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An analysis of renewable energy resources and options for the energy transition in Chile

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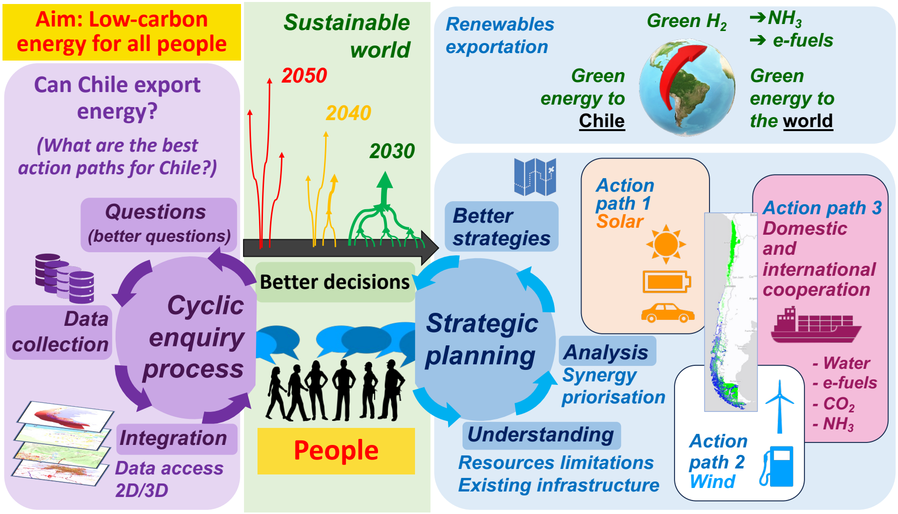
Abstract

This study analyses renewable energy resources, infrastructure, and practical options to accelerate the energy transition and unlock Chile's potential as an exporter of renewable energy and products. We analyse data on the potential of wind and solar energy to determine the best areas for renewable projects. The progress of the energy transition occurring in Chile is reviewed in the context of historical events. The abundant renewable energy resources far exceed current demand and offer exceptional harvesting conditions. However, geographical limitations and a lack of enabling infrastructure may limit the participation of Chile in the world net-zero economy. A comparison is made with the UK to provide a broader perspective. This identifies order-of-magnitude differences in the power available in different locations, highlighting the importance of considering where best to deploy limited resources. International cooperation is required to make the best use of the available renewable energy. Three practical international options to unlock Chile's potential are discussed. Further technical-economic assessment of these energy-transition acceleration paths is recommended. The data and results are integrated into a set of 2D/3D visualisations, facilitating visual insights and enabling a comprehensive understanding of the challenges and opportunities facing Chile.



Highlights

- Data on Chilean renewable energy and energy transition is consolidated.
- Opportunities and challenges for Chile in net-zero economy are highlighted.
- Practical energy transition acceleration paths are identified.
- Prototype user-targeted 2D/3D data visualisations are developed.
- The method used to guide the development of the visualisations is described.

Contents

1 Introduction

In the last decades, climate change and the necessity of reducing the impact on the environment have forced humanity to rethink its activities. One of the most impactful activities is the provision of energy to cities and industries. Renewable energy plays a central role in the sustainable transformation of national electrical grids [43], but unfortunately it is not equally distributed across the globe. The cumulative effect of factors such as geography, climate and weather is such that some countries have better harvesting conditions and/or a greater renewable energy potential than their energy demand, while others need to import energy [61]. Therefore, the provision of low-carbon energy for all people requires us to harvest energy and transport it between countries. This is a challenging task because, in contrast to fossil-fuels, renewable energy has low energy density and requires large areas of land. To deliver renewable energy, extensive infrastructure potentially crossing national borders need to be designed, agreed and constructed. International cooperation is required. In addition, given the extensive resources required [106], investment must be addressed in a strategic and cost-effective manner to make it acceptable in comparison with other needs. Moreover, the magnitude and impact of the enterprise requires coordinating the efforts of different organisations, investors, policy makers, politicians, and the broader society [106], and addressing societal issues such as skills shortages [25] or social conflicts. In this complex scenario, the efficient use of limited resources is crucial.

The magnitude of the energy sources required by developed countries makes it unlikely that they will achieve energy independence using only domestic renewables [34, 61]. Estimates indicate that two-thirds of the total global energy demand can be supplied by renewables [38], with most of the consumption centred in Asia (45%), North America (17%) and Europe (12%) [98]. It is therefore of interest to analyse the possibility of harvesting renewable energy in the most suitable areas of the world so that, regardless of their location, the harvesting conditions offer the highest yield and therefore the lowest price of production. These are the conditions that Chile, a non-industrialised country with a renewable energy potential that vastly exceeds the domestic demand, can offer to potentially become a major energy exporter in the net-zero world. The idea is that a reduced price of production will open up the possibility of energy transportation. Green-hydrogen derived products have been proposed as suitable alternatives for this purpose [34, 94, 105]. This way, renewable energy can be made available in the markets, reducing the world's energy stress in the early stages of the energy transition. The outstanding harvesting conditions in Chile are based on geographical aspects such as the extreme high irradiance in the Atacama Desert and constant high wind speed in Patagonia. Like Australia, Chile has developed strategies to generate an investment ecosystem that promotes the exportation of renewable energy to other countries [10, 19, 72].

However, the quantification of the Chilean opportunities in the net-zero economy is still not clear due to two specific problems. First, renewable energy projects depend on a number of interdisciplinary variables, such as geography, climate and weather, and their viability is affected by socio-political [2, 91], environmental [2, 91] and economical [54] factors. Although data is available, it is allocated in different domains and not organised nor integrated to easily grasp the challenge that means to harvest and transport the renewable energy. For example, data on solar and wind potential can be found independently [24, 107], as well as infrastructure information [50]. The fact that not all data is in one place, with easy access or readily comparable, makes it complex to communicate the opportunities and challenges of different solar, wind or hydro power projects, both at a national and global scale. The Chilean Ministry of Energy has made efforts in the direction of providing information portals [35, 36] with statistics, 2D maps and datasets, but these are not really integrated to make the most of the geographical implications.

Second, there is no overarching analysis of the opportunities, challenges and the sequence of actions that can be practically taken to efficiently implement the installation of the enabling infrastructure required to make use of the abundant Chilean renewable energy [109]. For instance, several recent studies have focused on the local land suitability under different perspectives [2, 91]. Another study suggests that wind energy from the Argentinian Patagonia could help Japan to reach net-zero targets [45]. Worldwide renewable energy road maps are centred on industrialised countries [51, 52] due to their demand. Data on non-industrialised countries like Chile can be found in recent global studies [75] and reports [53, 54], the latter highlighting Chile's curtailment problem without a proper analysis of the opportunities that enabling infrastructure could achieve. In Chile, strong efforts have been made to set up the basis for a societal transformation that enables the production of e-fuels [47] and ammonia [94], but the success is intimately dependent on the investment capacity and the commercial agreements. Moreover, many projects, such as the carbon storage in Iceland [26] and independent costumer/business initiatives [95] compete for the limited resources, and some past initiatives such as the LNG projects have resulted in arguably long-term inefficient solutions [40, 41, 101]. Prioritisation of these projects and the exploitation of synergies will only be possible if there is a proper understanding of the opportunities. Thus, tools that provide comprehensive and communicable views of the data to support the provision of better information to policymakers and investors will help make the most of the limited resources in a timely manner.

The **purpose of this paper** is to analyse the opportunities available to Chile in the energy transition, first, by organising and integrating Chilean data on renewable energy, infrastructure and the historical progress of the energy transition in an accessible way, and second, by making useful comparisons with the renewable energy potential in the UK and proposing synergistic action paths. The remainder of the paper presents (i) a preliminary analysis of solar and wind renewable energy potential identifying the best areas for energy harvesting and typical parameters for these energies, (ii) an analysis on existing infrastructure and its change along key milestones such as policy implementation through the energy transition process, (iii) a critical analysis of the challenges that Chile faces in harnessing the high renewable energy potential of its northern and southern areas, (iv) a comparison with the UK, where we highlight opportunities for a more efficient use of resources that open the door to innovative business models, and (v) a set of recommendations involving three practical solutions to boost the energy transition and to enable a net-zero world more rapidly. These suggestions are oriented to prioritise resource allocation and should receive further attention on following studies. Finally, prototype tools to visualise the results, a user guide, and a detailed description of a hierarchical set of questions that were used to guide the design choices underlying the visualisations are provided as supplementary material.

2 Methods

2.1 Selection of data

Information relating to Chile was collected and integrated to generate a comprehensive understanding of the renewable energy potential and available infrastructure. The data includes information on wind and solar energy resources [24, 107] such as wind speed and solar irradiation, and on energy infrastructure [35] such as energy concessions, gas lines, oil lines, seaports, fuel storage, and energy plants [29, 35]. Elements of civil infrastructure that identify populated areas and are indicative of energy demand such as traffic and transport elements [37], and buildings [50], have also been incorporated. As renewable energy sources depend on weather conditions, we have also included some geographical features such as waterways [37] and terrain relief [63], climate information such as the mean climate temperature [36, 83] and climate infrastructure such as the weather stations [36]. In addition, water storage infrastructure [36] was used to account for water demand and water stress. Country boundaries were taken from the Mapbox database [64]. Data on the location of cities was accessed through the National Statistics Institute (INE) and used to calculate distances [79].

The data are publicly available, often as collections from multiple contributors. This means they are not complete and may contain errors or inconsistencies, but they are useful to provide a better geographical overview than using average values assigned to a specific point or area. Issues that were detected were corrected. Some datasets were adjusted, *e.g.* by renaming them to improve their handling, re-encoding them with QGIS [86] to make them UTF-8 compliant or using PostGIS [84] to convert their coordinate system to EPSG:4326. Details are provided in Appendix A.

2.2 Solar and wind renewable energy potential

A three-criteria analysis was used to identify and quantify the extent of the best areas for wind and solar energy projects in Chile. The analysis explores all combinations of land areas that were rated as ‘good’ or ‘excellent’. The criteria address the most relevant suitability characteristics for wind and solar projects, respectively. In particular, annual wind characteristics, irradiation intensity and climate zones were considered. Furthermore, the long extension and complex geography of Chile, surrounded by sea-channels and mountains, poses a challenge for energy projects. Elevation is therefore another relevant factor to consider in both solar an wind farm projects. Data on elevation, wind speed and capacity factor is provided by the Wind Atlas [107], while solar irradiation is provided by the Solar Atlas [24]. Both databases contain worldwide data, meaning that the calculations could be easily reproduced for other countries. In the case of solar energy, we also included the mean temperature of the climate zone as a criterion.

