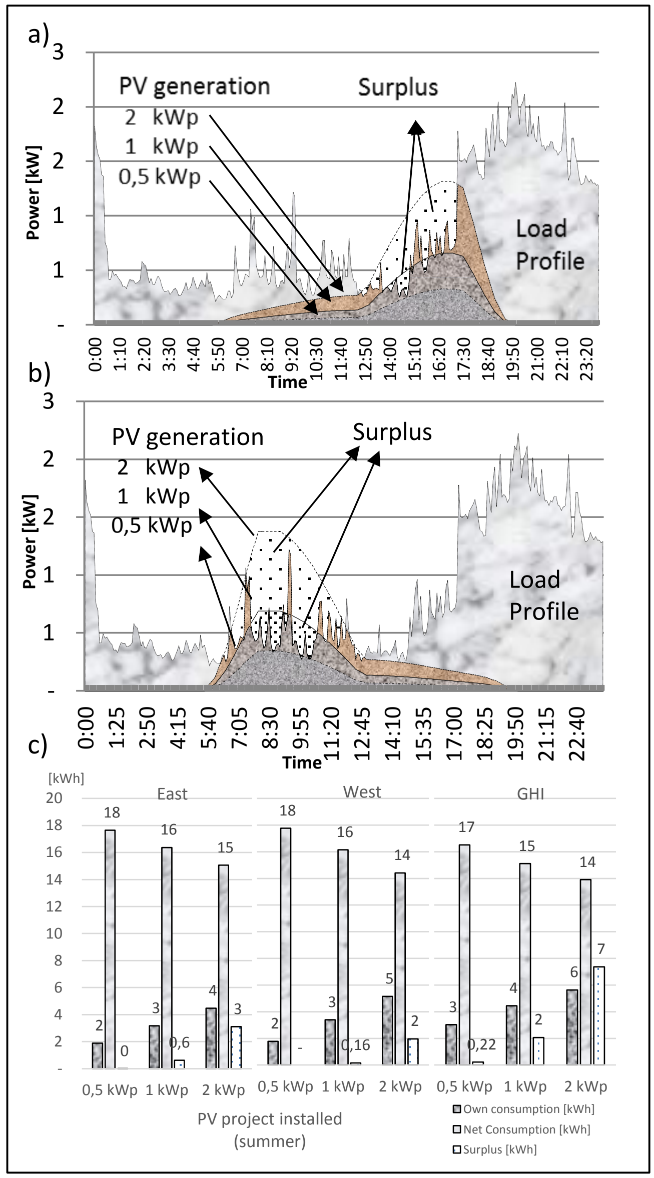

Fig. 2.3-8: generation curve for West and East PV module installation

Daily injected and self-consumed energy is different for each season. In the case illustrated in Fig. 2.3-9, in summer a facing north PV project injects almost twice the energy than in winter.

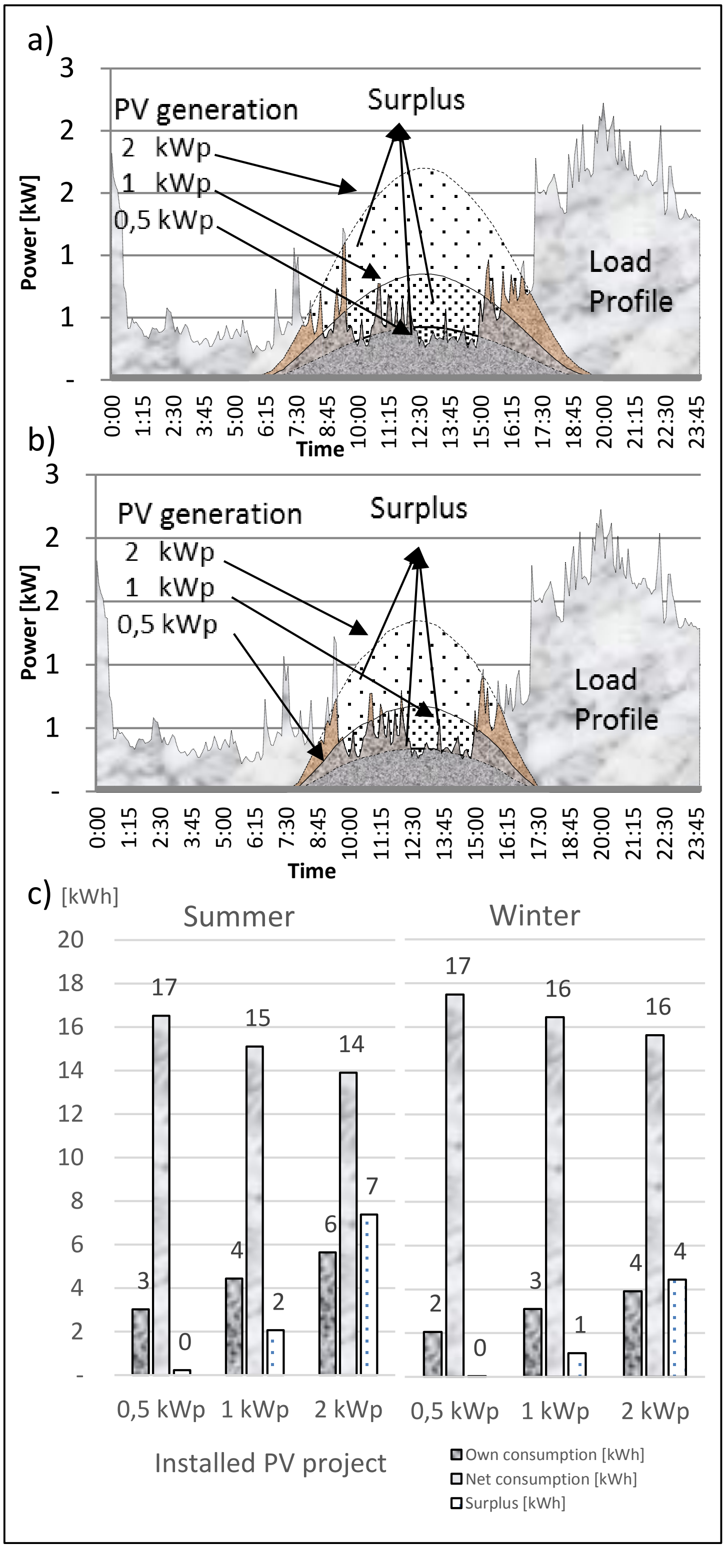

Fig. 2.3-9: generation curve for Summer and winter for a north PV module installation

2.4. RESULTS: CALCULATION OF ECONOMIC INDICATORS

Tilt and orientation that maximizes energy capture for 318 districts are presented, along with economic indicators of payback, levelized cost of energy, maximum investment cost per MW installed, and internal rate of return. Payback of representative districts, which are selected considering latitude, population, proximity to coast and radiation, is presented separately. Each indicator is plotted in colored maps per district to easily illustrate results.

2.4.1. Tilt and orientation that maximizes PV generation throughout different Chilean districts

The inclination and orientation that maximizes the capture of photovoltaic radiation for fixed panels are considered throughout the country (see Fig. 2.4-1 a). The optimal orientation is predominantly north facing, the result range extends from 150 to 200°, due to the characteristics of each district's cloudiness (in the morning, in the afternoon or through the day). Tilt angle from the north to the IV region have optimums between 15° and 27°, decreasing the tilt as they are further north. Tilt maximizing generation is maintained at around 27° from the IV region southward.

The increase on incident radiation for optimally oriented and inclined installation, in relation to a flat one, is from 4 to 12% (see Fig. 2.4-1 b). XV, I, II, III and IV regions have a gain of 4% to 10%, because the optimum inclination differs less with respect to the horizontal plane. From the IV region to the south, the optimum inclinations provide gains between 7% and 12%.

The southernmost part of Chile has greater cloudiness than the north, this causes a major scattered radiation component in the influence of to the total radiation received. The south of Chile is not suitable for PV installations due to a lower total radiation received and the obstruction of clouds.

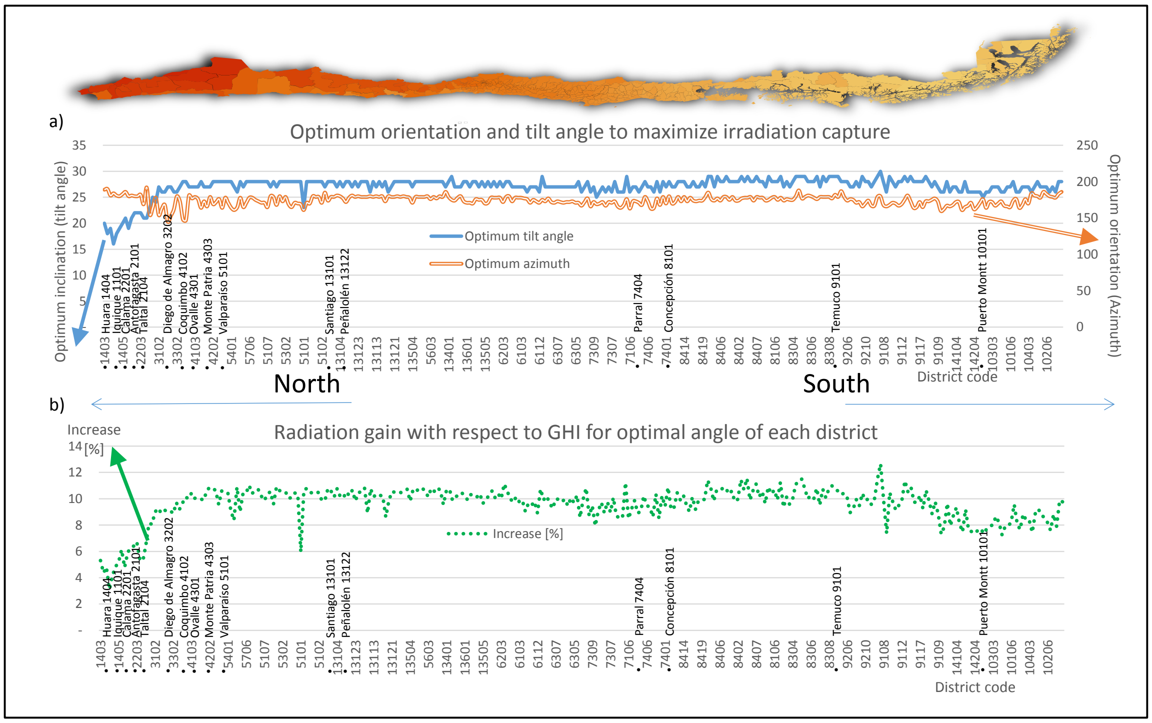

Fig. 2.4-1: (a) Tilt and azimuth angles for maximum radiation capture by districts in Chile, (b) radiation gain with respect to GHI for optimum angles