2.2.1 Ranking criteria for wind energy

Mean wind speed (at 50 m above the ground), capacity factor and elevation were used as suitability criteria to assess the wind energy potential. The criteria are summarised in **Table 1**. The wind speed and capacity factor are independently ranked as good (G) or excellent (E) based on ranges inspired by two types of wind turbines. A location rated EG would therefore have excellent wind speed and good capacity factor characteristics. Good is defined on the basis of sites with wind speeds of approximately 6 m/s and capacity factors in the range 25–35%. Excellent is defined on the basis of turbines that are optimised to take advantage of the strong winds and exceptionally high capacity factors found in Chile, exhibiting best performance at sites with wind speeds in the range 9–10 m/s and capacity factors above 55%.

It is important to note that these excellent conditions are not unique to Chile, as there are other places with similar conditions, such as close to the sea in Uruguay (9 m/s) [16], the coast of Ghana (9 m/s) [4] and some parts of Turkey (7–8.7 m/s) [100]. Note also that a wind speed of 6 m/s is a worldwide standard [49, 59, 61, 88], and that the average worldwide capacity factor for wind power has remained almost constant between 32.4 and 35.9% over the last 10 years, with maximum values between 42-46% around April and minimum values between 24-27% around September, according to 2022 data [27].

Table 1: *Suitability ratings for criteria applied to the analysis for wind farm projects.*

Feature	Wind speed (m/s)	Capacity factor (%)	Elevation (m)
Unsuitable high	> 12.5	-	> 500
Excellent (E)	7.5 – 12.5	0.5 – 1	20–500
Good (G)	4.5 – 7.5	0.33 – 0.5	
Unsuitable low	< 4.5	< 0.33	< -30
Seaside (SS)	-	-	0 – 20
Sea (Sea)	-	-	-30 – 0

Acceptable elevation is defined as 20–500 m. The rational for the lower limit is to avoid coastal areas, where it is assumed that there will be alternative calls on the use of the land. The rational for the upper limit is to avoid mountainous areas (of which there are many in Chile), where is it assumed that there will be little demand for power and where it would be costly to build and maintain facilities. We introduce some additional nomenclature to denote seaside (SS) and offshore (Sea) zones, with 0 to 20 m elevation and 0 to 30 m water depth respectively. The consideration of offshore zones is limited to a depth of 30 m, beyond which is it assumed that it will be less straightforward to install wind farms. These criteria result in 12 combinations of wind speed, capacity factor and elevation.

2.2.2 Ranking criteria for solar energy

Solar irradiation, mean climate temperature, and elevation were used as criteria for the solar projects as summarised in **Table 2**. The higher the direct normal irradiation (DNI), the higher the available solar energy. The DNI is ranked as good (G) or excellent (E). Good is defined as in the range 2000–2500 kWh/m^2/year, and excellent as greater than

2500 kWh/m^2/year. These values are typical of the range of values used in other studies [93].

Temperature affects the performance of solar panels. Optimal performance is usually achieved at temperatures between 20°C and 35°C [6, 73], with testing normally carried out at 25°C [62]. Chile has a north to south extension of more than 4270 km, which means that it experiences a wide range of climate conditions [83] with average temperatures ranging from -5°C to 18.5°C. We define good and excellent as requiring a minimum mean temperature of 11°C, as per Sarricolea *et al.* [36, 83]. Finally, we define good and excellent as requiring an elevation of between 20 and 2500 m above sea level, with a similar rational as for wind, except that it is assumed that higher elevations are practicable because the installation of solar requires the transport of less heavy equipment than wind.

Table 2: *Suitability ratings for criteria applied to the analysis for solar farm projects.*

Feature	**DNI (kWh/m^2/year)**	**Temperature (°C)**	**Elevation (m)**
Excellent (E)	> 2500	> 11	20–2500
Good (G)	2000–2500	> 11	20–2500
Unsuitable low	< 2000	-	-

2.2.3 Estimation of wind and solar energy potential

The land areas with different combinations of wind speed, solar irradiation and capacity factors were calculated across Chile and the UK. The analysis for wind was restricted to areas with capacity factors in the range 35–100%, wind speeds in the range 4.5–12.5 m/s, and elevations between 20–500 m. In the case of solar, it was restricted to areas with DNI in the range 0–3900 kWh/m^2/year and elevations between 20–2500 m.

The resulting land areas were used to estimate the overall renewable energy potential. The power generated by a wind turbine can be calculated as follows [61]

$$\frac{P}{A} = \frac{\pi}{200}\eta_{\mathrm{w}}\rho v^3, \tag{1}$$

where P is the power generated, A is the land area required and η_{w} is the efficiency (assumed to be 50%) of the turbine, ρ is the density of the air and v is the wind speed at the height of the turbine (assumed to be 50 m above ground level). We rearrange equation (1) and multiply by a capacity factor, CF, to find the actual power generated

$$P = \frac{\pi}{200}\eta_{\mathrm{w}}\rho v^3 A \cdot \mathrm{CF}. \tag{2}$$

Note that both the power generated and the land required depend on the diameter of the turbine. However, these dependencies cancel such that equations (1) and (2) are independent of the diameter.

The power available from solar installations needs to consider the area of the panels and the land required to support them. The calculation requires the global horizontal irradiance (GHI), which considers a DNI component and the diffuse horizontal radiation (DIF) caused by the reflection of light from clouds [81]

$$\mathrm{GHI} = \mathrm{DNI} \cdot \cos(\theta) + \mathrm{DIF}, \tag{3}$$

where θ is the solar zenith angle. The calculation is complex because the zenith angle varies with the latitude, time of day and time of year, and the DIF depends on the weather [3]. Given that our aim is to characterise the suitability of the land and analyse action paths for Chile, we make a conservative estimate of the solar potential for the purposes of comparison. We adopt the following equation

$$P = \eta_{\mathrm{s}} \eta_{\Theta_{\mathrm{opt}}} \mathrm{DNI} \cdot A \cdot \Phi_{\mathrm{A}}, \tag{4}$$

where η_{s} is the efficiency of the solar panels (assumed to be 20% [61]), and $\eta_{\Theta_{\mathrm{opt}}}$ is a fixed angle efficiency (taken as 74% [60]) that accounts for the effect of mounting the panels at a fixed angle as opposed to using a tracking system to ensure the panels maintain the optimum angle. A is the available land and Φ_{A} is a factor that describes the proportion of land that can be covered in panels. Values of Φ_{A} between 1/1.3 and 1/1.68 were estimated by considering the shadow cast by a panel mounted 1 m above the ground at the optimal tilt angle [24] for the northern and southern ends of the area in analysis. We conservatively used a value $\Phi_{\mathrm{A}} = 1/2$ based on the examination of a sample of satellite images of solar farms in Chile. Note that most of the best solar areas in Chile are located in the Atacama desert, where clear skies support neglecting the DIF.

2.3 Data integration

The data used in this work was consolidated using tools developed by The World Avatar (TWA) project. The goal of TWA is to create a digital model that represents multiple aspects of the real world to support the analysis of cross-domain problems. The approach includes the use of dynamic knowledge graphs and autonomous computational agents. TWA offers a variety of tools, some of which were used for the analysis of Chile. In particular, the Stack Manager [66] and the Stack Data Uploader [65] were used to process the data used by the analyses and create 2D and 3D visualisations using The World Avatar Visualisation Framework (TWA-VF) [67]. QGIS [86] was also used to support some of the calculations. This work uses a unique approach to organise and communicate the results of the analyses. The approach seeks to answer a hierarchical set of questions. The approach, questions and consequent design choices are described in detail in Appendix A.

3 Results and discussion

Chile possesses vast tracts of land with exceptional conditions for harvesting renewable energy, but the technological challenge associated with this pursuit is not fully understood. These challenges depend mostly on geographical constraints, which are not so easy to appreciate without an understanding of the unique geography of Chile. Therefore, our analysis is focused on understanding the geospatial constraints on the electrical grid and the possibility of its decarbonisation. First, we determined the most suitable areas to develop solar and wind energy projects and discuss the validity of our predictions. Second, we review the progress of the energy transition over the last decades. Third, we discuss the challenges faced by Chile. Fourth, we compare the renewable energy potential of Chile with that of the UK. And fifth, we discuss some recommendations to overcome these challenges.

3.1 Geospatial analysis of renewable energy potential in Chile

Chile is a long country, running approximately 4,300 km north to south. It is divided into five macro-zones: *Norte Grande* (Far North), *Norte Chico* (Near North), *Centro Sur* (Central Chile), *Sur* (Southern Chile) and *Austral* (Southernmost) macro-zones. *Norte Grande* and *Norte Chico* are often also known as the north of Chile. Normally, the *Metropolitana* region is included in the *Centro Sur* macro-zone. The *Austral* macro-zone includes Patagonia, but is sometimes divided into an Austral zone and Southern Patagonia. In the analyses that follow, we refer to the macro-zones except where explicitly stated.

Figure 1 shows the potential for renewable energy in the different regions of Chile. The areas with the greatest potential are located far from populated centres, at both extremes of Chile in the *Norte Grande*, *Norte Chico* and *Austral* macro-zones. The *Austral* macro-zone is abundant in wind energy, both onshore and offshore, while the north is abundant in solar energy. In Fig. 1(c), we highlight the lowlands that are rated as excellent (E) with respect to the elevation wind power criteria. These exhibit the highest population density, mainly in the *Centro Sur* and *Sur* macro-zones. The highlands, with an elevation above 500 m, and the maritime areas, with a depth below -30 m, are labelled unsuitable (U). These areas highlight the geographical challenges, including Andes mountains to the east and the presence of many channels in the south.