2.4.2. Payback for different districts in Chile

Payback is deeply linked to the investment cost of the PV project and the incident radiation. Fig. 2.4-2 presents the payback period for 11 inland districts (top) and 6 coastal districts (lower), for an investment cost of 2.000 and 3.000 USD/kW, considering power generation facilities which are completely self-consuming or completely injecting into the network. A longer period of payback can be seen in the coastal sector attributable to increased cloudiness. Payback is longer in the south of the country. Southernmost presented district in the figure corresponds to Puerto Montt with 27-year payback for an investment cost of $ 3,000 / kW, without self-consumption. Shorter payback is located in Taltal, with 5 year for a $ 2,000/kW cost and considering only self-consumption. Changes in the amount of self-consumed energy and cost of the project can double the payback period. The results are the range in which the period of investment is estimated. For more details review Table 10, PB2000 and PB3000 rows.

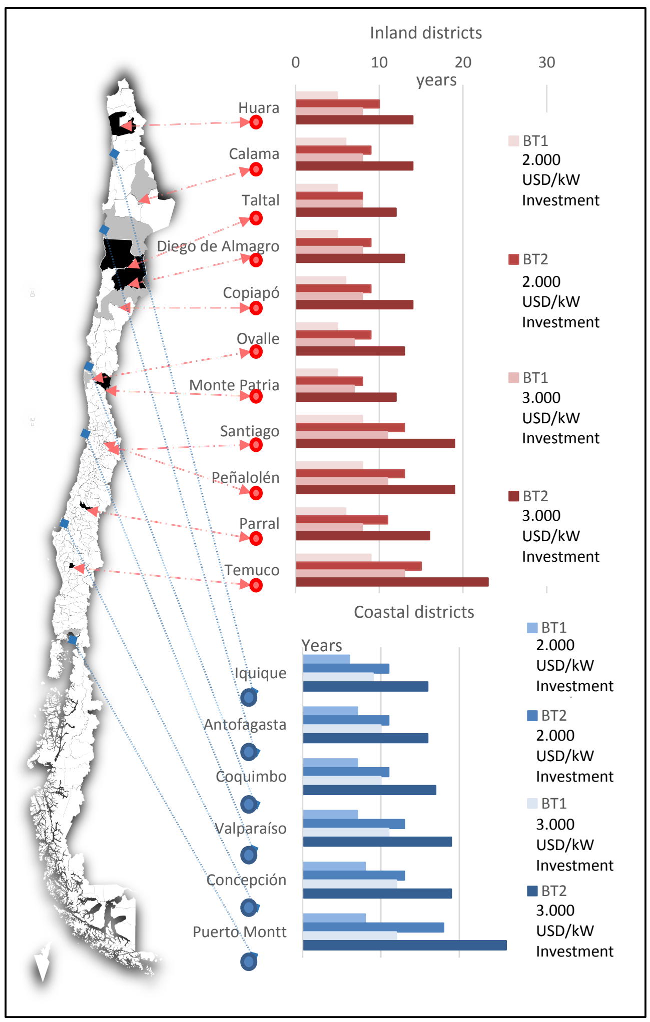

Fig. 2.4-2: Payback range for coast and central districts in Chile

2.4.3. LCOE for different districts in Chile

The “Levelized Cost Of the Energy” (LCOE) represents the price at which electricity must be sold throughout the lifetime of the project to equal the sum of all project costs. Due to the decrease in the PV panels cost, a 2.000 USD/kW is considered as expected value of PV projects, 2.500 USD/kW a typical price and 3,000/kW an easily achievable price in the current market (more than 3.000 USD/kW is considered as expensive). Fig. 2.4-3 summarizes the rate paid by the grid energy injection (BT2 ▲) and LCOE for an investment (●) of 2.000 USD/kW (a), 2.500 USD/kW (b) and 3.000 USD/kW (c) and finally the electricity retail rate (■).

PV project is considered profitable when levelized cost is lower than incomes from energy sales price. Energy sales price is in the range between BT1 and BT2 as the weighted price rate between the injected energy and self-consumed energy (valued at BT2 and BT1 respectively). For example, in the case of the Metropolitan Region at a 2.000 USD/kW cost of investment, the BT2 rate is 51 CLP /kWh, levelized cost is 72 CLP/kWh and BT1 rate is 86 CLP/kWh, for the average of residential installation in the region, the project is profitable if more than 60% of the energy is used for own consumption. Considering Santiago district (see Table 9) the project is profitable if more than 68% of the energy is used for own consumption. In Ovalle it is always profitable. Note that 2.500 and 3.000 USD/kW are not profitable in Santiago district.