The capacity of the Chilean electricity grid and the renewable energy potential are illustrated in Fig. 1(d). The capacity of the grid increased from 22.4 to 32.6 GW between 2018 and 2023, while the share of renewables increased from 42 to 63%. In addition, we estimate that covering 3.6% of the best areas for wind projects would be sufficient to match the 12.1 GW (2023) installed capacity of fossil fuels [29]. In contrast, only a 0.3% coverage of the best areas for solar projects would be required to achieve the same. This is not necessarily surprising as Chilean energy consumption is relatively small, at only 0.27%

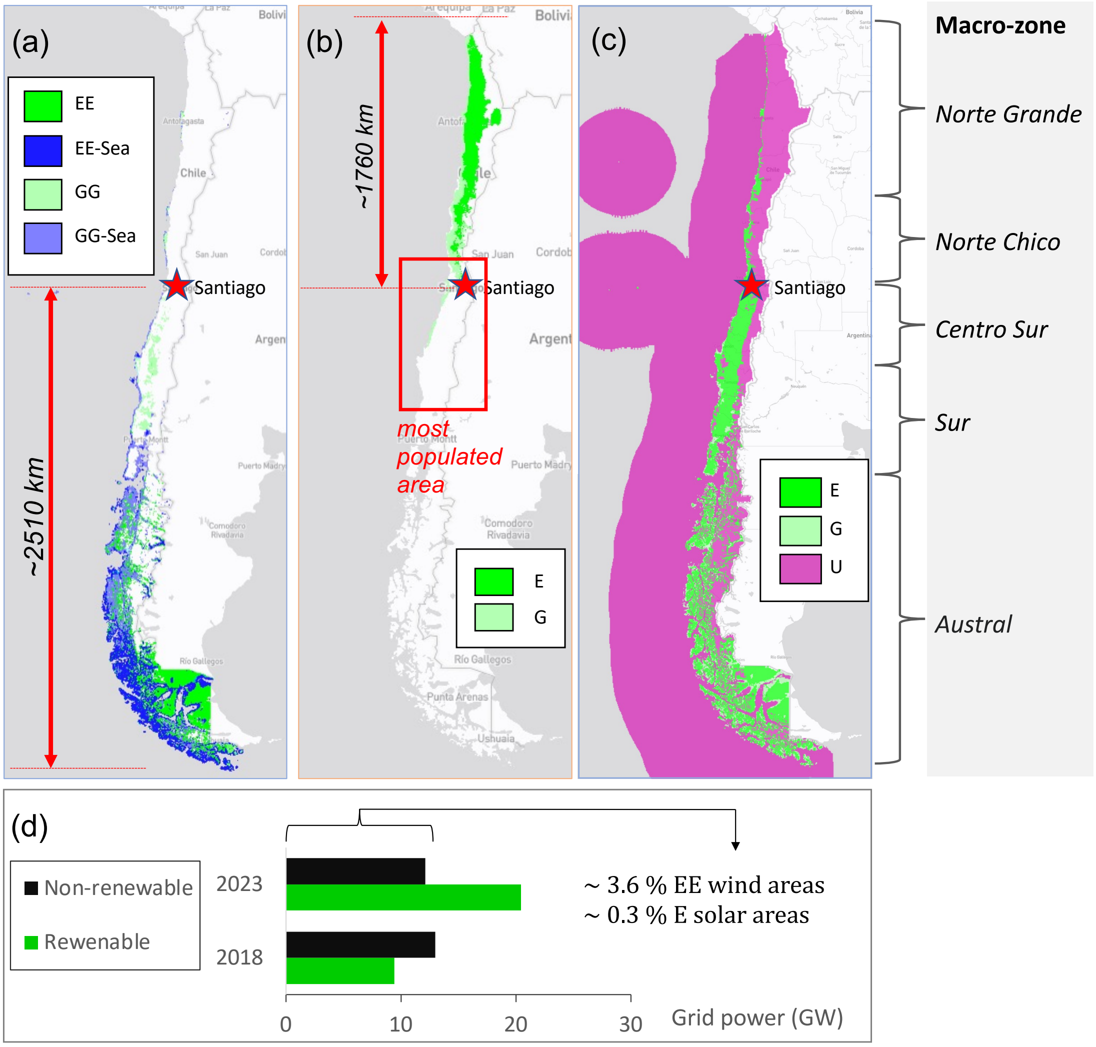


Figure 1: *Renewable energy potential in Chile: (a) best areas for wind projects based on wind speed, capacity factor and elevation (green for onshore, blue for offshore, darker colours represent excellent (EE), lighter colours represent good (GG) conditions); (b) best areas for solar projects based on DNI, elevation and climate (E denotes excellent, G denotes good conditions); (c) elevation suitability for the wind analysis (excellent (E): > 20 m & < 500 m; good (G): > -30 m & < 20 m; unsuitable (U): > 500 m & < -30 m); and (d) comparison between the capacity of the electricity grid in 2018 and 2023, and the renewable energy that could be produced from wind and solar power.*

3.1.1 Solar energy potential

Figure 2 compares the most suitable areas for solar projects with existing infrastructure. The location of the existing infrastructure is largely consistent our assessment of the most suitable areas. In general, most of the solar farms are located within the calculated suitable areas in the *Norte Grande* and *Norte Chico* macro-zones. However, the extraordinary geography of Chile causes some exceptions. These are circled in Fig. 2 and are described below.

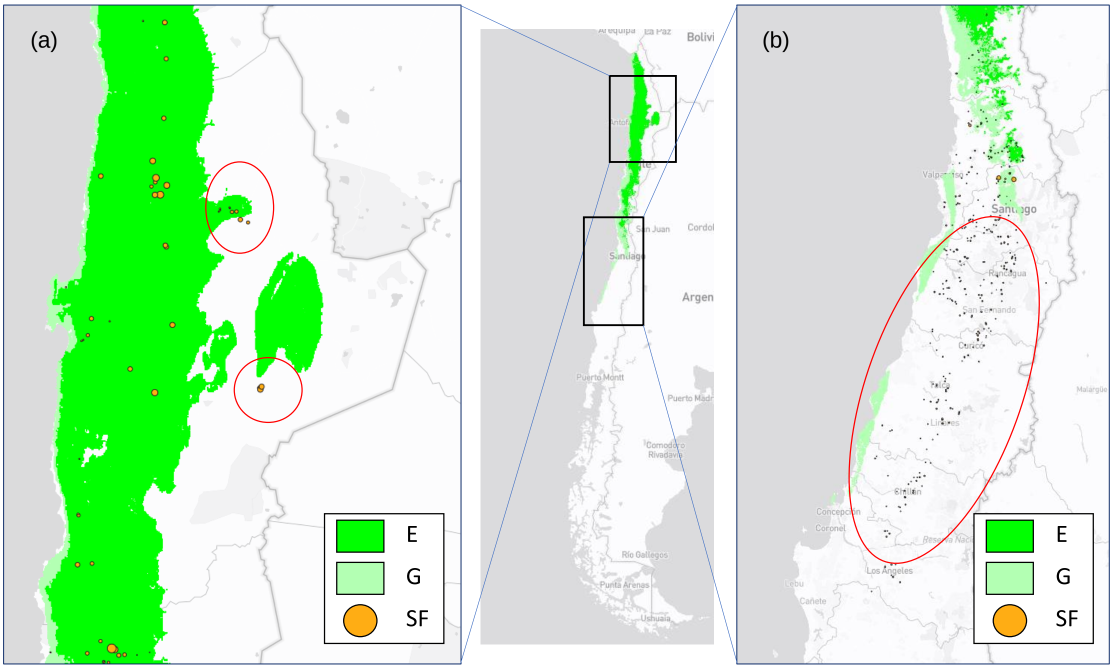


Figure 2: *Good (G) and exceptional (E) areas for solar projects and existing solar farm (SF) infrastructure: (a) plants out of criteria in the region of Antofagasta and (b) small solar farms out of criteria in the Centro Sur macro-zone. The size of the markers showing the solar farms indicates the relative power of the plants in each image.*

Nine solar farms are located in regions with elevations exceeding our chosen criterion. Eight are in the region of Antofagasta in Fig. 2(a). The ninth is a small 2.9 MW plant located in the region of O'Higgins in Fig. 2(b). The reason for these exceptions is the presence of local demand, which motivates the development of local power infrastructure. Antofagasta exhibits high irradiation values and needs power for the mining industry. Its solar farms have some of the highest DNI values among all plants. For example, Sol de Lila, Andes Solar II, Andes Solar IIB and San Pedro are in areas with DNI in the range of 3492–3557 kWh/m^2/year. These are all installations completed after 2021.

More profound differences are seen when evaluating the temperature criterion. Fig. 2(b) shows many small solar farms outside the most suitable area in the *Centro Sur* macro-zone. The mean temperature at the locations of these plants is 11°C, at the limit of our criterion. The best regions, located in Antofagasta and Atacama, have a warmer and drier climate. The total extension of the area rated excellent (E) is 14,164 km^2 and intercepts different climate zones: 57% semiarid, 27% cold desert, 10% Mediterranean, and 5% warm desert. In contrast, the good (G) area has an extension of 133,382 km^2, of which 72.4% is cold desert, 22.9% is semiarid, and 4.8% is warm desert. The solar farms that are out of criteria are located in regions with a Mediterranean climate with winter rains. For completeness, we provide a more detailed colour-coded representation of the criteria in Appendix B, where the best areas can be distinguished from other suitable and less suitable areas. Fig. 2(b) also demonstrates that solar power is being developed in a highly decentralised way. Only 27 out of 471 solar farms have a power greater than 100 MW, while 417 have power less than 20 MW and 260 are small installations with power less than 5 MW. In contrast, as will be seen next, wind farms are fewer and more centralised.

In summary, the selected criteria are consistent with most decisions that investors have taken. However, higher elevations might also be suitable in Antofagasta, and average climate temperatures of 11 °C could be acceptable in the *Centro Sur* macro-zone. The construction of small solar farms in the *Centro Sur* macro-zone provides other practical benefits, as it is closer to the energy demand of more populated cities. Likewise, the solar plants at high elevations in Antofagasta can provide energy to the local mining industry. Nevertheless, conditions for harvesting solar power are more favourable in the north.

3.1.2 Wind energy potential

Figure 3 compares the most suitable areas for wind projects with existing infrastructure. The location of existing infrastructure is largely consistent with our assessment of the most suitable areas, with a few exceptions in the highlands of Antofagasta. There are only 58 wind farms, far fewer than the 471 solar farms. None are located above 2500 m, although nine are located at elevations greater than 500 m, *i.e.* exceeding our elevation criterion. The nine wind farms are relatively new, being implemented since 2014, and have a capacity of 1046 MW. This accounts for 24% of the national electrical capacity. Seven are located in Antofagasta, see Fig. 3(b), and two in Los Lagos. We conclude that our criteria are appropriate, although higher elevations may also be acceptable.

Fig. 3 shows that the regions with the best conditions are in the south, but that they do not have any wind farms. This is because of the distance – about 2,000 km – between these regions and the demand associated with the most densely populated areas. The investment has mainly been in areas that match the international standard defined by our good (G) criteria (see Section 2.2.1). These areas are mostly located on the coast. This can be seen in the GG areas in Fig. 3(c) and (d). Five out of the ten largest wind farms are in Atacama (205, 189, 188, 175 and 168 MW), three in Antofagasta (182, 159 and 155 MW), one in Los Lagos (159 MW), and one in La Araucanía (180 MW). **Table 3** summarises the area available against each ranking criteria. The suitable areas (*i.e.* the total area in Table 3) is equivalent to 21.7% of the total area of the continental territory of Chile.