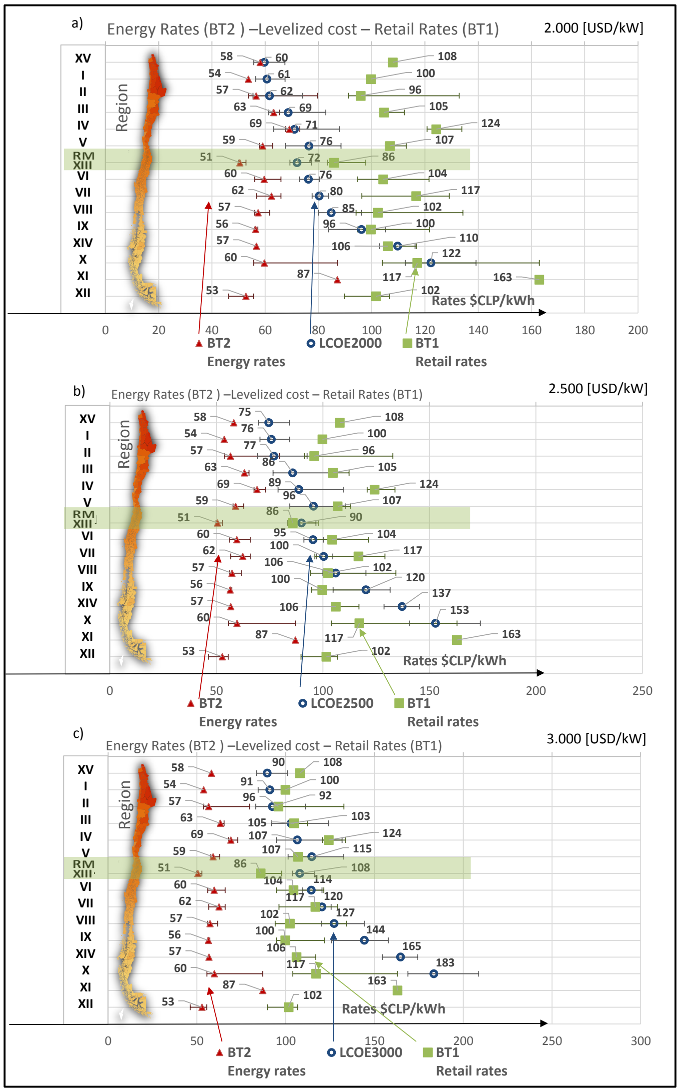

Fig. 2.4-3: Levelized cost and energy rates for different PV project cost (a) 2.000 USD/MW, (b) 2.500 USD/MW, (c) 3.000 USD/MW

TABLE 9: LOCATION, LCOE AND RATES EXAMPLE FOR UNDERSTANDING FIG. 2.4-3

District Region Number/ Region Name	Energy Rate (BT2 rate)	LCOE 2,000 USD/kW	Retail rate (BT1 rate)	LCOE 2,500 USD/kW	LCOE 3,000 USD/kW
Santiago XIII/RM	49,9	72,6	83,5	90,8	108,9
Ovalle IV/Coquimbo	73	70,4	133,9	88	105,6

In northern Chile, 14 districts have a levelized cost less than the BT2 rate considering an installation cost of $ 2,000/kW, which means that even without self-consumption, the project is profitable. In the event that the investment cost exceeds the 2.500 USD/kW, no project district present profitability for pure network injection. By contrast, with a total cost of 1.500 USD/kW, PV systems reach grid parity in most of northern and central Chile (see Fig. 2.4-4).

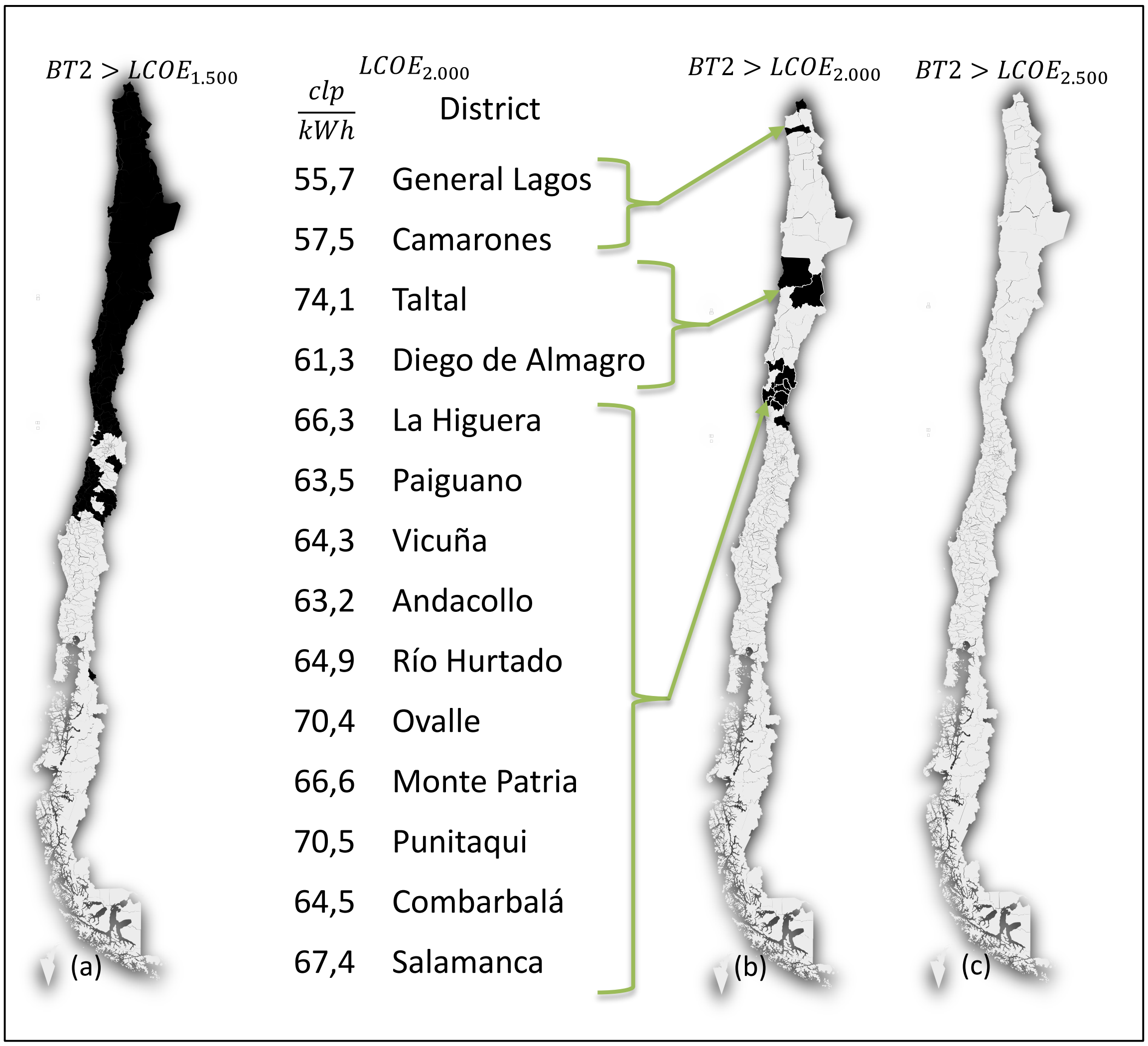

Fig. 2.4-4: Districts whose levelized cost is lower than energy rate BT2 for investment of 2.000 $USD/kW and 10% discount rate (district name; LCOE 2.000)

Full electricity auto-consumption PV installations are profitable for most of the northern country with 2.000 and 3.000 total investment cost (see Fig. 2.4-5) due to high residential electricity rates. Except for Antofagasta, Mejillones, Tocopilla, and Iquique, the north of the country reaches parity with the grid. Costs below 2.400 USD/kW investment allow grid parity from the center of the country to the north. Values lower than 2.000 USD/kW do not reach grid parity in the southern part of the country.

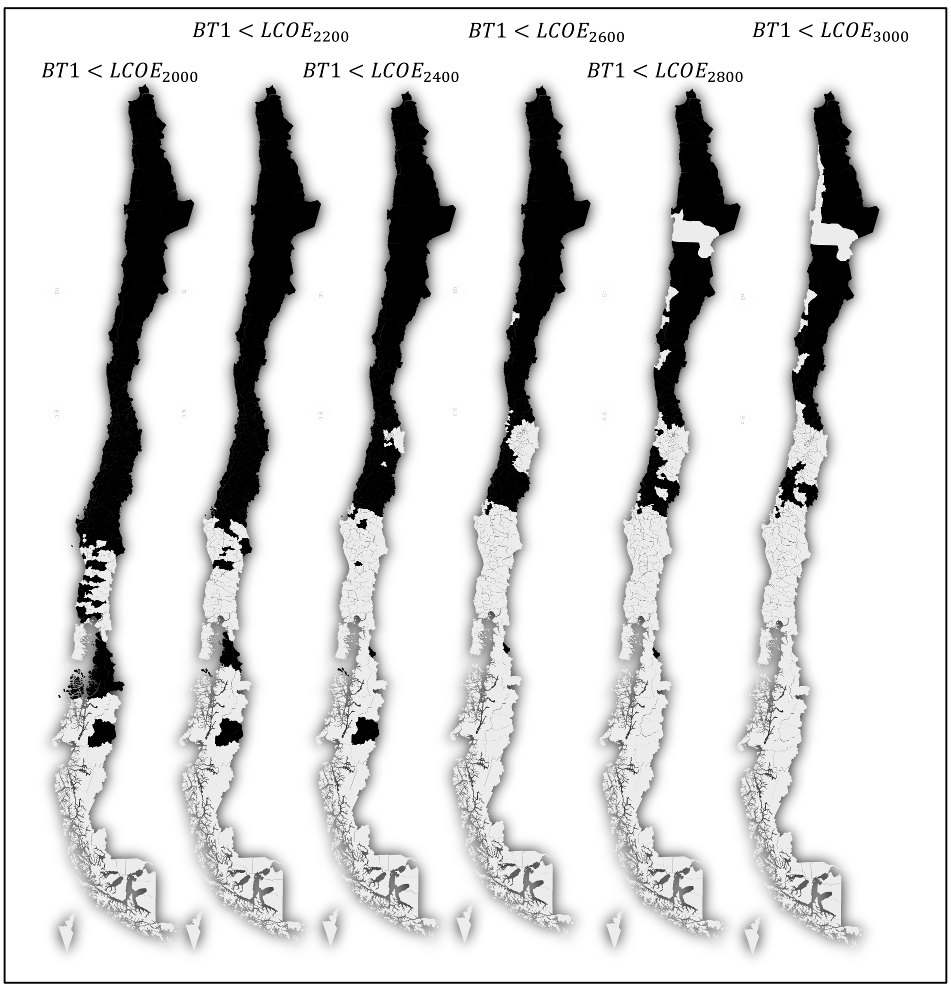

Fig. 2.4-5: Districts whose LCOE is lower than residential rates (for investment from 2.000 to 3.000 USD/MW and 10% of discount rate)

2.4.4. LCOE, Payback, Max investment cost and IRR colored maps.

LCOE, Payback, Max investment cost and IRR are presented in colored maps (Fig. 2.4-6). 35 representative districts are selected due to population, latitude, proximity to the sea and electricity tariff. Representative districts economic indicator are tabulated (see).