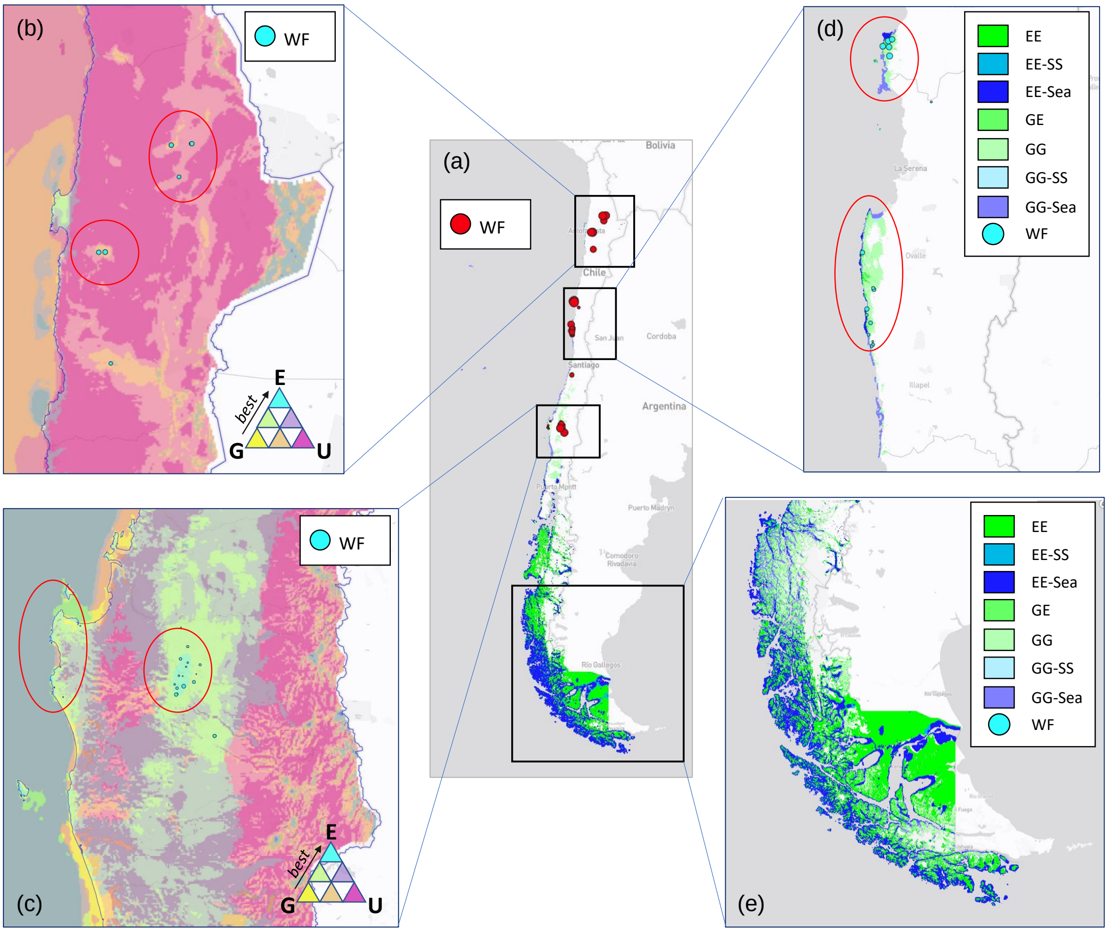


Figure 3: *Good (G) and exceptional (E) areas for wind projects and existing wind farm (WF) infrastructure: (a) region of Antofagasta in Norte Grande zone, (b) region of Biobío in the limits of Centro Sur and Sur zones, (c) region of Coquimbo in the Norte Chico zone, (d) region of Magallanes in the Austral zone. The size of the markers showing the wind farms indicates the relative power of the plants in each image.*

Table 3: *Land area versus ranking criteria for wind farm projects.*

Feature	Area (km^2)	Relative proportion (%)
EE	65,367	40
EE-SS	6,463	4
EE-Sea	30,922	18.9
GE	14,964	9.2
GG	32,021	19.6
GG-SS	2,597	1.6
GG-Sea	11,155	6.8

3.2 Historic analysis of the development of renewable energy in Chile

Chile has faced several energy crises between 1998 and 2014. This was due to a reliance on hydroelectric power and external energy sources [31, 87]. **Figure 4** shows the types of infrastructure additions made since 1999, at which point there were almost equal shares of fossil fuels and hydroelectric power. According to Natorski and Solorio [80], between 1998 and 1999, drought and increased demand caused electricity blackouts. These led Chile to depend on gas supplies from Argentina. A second event occurred in 2007, when a new drought and a cut in gas supplies from Argentina led to new energy disruptions. This perhaps inspired the work of Watts and Jara [104] who explored the potential use of wind power. Since then, regulations have been modified to reduce rising energy prices and make the Chilean economy more competitive. Although a Law on Renewable Energies (LRE) was adopted in 2008 and amended in 2013, not much investment was made during this period, with Fig. 4(a) and (b) showing that only a limited number of wind and solar farms were built. Most new additions between 1999 and 2014 used fossil fuel and hydroelectric power.

In 2014, drought and reduced gas supplies from Argentina [90] triggered another crisis. According to Furnaro [33], OECD data shows that electricity prices increased 365% between 1998 and 2015. At the time, the government and engineering institutions shifted their priorities towards developing a more reliable energy grid. In 2015, a new strategic policy, the Energy 2050 Policy was adopted [80]. This established targets for 2035 and 2050, declaring reliability, inclusiveness, competitiveness, and sustainability as the central pillars of the energy strategy [18]. Among the targets, Chile aims to become an energy exporter and have a grid based on 70% renewable energy by 2050. Since the introduction of the policy, assessments of different energy sources have been carried out, including solar [15, 111], wind [12, 68], nuclear and LNG [20]. These were considered necessary to plan future projects and guarantee the required energy for the country.

By 2015, the opening of the electricity market to renewable energy had made Chile the fourth most attractive country in which to invest in clean energy [33]. As a result, investment in wind and solar projects accelerated and the share of renewables started to increase, reversing a trend that had persisted since 1999. Other government actions included the unification in 2017 of the two major electrical systems, the Norte Grande Interconnected System (SING) and the Central Interconnected System (SIC). The new grid, the National Electric System (SEN), connects the electrical grids from Arica to Chiloé [22]. The impact of these measures is evident in Figure 4(c), where the infrastructure added between 2014 and 2018 includes significant solar and wind installations. The additions are mostly solar in the *Norte Grande* and *Norte Chico* zones, wind in a few coastal sites, and hydroelectric in the *Centro Sur* and *Sur* zones. The addition of fossil power infrastructure was limited, with the data showing that in 2018, the total renewable capacity was 9.4 GW, close to the 13 GW fossil fuel capacity.

Since then a few studies have critically analysed the Chilean energy transition through political-economic approaches. In 2018, Nasirov et al. [77] highlighted the success of the policy reforms even though the renewable projects competed in the markets without any subsidy against other conventional sources of energy. The authors emphasised the need to maintain persistent and consistent government policies and identified addressing

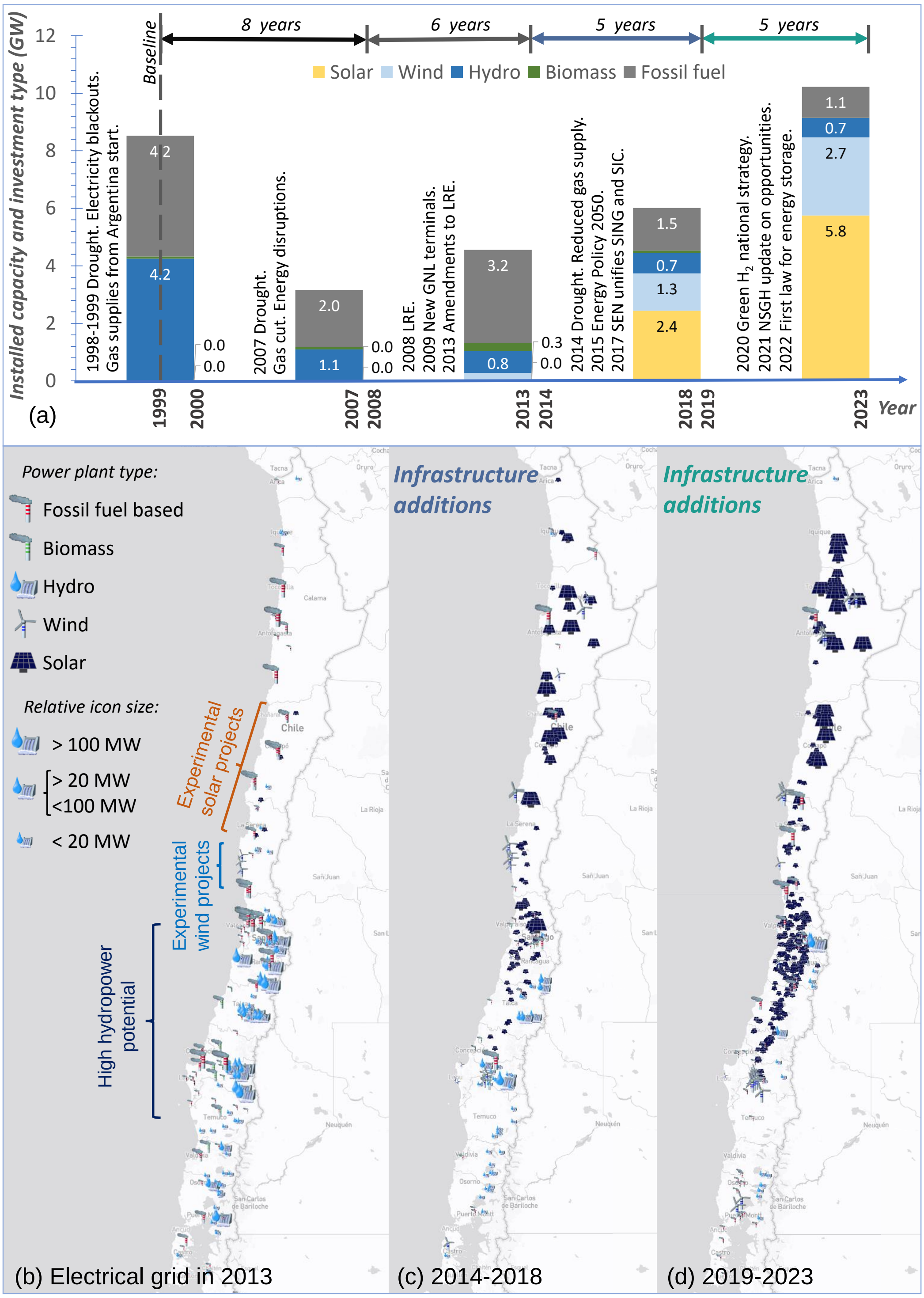


Figure 4: *Development of the energy transition in the Chilean electrical grid: (a) timeline and new infrastructure by energy source, (b) electrical grid in 2013, (c) infrastructure additions between 2014 and 2018, and (d) infrastructure additions between 2019 and 2023. The Austral macro-zone has been neglected due to incipient development and low electricity demand. Raw data taken from [29].*

transmission challenges as critical factors to attract investment. Bustos et al. [13] analysed the potential role of the energy storage systems as possible substitutes for transmission expansions. In 2020, Flores-Fernandez [31] made a critical analysis of the Chilean energy transition focusing on political aspects such as the democratisation and decentralisation of the energy system. The same year, Furnaro [33] analysed the impact of the neo-liberal energy governance, highlighting the quick stimulation of the renewable sector, but also the socio-ecological impacts and uncertainties created by energy projects. These included topics such as large protests across the country against hydroelectric power projects and the focus on centralised electricity delivery to large users as opposed to residential users. Socio-environmental factors were also considered by Vallejos-Romero et al. [102], who analysed conflict and risk management over renewable energies in relation to the trust of citizens, companies and the public sector.