Considering the average LCOE for the northern regions of the country, the levelized cost is between a minimum of 41 CLP/kWh in 1,500 USD/kW PV projects and a maximum of 95 CLP/kWh in PV projects of 3.000 USD/kW. Investment payback has a range between 5.3 years (2.000 USD/kW of total cost and self-consumption) and 9.7 years (2.000 USD/kW without self-consumption). Maximum investment cost to reach grid parity without self-consumption is located on region I with a cost lower than 1.800 USD/kW, region II and III less than 1.900 USD/kW and XV region lower than 2.000 USD/kW. The IRR is between 8 and 21%, depending on the installation cost.

Central regions of Chile have less favorable PV projects economic indicators. LCOE range is between 63 and 116 CLP/kWh, payback range is between 6.2 to 11.8 years and maximum PV project cost must be less than 1.500 to reach grid parity without self-consumption of electricity. IRR range is between 7 and 13%, just skirting the minimum expected return (often considered 10%).

From VIII region to the south, LCOE exceeds 80-120 CLP/kWh, the payback period is longer than the useful life time of the project, the maximum price of investment is less than 1.400 USD/kW and IRR does not reach 10%.

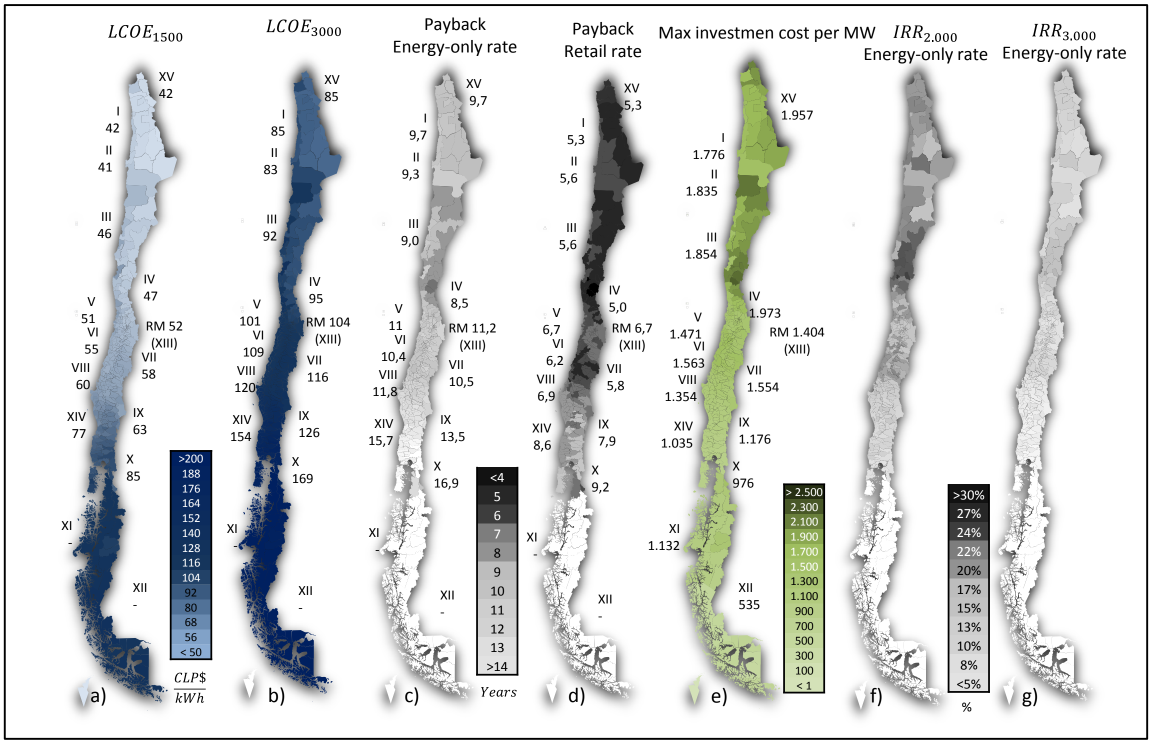

Fig. 2.4-6: PV project economic analysis 2.000 and 3.000 $USD/kW– a,b) LCOE1500 and LCOE3000 (minimum per region) $USD/kW, c,d)payback, e) grid-parity investment cost $USD per MW and f,g) IRR