In 2020, the Chilean Ministry of Energy published a national strategy for the development of green hydrogen [72]. The following year, the strategy was updated to include topics on investment opportunities [19]. These highlight the possibility of producing the world's cheapest green hydrogen, inviting investors, and providing information on the key elements that make Chile a suitable location for renewable energy projects. Fig. 4(d) shows strong investment since 2019. Many decentralised solar power additions are visible in the *Norte Chico* and *Centro Sur* macro-zones. In the latter, the new additions coexist with significant hydroelectric power and small biomass power plants, which are linked to the forestry industry in the region. Wind farms are spread from north to south in selected sites, albeit without any significant investment in the extreme south zone. By 2023, the total renewable capacity was 20.45 GW, almost double the 12.1 GW fossil fuel capacity [35, 36]. At the moment, re-purposing of fossil-fuel installations (*e.g.*, for the combustion of green hydrogen) is being considered to support renewable energy, while energy storage is crucial to warrant the reliability of the system.

In recent years, more transmission lines have been announced to boost solar projects that could feed the central and northern areas [39, 58]. More recently, the government has declared the start of a new stage in the energy transition [76]. As investment in solar energy has been successful in the north of Chile, the focus should be placed on energy storage. Storage methods including water pumping, batteries, compressed air, flywheel energy storage, hydrogen, and thermal energy storage are being considered [23], and a new set of policies are being discussed to warrant a set of rules that promotes long-term investment. The first energy storage law was published in November 2022 [70]. The law contains relevant information on the pricing of the stored energy and the control model. According to Sauma [92], it is not clear whether the same control system should be used for every storage system; this decision will impact the incentive for investors.

In the southern end of the *Austral* macro-zone, the pilot production of green hydrogen by electrolysis using renewable energy has started as a first step towards the energy transformation. In a second step, the hydrogen is converted into other products that are easier to handle and to transport, in particular e-fuels [47]. The installation is working to demonstrate the process, gather data, prove interest in the business and develop human resources in the field. Other projects in development are planning to fabricate ammonia [14, 94] and methanol [69], and there is already a methanol factory in the vicinity. These products could be transported by sea. According to the Chilean Green Hydrogen Strategy, the area could provide the cheapest green hydrogen in the world, an advantage provided by the exceptional potential for wind power. Cheap carbon-free electricity has been identified as the main challenge for CO_2 capture and utilisation systems [1], which has motivated plans to capture CO_2 [46].

Chilean institutions such as the Ministry of Energy and the Chilean Economic Development Agency (CORFO) have actively worked to promote the energy transition. They have promoted networking activities between companies, investors, policymakers, politicians, state institutions, educational institutions, and others. Active debate and communication have been promoted through many seminars organised by public and private institutions. Some of these have focused on discussing the local problems and opportunities of the different zones of Chile [32, 89].

3.3 Comparison with the UK

A comparison with the renewable energy potential of the UK was made on the basis of the land availability for different combinations of the criteria described in Section 2.2.

Figure 5 shows our analysis for solar energy. Fig. 5(a) shows the impact of the criteria in Chile. For example, considering only elevation gives a modal DNI between 2000 and 2100 kWh/m^2/year. If we add the average temperature criterion, most land with DNI in this range is now excluded. The modal DNI is now greater than 2850 kWh/m^2/year, which is consistent with Chile having some of the highest DNI measurements in the world [111]. Our good (G) and excellent (E) rankings, which require DNI greater than 2000 and 2500 kWh/m^2/year respectively, include most of the areas identified by the elevation and climate criteria. Fig. 5(b) shows the situation in the mainland UK mainland. There is no land available with DNI higher than 1000 kWh/m^2/year. To facilitate further comparison, Fig. 5(c) shows a parallel axis that indicates the relationship between the DNI and power available as a multiplier of that available at 950 kWh/m^2/year, approximately the maximum DNI in the UK. We observe that a large amount of land in Chile offers more than three times the maximum solar power density available in the UK.

Figure 6 shows our analysis for wind energy. The analysis shows the land available for the intersection of the mean wind speed 50 m above the ground and capacity factor. Each wind speed interval is labelled by its mean, for example, 5 m/s represents the interval 4.5–5.5 m/s. In the case of capacity factor, the labels show the minimum value for each interval. In the case of Chile, Fig. 6(a) shows significant areas in the range 5–6 m/s with 30% minimum capacity factor, which is the typical international standard. However, there are also significant areas with much better characteristics. The maximum availability is 10,960 km^2 with a wind speed between 8.5 and 9.5 m/s and a minimum capacity factor of 60%. Fig. 6(b) shows the situation in the mainland UK. The UK has 55,653 km^2 with wind speeds between 6.5 and 7.5 m/s and a minimum capacity factor of 45%. This corresponds to a higher wind potential than the worldwide standard. This information could be useful to estimate demand limits when fabricating wind turbines at a large scale.

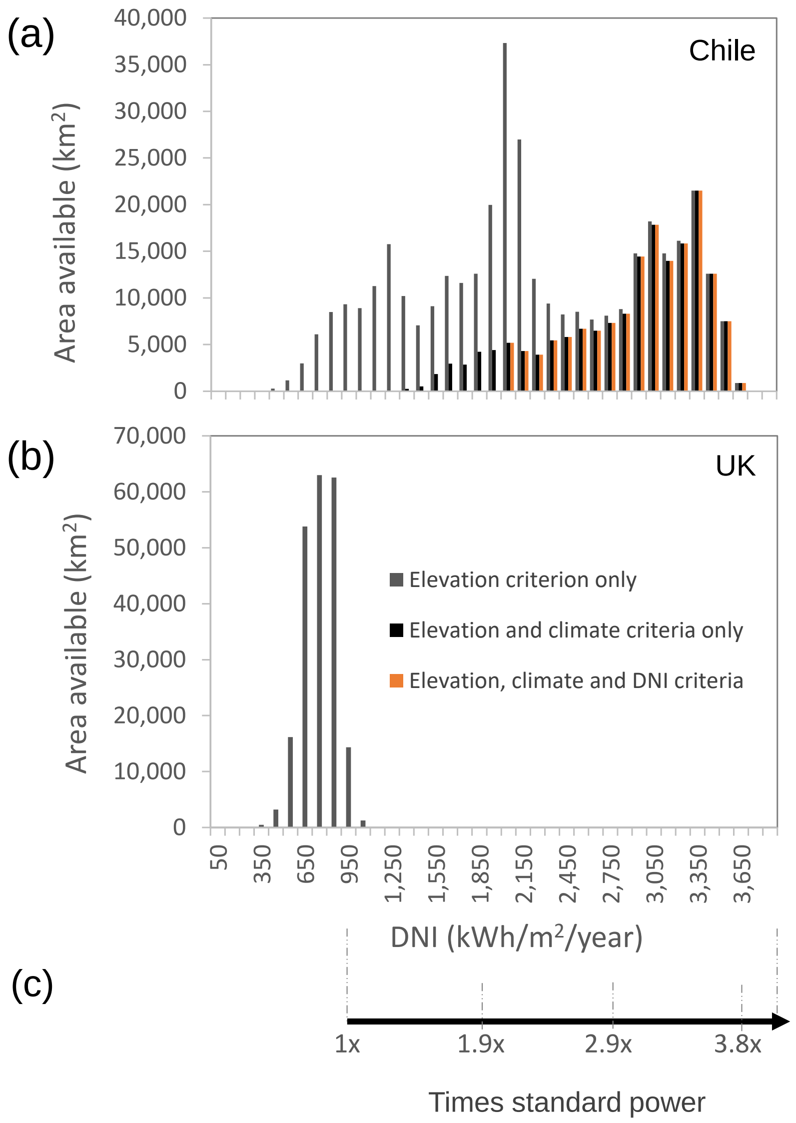


Figure 5: *Solar power characterisation: (a) Chile, (b) UK, and (c) power to DNI reference axis.*

To facilitate further comparison, Fig. 6(c) and (d) show reference axes that indicate the power available as a multiplier of the power at conditions based on the international standard of 5 m/s and 30% capacity factor. The power varies as the cube of the wind speed, such that locations in Chile with mean wind speed between 8.5 and 9.5 m/s and a minimum capacity factor of 60% could operate at more than six times the power density of the world standard. This highlights the distinction between the areas rated good and excellent. As shown in Fig. 1, the good (G) areas are located in the *Centro Sur* and *Sur* macro-zones, whereas the excellent areas (E) are located in the *Austral* macro-zone. In addition, there is some land with capacity factor above 65%. The higher the capacity factor, the more constant is the energy supply and less storage is required. However, these areas are isolated from populated centres, so it would still be necessary to transport the energy.