TABLE 10: 35 DISTRICTS OF CHILE. CODE PRESENTED BY REGION AND DISTRICT CODE

				Angle (°)		Gain	Rates		Cap Energy		Gen energy		LCOE GHI		Payb 2000		Payb 3000		IRR at BT2		Capacity F	
Cod	District	Reg	Pop.	O1	I1	G1	BT1	BT2	GHI	< Opt	GHI	< Opt	2000	3000	BT1	BT2	BT1	BT2	2000	3000	GHI	Opt
1101	Iquique	I	184,838	184	16	3.11	99.8	53.7	2,210	2,279	1,768	1,823	67.5	101.2	5.7	10.8	8.6	16.7	16%	9%	20%	21%
1403	Colchane	I	1,647	189	20	5.31	99.8	53.7	2,646	2,786	2,116	2,229	56.4	84.5	4.6	8.8	7.0	13.5	21%	13%	24%	25%
1404	Huara	I	3,232	181	19	4.81	99.8	53.7	2,519	2,640	2,015	2,112	59.2	88.8	4.9	9.3	7.4	14.2	19%	12%	23%	24%
1405	Pica	I	15,488	183	20	5.17	99.8	53.7	2,526	2,656	2,020	2,125	59.0	88.5	4.9	9.2	7.4	14.2	20%	12%	23%	24%
2101	Antofagasta	II	360,743	192	21	5.28	91.3	53.7	2,210	2,327	1,768	1,862	67.5	101.2	6.1	10.6	9.3	16.4	15%	8%	20%	21%
2104	Taltal	II	10,779	155	23	6.51	132.8	79.6	2,012	2,143	1,610	1,715	74.1	111.1	4.5	7.7	6.9	11.7	21%	13%	18%	19%
2201	Calama	II	148,078	180	22	6.30	91.3	53.7	2,632	2,798	2,106	2,239	56.6	84.9	5.0	8.7	7.7	13.4	19%	11%	24%	26%
2202	Ollagüe	II	251	186	21	6.14	91.3	53.7	2,690	2,855	2,152	2,284	55.4	83.1	4.9	8.5	7.5	13.1	19%	11%	25%	26%
2203	San Pedro de Atacama	II	8,367	182	22	6.73	91.3	53.7	2,629	2,806	2,103	2,245	56.7	85.1	5.0	8.7	7.6	13.4	19%	11%	24%	26%
3101	Copiapó	III	158,081	163	26	9.28	103.8	62.9	2,277	2,489	1,822	1,991	65.5	98.2	5.0	8.4	7.6	12.8	19%	11%	21%	23%
3202	Diego de Almagro	III	12,791	178	24	8.07	103.8	62.9	2,432	2,628	1,946	2,103	61.3	91.9	4.7	7.9	7.2	12.1	20%	12%	22%	24%
3302	Alto del Carmen	III	4,839	180	26	8.88	103.8	62.9	2,348	2,557	1,879	2,046	63.5	95.2	4.9	8.1	7.4	12.5	20%	12%	21%	23%
4102	Coquimbo	IV	206,094	147	28	9.66	120.8	67.7	1,697	1,861	1,358	1,489	87.8	131.8	5.8	10.6	8.8	16.3	16%	9%	15%	17%
4105	Paiguano	IV	4,486	181	27	10.13	120.8	67.7	2,347	2,585	1,878	2,068	63.5	95.3	4.1	7.5	6.2	11.4	23%	15%	21%	24%
4301	Ovalle	IV	110,141	164	28	10.09	133.9	73.0	2,118	2,332	1,694	1,865	70.4	105.6	4.1	7.7	6.2	11.8	23%	15%	19%	21%
4302	Combarbalá	IV	12,484	179	27	10.59	133.9	73.0	2,311	2,556	1,849	2,044	64.5	96.8	3.7	7.0	5.7	10.7	26%	16%	21%	23%
4303	Monte Patria	IV	31,986	173	27	10.00	133.9	73.0	2,239	2,463	1,791	1,970	66.6	99.9	3.9	7.2	5.9	11.1	25%	16%	20%	22%
5101	Valparaíso	V	273,543	161	23	5.96	107.7	59.1	1,691	1,792	1,353	1,433	88.2	132.3	6.7	12.6	10.3	19.6	13%	7%	15%	16%
6101	Rancagua	VI	242,833	179	28	11.13	94.7	56.0	2,045	2,273	1,636	1,818	72.9	109.3	6.0	10.4	9.2	16.0	15%	9%	19%	21%
7101	Talca	VII	238,817	173	27	9.88	115.9	59.3	1,913	2,102	1,530	1,681	77.9	116.9	5.3	10.6	8.1	16.4	18%	10%	17%	19%
7105	Maule	VII	20,695	171	26	8.91	120.4	61.0	1,871	2,038	1,497	1,631	79.7	119.5	5.3	10.7	8.0	16.5	18%	11%	17%	19%
7404	Parral	VII	37,910	173	28	9.92	129.1	65.9	1,829	2,011	1,464	1,609	81.5	122.2	5.0	10.0	7.5	15.4	19%	11%	17%	18%
8101	Concepción	VIII	227,768	178	29	11.55	94.1	56.4	1,781	1,987	1,425	1,589	83.7	125.6	7.0	11.9	10.6	18.4	13%	7%	16%	18%
8301	Los Ángeles	VIII	195,813	177	29	11.50	107.0	57.2	1,789	1,994	1,431	1,596	83.3	125.0	6.1	11.7	9.3	18.1	15%	8%	16%	18%
8401	Chillán	VIII	175,585	176	29	10.87	106.2	57.2	1,829	2,028	1,464	1,623	81.5	122.2	6.0	11.5	9.2	17.7	15%	9%	17%	18%
9101	Temuco	IX	298,575	170	27	9.14	105.6	57.3	1,478	1,613	1,182	1,290	100.9	151.3	7.7	14.6	11.7	22.9	11%	5%	13%	15%
9205	Lonquimay	IX	11,341	180	30	12.65	94.7	56.0	1,778	2,003	1,422	1,602	83.9	125.8	6.9	11.9	10.5	18.4	13%	7%	16%	18%
10101	Puerto Montt	X	230,885	174	28	9.57	121.1	56.7	1,292	1,415	1,033	1,132	115.4	173.1	7.6	17.0	11.7	26.8	11%	6%	12%	13%
13101	Santiago	XIII	171,616	180	26	8.91	83.5	49.9	2,053	2,236	1,642	1,789	72.6	108.9	7.0	12.0	10.6	18.5	13%	7%	19%	20%
13114	Las Condes	XIII	283,226	181	27	10.23	83.5	49.9	2,088	2,302	1,670	1,841	71.4	107.1	6.8	11.6	10.3	18.0	13%	7%	19%	21%
13118	Macul	XIII	100,942	180	28	10.50	83.5	49.9	2,086	2,306	1,669	1,844	71.5	107.2	6.8	11.6	10.3	17.9	13%	7%	19%	21%
13122	Peñalolén	XIII	244,903	180	28	10.47	83.5	49.9	2,081	2,299	1,665	1,840	71.6	107.4	6.8	11.6	10.3	18.0	13%	7%	19%	21%
13203	San José de Maipo	XIII	14,375	186	27	9.56	85.7	50.7	2,054	2,250	1,643	1,800	72.6	108.9	6.7	11.7	10.3	18.1	13%	7%	19%	20%
13402	Buin	XIII	72,480	176	28	10.34	88.2	51.1	2,046	2,257	1,637	1,806	72.9	109.3	6.5	11.5	10.0	17.9	14%	7%	19%	21%
14101	Valdivia	XIV	158,626	168	27	8.73	105.1	56.7	1,448	1,574	1,158	1,260	103.0	154.4	7.9	15.2	12.1	23.8	11%	5%	13%	14%

O1 = Orientation with maximum radiation (with I1), I1= Inclination with maximum radiation captured (with O1), G1= Gain for I1 and O1 respect GHI, Rates = Energy rate for BT1 and BT2 tariff for June 2013, Cap energy = Captured energy per m^2, Gen energy = Generated energy per kW installed, Payb 2000 = Payback at 2000USD per kW installed, Payb 3000 = Payback at 3000 USD per kW installed, IRR= Internal Rate of Return, CapacityF= Capacity factor, GHI = Global Horizontal Irradiance, Opt = PV project mounted with optimum otientation and inclination angle.

2.5. CONCLUSIONS

Residential PV panel installation has proliferated worldwide in conjunction to a tendency to value sustainability. Projects in different tilted roofs, PV project sizes, orientation, installation and radiation, the economic evaluation of PV potential in Chilean residential sector were evaluated. Information is presented in tabular form for 35 representative districts, and the results are illustrated for 318 districts on colored maps.

Technical and economic PV project's potential is related to population density, radiation levels, cost of photovoltaic projects and electricity rates where energy is injected. With the current policy of electricity tariffs for 2014 (without financial incentives from the government), the economic feasibility of PV projects are located in northern of Chile, especially in the III region. Residential PV project with full self-consumption generate energy is particularly economical because of high rates of residential rates, however, there is the risk of not being able to fit the consumer generation. Even without self-consumption, 14 profitable districts for PV projects are identified.

Chilean optimal orientation to place PV panels is between 145° and 192°. The orientation influences the period of maximum PV generation. East PV installation reaches the maximum generation during the morning and west PV installation during the afternoon. The tilt angle which maximizes the radiation is presented for 318 districts. Average tilt angle that maximized incident irradiation is 27°. The northern area of the country has the best performance for inclinations between 15 and 27° meanwhile southern areas between 25 and 30°. Differences in the tilt angle that maximize generation are due to the position relative to the sun and climate aspects such as cloudiness and rainfall. PV rooftops projects having a tilt angle difference lower than 10° from the optimal tilt and an orientation between the north-east and north-west is recommended. Facilities on these roofs show a decrease in the annual cumulative generation of less than 5% from the peak calculated.

The north of the country as some districts as Combarbalá and Monte Patria have a payback period of even less than 6 years for 3.000 USD/kW of installation cost. By contrast, in the southern zone as Puerto Montt district, the payback period exceeds 25 years, meaning it exceeds the duration of the project.

Chile is an excellent place to install PV for projects with access to low cost purchase and installation due to high radiation levels and high electricity tariffs. Without the need of subsidies, there are profitable areas for residential installations, however, the installation of photovoltaic modules is not available to the entire population due to the high initial investment. Enabling the use of this technology in low-income areas requires government participation in terms of sustainable policies or subsidies.

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A P P E N D I X

ANEX A: SUBMITED MAIL CONFIRMATION

14/8/2014

Renewable Energy rene-editor@cut.ac.cy a través de uc.cl

para dwatts98, jtmolina, hren, yarela.flores

Dear Dr. David Watts,

We have received your article "PV Installation on Building Rooftops and Façades in Chile: Technical and economic potential" for consideration for publication in Renewable Energy.

Your manuscript will be given a reference number once an editor has been assigned