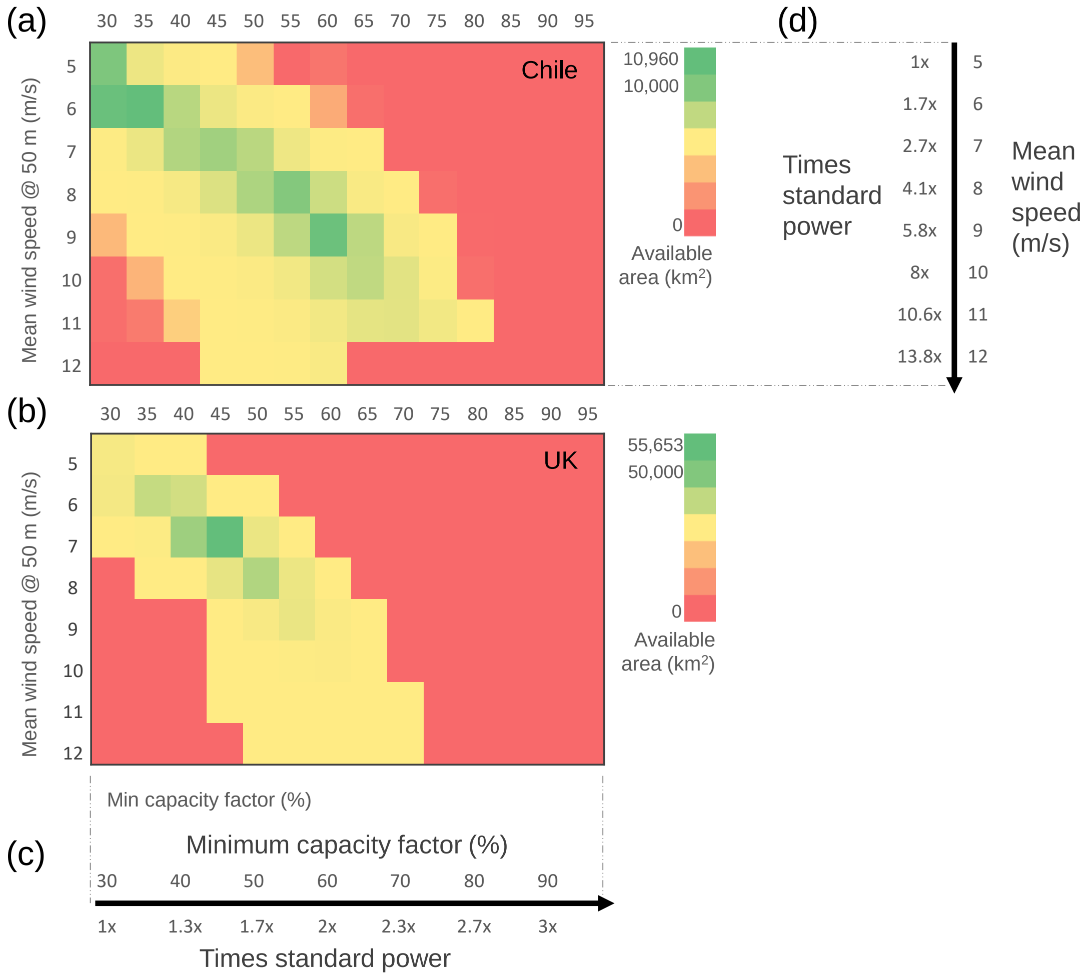


Figure 6: *Onshore wind power characterisation: (a) Chile, (b) UK, (c) power to capacity factor reference axis, and (d) power to wind speed reference axis.*

3.4 Challenges for Chile to become an energy exporter

Chile has abundant renewable energy resources and has experienced fast growth in renewables over the last five years, but the question of whether Chile could become an energy exporter remains. The most suitable areas for wind projects are concentrated in the extreme south, while the best land for solar projects is in the north close to the desert. The former are approximately 2,000 km south, the latter 1,000 km north from the capital, Santiago. This establishes an important geographical challenge, as most of the population and industry is in close proximity to the capital. However, the magnitude of the Chilean domestic demand is not significant. If progress continues, Chile should achieve net-zero targets before 2050, but this progress is not ambitious at the broader scale and could be enhanced. In this section we analyse the opportunities and challenges that the *Norte Grande*, *Norte Chico* and *Austral* macro-zones face to exploit their energy resources in the context of their geography, infrastructure and demand.

3.4.1 *Norte Grande* and *Norte Chico* macro-zones

The installation of solar power in the north of Chile during the last few years has reached the point where it is no longer possible to use all the generated solar energy due to the lack of proper transmission or storage, see Fig. 4(c) and (d). This curtailment phenomenon has been reported in recent international reports [53]. Since only one percent of the most suitable areas for solar energy are required to replace the existing fossil fuel-based capacity, the selection of the locations for investment can be determined by other conditions. An important consideration could be the proximity to the demand, transmission, or energy storage facilities. We identify four major challenges for the progress of the energy transition:

1. The management of the harvested energy becomes a crucial aspect.
2. Energy storage becomes more relevant as more harvested energy is available.
3. The transmission lines require modifications.
4. Additional daylight demand could be introduced, such as electric applications (*e.g.*, electric cars).

The first challenge relates to the dependence of renewable energy sources on the climate. Addressing the challenge requires additional measures to ensure a stable electrical system. Transmission lines, storage, and a robust management system are needed. Technological tools such as cyber-physical systems (CPS) are likely to play an important role. Data will be a key asset. Currently, there exists an entity called *El Coordinador* [22] that is responsible for data coordination and the cost-effective use of facilities. Infrastructure capacity will soon exceed demand in Chile, and therefore, installed capacity will cease to be a relevant measure of the energy transition. Instead, information on actual energy production will be required in order to analyse and track progress. Instantaneous monitoring would need to include weather information. Real-time digital twins could provide solutions to this problem. As an example, a digital twinning approach has been used in the context of The World Avatar [5] to study wind energy prices in the UK [7, 8]. Indeed, the expansion of variable renewable energy generation has propagated numerous challenges for the UK's national energy system and will certainly be a challenge for Chile as the country advances through the energy transition.

The second and third challenges relate to each other. The government is working on policies to boost investment in energy storage [76], to provide location aids to develop such projects, and has created institutions to regulate the energy storage market. The Andes and the existing hydroelectric power infrastructure in the *Centro Sur* and *Sur* macro-zones offer an opportunity to store solar energy in the form of pumped hydroelectric storage. Other options include batteries and the production of fuels like green hydrogen. However, renewable energy and energy storage projects rely on access to a transmission system. The SEN transmission system connecting cities from Arica to Chiloé is a major step in this direction. However, the SEN requires further adjustment, and new transmission lines are being considered. These are all relevant factors for investment decisions.

Finally, the fourth challenge requires demand planning. For example, charging points for electrical cars could be built to make use of the additional solar energy that is available during the day. A transmission system is again a necessity. Factors such as private investment and behavioural change in consumers are also relevant. This is therefore a more complex change that requires a longer time frame to address it.

3.4.2 *Austral* macro-zone

Unlike solar, the best areas for wind projects lack connectivity to the rest of Chile. Only 3.6% of these areas are required to match the existing fossil capacity, but the realisation is complex because of the distance and geography. Maritime transport is the preferred method of moving goods between the *Austral* macro-zone and the rest of Chile. Moreover, numerous sea channels and poor weather conditions compound the difficulty of navigation. The demand in the *Centro Sur* macro-zone can be fulfilled more easily using solar alternatives and the transmission system to supply power from the north.

Nevertheless, the renewable energy potential of the *Austral* macro-zone is worth analysing, as it may alleviate pressure on global needs. We examine the potential to understand the magnitude of an intervention in the very best areas. **Figure 7** shows the areas with high wind speeds and capacity factors. There are 14,063 km^2 with mean wind speeds between 9 and 10 m/s at 50 m above ground, of which 7,480 km^2 are within 100 km of existing ports (yellow areas in Fig. 7). The potential power of the latter is 55.7 GW. Similarly, there are 7,220 km^2 with mean wind speeds between 10 and 11 m/s at 50 m above ground, of which 1,325 km^2 are within 100 km of existing ports (red areas in Fig. 7). The potential power of the latter is 13.5 GW, giving a total of 69.3 GW. To place this number in context, it is similar to the total generation capacity of the current UK electrical grid [78].

Despite their isolated location, these areas have significant advantages. They offer large areas of land with excellent conditions for wind power close to ports that provide access to the Atlantic and Pacific Oceans. These conditions are unusual. In general, there are very few onshore areas of the world with constant high wind speed. The sea channels in the region are also shallow enough to offer the possibility of offshore wind power, if it provided additional benefit. As an example, the USA recently launched the first commercial-scale offshore wind project in an area of high wind energy [103]. Only a few studies have addressed this issue in the extreme south of Chile. Becerra et al. [12] found that the coastal geographical distribution poses a financial challenge for the viability of small scale wind farms for residential purposes. In a different study, Mattar and Guzmán-Ibarra [68] performed a techno-economic feasibility for offshore wind projects, finding that those in the *Austral* macro-zone would have the lowest levelised cost of energy.

If renewable energy infrastructure is built, and assuming the energy is used to produce energy-intensive products, transport of products would require maritime routes. Navigation from the *Austral* macro-zone is arguably more expeditious towards the Atlantic. This is an option that Chile is trying to develop [19]. The most plausible partners are France or Germany [14, 47]. It is worth considering the straight-line distances from Punta Arenas as a reference. The distance from Punta Arenas to Santiago is 2,189 km, to Paris is 13,263 km, and to Berlin is 14,099 km. A possible competitor for European business is Australia, where the distances from Canberra to Paris and Berlin are 16,919 and

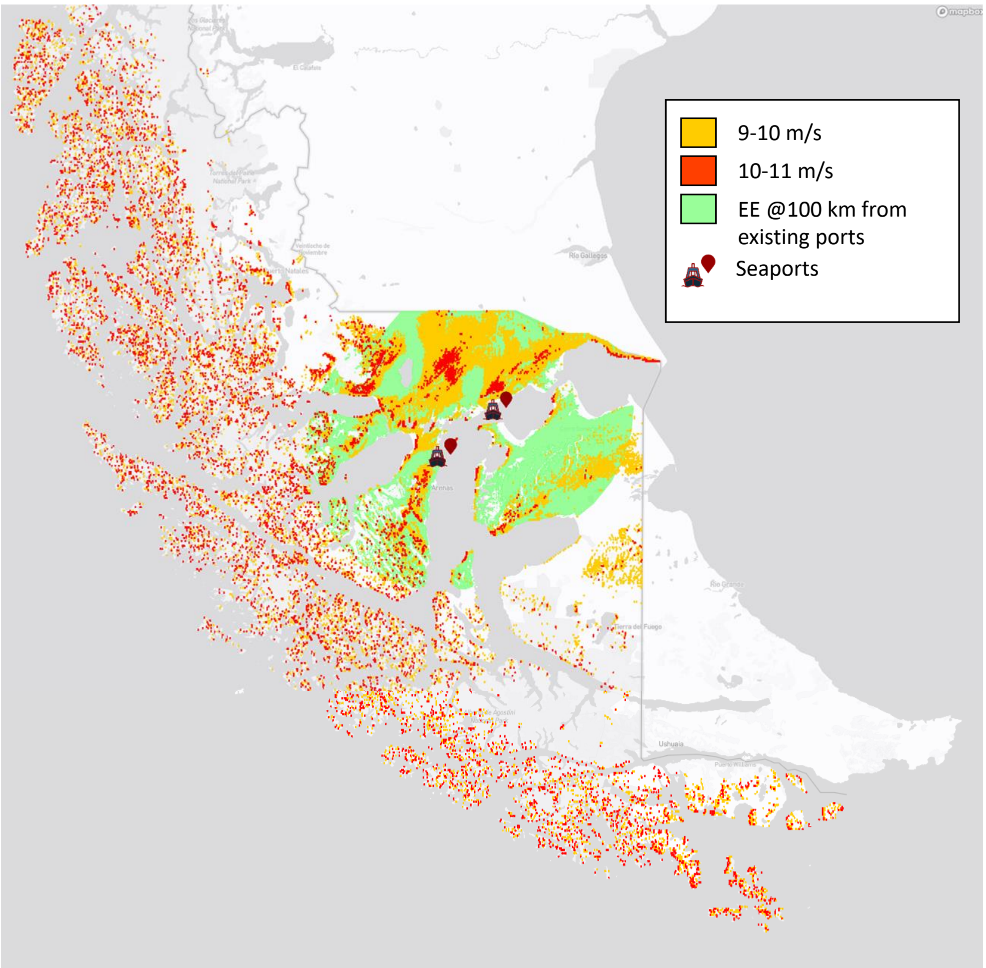


Figure 7: *Areas in the Austral macro-zone with a capacity factor of at least 60% and high wind speed at 50 m above ground, in contrast to areas rated EE within 100 km radius of existing ports.*

16,065 km respectively. The distances from Chile and Australia are quite similar, but the route is perhaps more accessible across the Atlantic Ocean from Chile.

Potential energy-intensive products include ammonia, e-fuels and methanol. Green hydrogen would be used as an intermediate, where a recent study [96] has shown that it is only possible to produce green hydrogen by electrolysis at low cost with low greenhouse gas emissions in a few specific locations. The use of hydrogen as an intermediate alleviates difficulties associated with the transport of hydrogen, but raises questions of efficiency. Heuser et al. [45] consider that the transformation of renewable energy into a fuel should have an efficiency around 50%. This efficiency might be economically acceptable for a project that benefits from wind power density that is several times better than under standard conditions.

The challenges for the development of the *Austral* macro-zone are different from those facing the north of Chile and relate mainly to enabling infrastructure. Fig. 7 shows the area surrounding the Magellan Strait. The area is surrounded by seawater, with no major sources of sweet water. The configuration of the ports must be analysed because the Magellan Strait is not too deep, which could be a problem for large ships. There are also many protected areas and there will be important environmental concerns. A new transmission system might also be needed. Economies of scale are important, and these projects demand compromise and international cooperation. We summarise the key points for the development of the *Austral* macro-zone:

1. Consolidate international collaborations.
2. Build enabling infrastructures (*e.g.*, a dedicated port and transmission system).
3. Analyse prioritisation of investment.
4. Harmonise local and national plans, looking for synergistic action paths.

3.5 Options to accelerate the energy transition

The options described below are proposed to support the energy transition on the basis of the analyses in this paper. **Figure 8** summarises the proposals. The role of the visualisations developed as part of this work in identifying the options and in providing tools to communicate them to the relevant stakeholder communities is described in Appendix A.

3.5.1 Electrification in *Centro Sur* and *Sur* macro-zones

The introduction of electric vehicles in the *Norte Grande*, *Norte Chico*, *Centro Sur* and *Sur* macro-zones presents an opportunity to use the abundant solar energy, while enabling the possibility of demand management to address the variability of renewable power. It would extend decarbonisation to the transport sector, and make better use of energy because electric cars are more efficient than their fossil-fuelled counterparts. However, pushing this measure at this early stage would stress the finances of local communities.

3.5.2 Exploiting economies of scale in shipping in the *Austral* macro-zone

The major challenge facing the *Austral* macro-zone is for Chile to reach trade agreements and consolidate the investment required to build enabling infrastructure. Economies of scale are relevant and should be analysed at the earliest stages. They should be evaluated in conjunction with the required resources, for example, the lack of water for electrolysis and the lack of CO_2 for e-fuels.

If projects to produce ammonia, e-fuels or methanol are successful, there will be a need to transport the products. In general, the transport of chemicals by ship is suitable and cheap compared to the energy cost of their production. As a reference, the price of green hydrogen ranges between 3.5 and 5 EUR/kg [85], while the cost of maritime transport is of the order 0.0013 GBP/kg per 1000 km [28]. The creation of a new industry in a location far from populated and industrialised centres is complex for a developing country such as Chile. A quick analysis of the possible alternatives that could facilitate a green hydrogen industry leads us suggest the promotion of domestic and international business cooperation. For example, ammonia and CO_2 can be stored in similar tanks, likewise e-fuels and water. The storage conditions for ammonia are -33°C at atmospheric pressure [56], and for CO_2 are -25°C at 16 bar [28]. One approach might be to export ammonia to Europe and import CO_2 from existing CCS facilities on the return trip. The CO_2 could be used to produce e-fuels for existing vehicles in Chile. Ships delivering these e-fuels to the *Centro Sur* and *Sur* macro-zones could return with water.

The synergies and circularity of a process like this are such that it could start with a lower budget than other options and could support the decarbonisation of partner countries. Alternative options under consideration include the construction of a desalination plant and/or a direct air capture plant to produce CO_2, both of which would require large capital investments. Environmental concerns have also been raised regarding the impact of desalination [21]. Gasification of wood provides another possible route to produce CO_2. Our proposal would avoid this need, decreasing the local environmental impact. Instead of investing in facilities to produce water and CO_2, investments could be made in storage tanks and the modification of suitable ships to make them dual-purpose. National and international cooperation would be essential to make this a reality.

3.5.3 Optimal use of finite resources

The solar intensity in the UK is low compared to Chile. If we assume that solar panels might be placed in the best areas of the UK, the same panels could produce 2–3.5 times more energy in Chile. This raises a question about how to deploy finite resources. For example, concerns have been raised regarding the availability of metals to support the energy transition [74]. The durability of solar panels has been reported to be 20–30 years [57]. They also suffer an annual decrease in efficiency of 0.7–3.19%, with the decrease being larger in humid tropical conditions [9]. Climate change and the energy transition are global problems and the efficient use of finite resources is important. A better understanding of the opportunity costs and challenges of different options is essential.

3.5.4 Synergistic effects

Synergies between the proposals could be developed through planned implementation. Chile has enormous potential for renewable energy and has committed to the energy transition, nevertheless, it lacks the resources and expertise to make all the necessary investments in the short term. Prioritising spending is essential. Investments could be prioritised by simultaneously targeting the following objectives: (a) maximising the use of existing equipment and infrastructure, and (b) minimising expenditure that does not contribute strongly and in a timely manner to the use of renewable energy.

International collaboration could facilitate the construction of the enabling infrastructure, and achieve significant environmental benefits. Innovative international business models could incentivise the investment in the most suitable areas for renewable projects. Such actions could enable nations like Chile to focus investment on storage and building the enabling infrastructure to export energy. If international collaboration could facilitate the provision of captured carbon, and national collaboration could facilitate the provision of treated water; then ammonia and e-fuel industries could operate without the need for desalination or carbon capture plants, as has been previously suggested by the interested companies [46, 97]. This could provide green ammonia for the world and e-fuels for Chile, eliminating the need to import fuels for existing cars. It would require the modification of ships and perhaps revision of regulations. Finally, this could delay the electrification of transport in Chile, allowing the country to focus on the enabling infrastructure for a deep energy transition. Electrification could be completed as a next step, freeing e-fuels for international requirements.

The success of such a strategy relies on the ability to reach agreements. The role of stakeholders such as investors, policymakers and governments is critical. The development of technologies and their implementation depend on the economic capacities to invest, taking the necessary risks, and also, reducing the risks by ensuring a final demand at reasonable prices. While the participation of Chile in a net-zero economy is guaranteed, the share and the speed of the process ultimately depends on an efficient discussion and the consequent action of all parties involved.

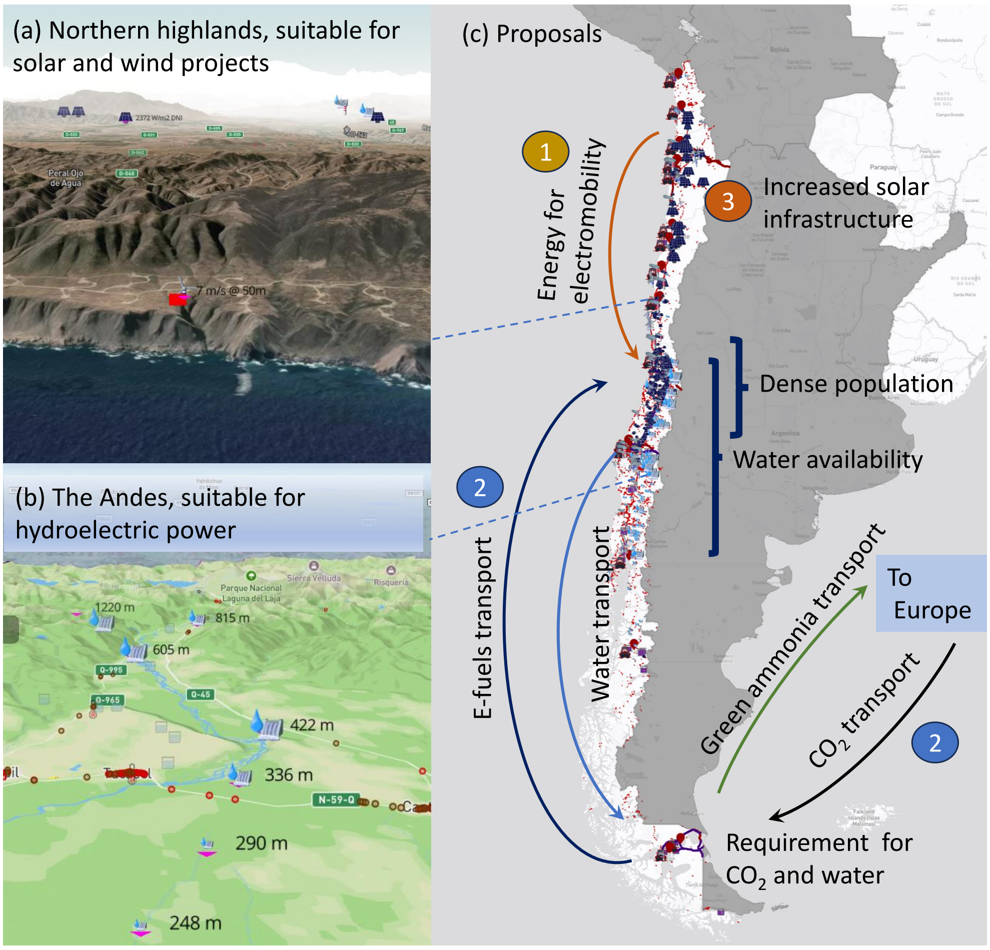


Figure 8: *Geographic implications of the proposed energy transition strategies: (a) renewable power in the north of Chile, (b) hydroelectric power in the Andes, and (c) geo-location of the synergistic proposals.*

4 Conclusions

We have consolidated and integrated data describing renewable energy and infrastructure relevant to the energy transition in Chile. The available renewable energy significantly exceeds domestic demand and there is an opportunity for Chile to become an energy exporter in the world net-zero economy. Chile has large tracts of land with optimal characteristics to harvest wind and solar energy. In the north, Chile experiences some of the highest irradiation values in the world, at least tripling the solar power per unit area available in the UK; in the south, high onshore wind speeds and capacity factors offer up to five times the typical international standard wind power per unit area. The sites in the south are close to existing ports with access to Atlantic and Pacific maritime routes.

The geography and the lack of enabling infrastructure are the most important challenges that must be addressed to take advantage of the abundant renewable energy in Chile. The north of Chile is closer to centres of demand but requires energy storage and better connections to the national transmission system. In the south, the *Austral* macro-zone offers large quantities of renewable energy and, with the development of a port and wind energy, might be a suitable location to manufacture energy-intensive products such as e-fuels and ammonia for transport via maritime routes.

We propose options to accelerate the energy transition that take advantage of the existing infrastructure and exceptional conditions for renewable energy in Chile. The development of solar power in the north of Chile will allow the electrification of most of the national demand. The possibility of ammonia and e-fuels projects in the south should be analysed to explore the potential synergy in transporting raw materials and products. Investment in e-fuels could initially fulfil internal demand for fossil fuels, securing the development of infrastructure that could eventually support the export of energy products.

International cooperation could facilitate the development of these projects. For example, the availability of CO_2 from carbon capture projects in Europe could be aligned with conversion of CO_2 in Chile. New business initiatives are recommended to be analysed in order to make these projects real. The opportunity cost of not doing this will be to dilute efforts, and risk investments being diverted towards less efficient low-reach projects.

The integration of the data into a single platform facilitated our understanding and analysis of the challenges and opportunities in Chile. The development of 2D and 3D visualisations was a key component of understanding the geography, resources and infrastructure, allowing us to focus on sustainable holistic proposals rather than a narrow analysis of a particular area. Developing such visualisations as communication and analysis tools is relevant to the ability to advance strategically in the energy transition, as different organisations can gain insights and make better contributions to the assessment of opportunities and challenges. The integral use of programming, engineering, design and communication skills is needed to enable the development of these digital solutions and should be promoted. A description of the question-based approach that we used to guide the development of the visualisation is provided in Appendix A. In the future, the insights from the processes followed in this work will be adopted in The World Avatar, where we seek to use an approach that combines ontologies and autonomous computational agents to raise the level of automation and decision intelligence in the data integration and analysis.

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Data and code availability

The visualisations developed in this work are available at https://theworldavatar.io/demos/chile. The visualisations use open-source data that can be accessed via the information in the references. The codes used in this work are available under an open-source license at https://github.com/cambridge-cares/TheWorldAvatar.

Nomenclature

CPS	Cyber-physical system
DNI	Direct Normal Irradiation
E	Renewable potential ranked as "excellent"
G	Renewable potential ranked as "good"
INE	*Instituto Nacional de Estadística* (National Statistics Institute of Chile)
IRENA	International Renewable Energy Agency
LRE	Law on Renewable Energies
Sea	Renewable potential attribute denoting areas with water depth between 0 and 30 m
SEN	*Sistema Eléctrico Nacional* (National Electric System)
SIC	*Sistema Interconectado Central* (Central Interconnected System)
SING	*Sistema Interconectado del Norte Grande* (Far North Interconnected System)
SQL	Structured Query Language
SS	Renewable potential attribute denoting areas with elevation between 0 and 20 m
TWA	The World Avatar
VRE	Variable renewable energy

A Development of visualisations

This section describes the question-based approach that we used to guide the development of prototype visualisation tools. We provide details of the data used and the corrections made to it. We discuss the design choices, and the role of visualisations in our analyses and in providing tools to communicate with different stakeholder communities. We critically assess their usability and retrospectively analyse the procedure we followed.

The visualisations provide unified descriptions of Chile's existing renewable energy resources and infrastructure and are available at https://theworldavatar.io/demos/chile.

A.1 A digital tool for the energy transition

Achieving global sustainability requires a societal effort and a good strategy. A practical example is the success of Chile in attracting funding to decarbonise its energy infrastructure. Chile aims to participate in the green hydrogen economy [19, 72]. A common strategy for starting new businesses is the creation of pilot projects such as the HIF pilot plant in Chilean Patagonia [44]. This provides proof of concept. The HIF project includes a virtual tour and also allows a choice of different aerial drone views [47]. This is a powerful way to communicate information about existing infrastructure. It is of particular value for Chile, where distance and geography make it difficult to understand the characteristics of different regions, the implications of the climate, and local social conflicts [102].

The data needs to achieve sustainability are varied. At a local level, there is a need to connect society with strategic goals so that people can develop the necessary skills and integrate into the industries to come. Recent concerns that the energy transition may be threatened by a shortage of STEM skills in the UK [25] show that this topic is relevant to any country undertaking technological transformation. Another example is how to fund new infrastructure. World leaders recognise that the question of how to make people and communities to collaborate at the required speed and magnitude is a problem that is common to all paths to carbon neutrality [106]. Communication must be clear and comprehensive to understand the options. The necessary information must be accessible and easy to digest by those who need it. Without these things, there is a risk that efforts will be diluted, resulting in ineffective isolated efforts instead of strategically-aligned solutions. Digital tools could facilitate this communication, improving and accelerating the energy transition debate through a better understanding of problems and solutions. This motivates the following document.

The challenge we seek to address is how to integrate the use of programming, engineering, design and communication skills to develop such a visualisation. Our work is applicable to any location and facilitates data accessibility. We leverage 3D views to provide an intuitive way to understand the geographic aspects of data. The visualisations must be understandable to users and specialists in other areas so that they can develop their own insights. This will help users formulate better questions, promoting the inclusion of more perspectives and insights in the energy transition debate. This collaboration and formulation of better questions should, in turn, lead to better strategies.

A.2 Design process

The integration of data from multiple sources and domains allows users to develop cross-domain insights that might not be apparent when examining bits of the problem in isolation. This is useful for the many problems that require multidisciplinary approaches. Questions of sustainability are a key example. However, making such insights accessible to target users is not trivial. Firstly, it is required to have proper access to the data. Secondly, it is necessary to allocate the information in suitable databases. Thirdly, it is necessary to determine who the users of the information will be, what their questions are, and what information needs to be communicated. Finally, it is necessary to define a set of subjective principles to guide the development of the visualisation; the principles that we adopted were clarity and simplicity.

Figure A.1 illustrates the design process. The process starts by identifying a set of target users and corresponding questions that must be associated with data. The data must be

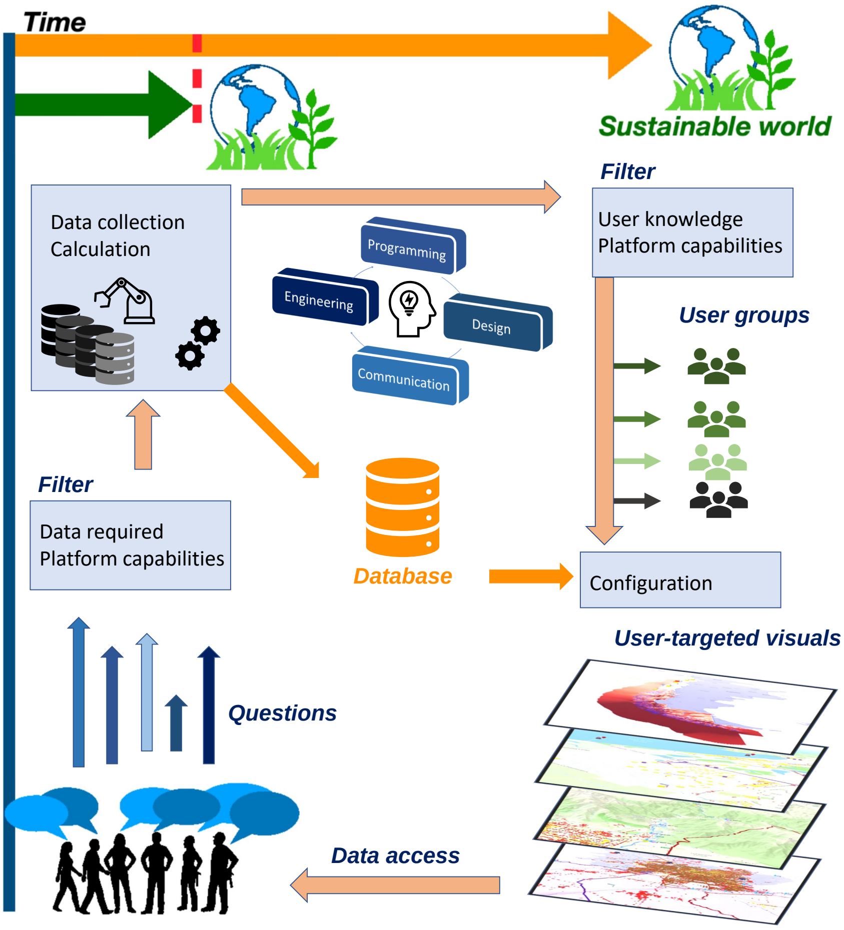


Figure A.1: *Development cycle for visualisations to accelerate the energy transition. Starting from a set of target questions selected to clarify the problem, data is collected and visualisations configured for target users.*

collected and stored in a way that allows new information to be calculated and associated with the data. The delivery of insights must be addressed with the understanding of the user in mind, and may be limited by the capabilities of the digital tools. This requires the use of complex skills such as programming, engineering, design and communication. The resulting user-targeted visualisations can then be made available to facilitate access to and the discovery of insights. The process is cyclic, as access to data and the development of insights typically leads to new questions.

The final outcome should be visualisations enhanced with data that allow users to find the insights that answer their questions. What this looks like depends on the aims, which are specified via the questions. In our case, the questions are associated with things we need to know to achieve a sustainable world and the visualisations took the form of maps, however, this does not have to be the case. The prototype visualisations are available at https://theworldavatar.io/demos/chile. The link opens with a portal that provides a quick user guide and access to the visualisations for different users. The visualisations take advantage of the ability of the underlying mapping libraries to zoom in and out to switch between local and national-scale views, and to switch between 2D and 3D projections. **Figure A.2** shows two example views.

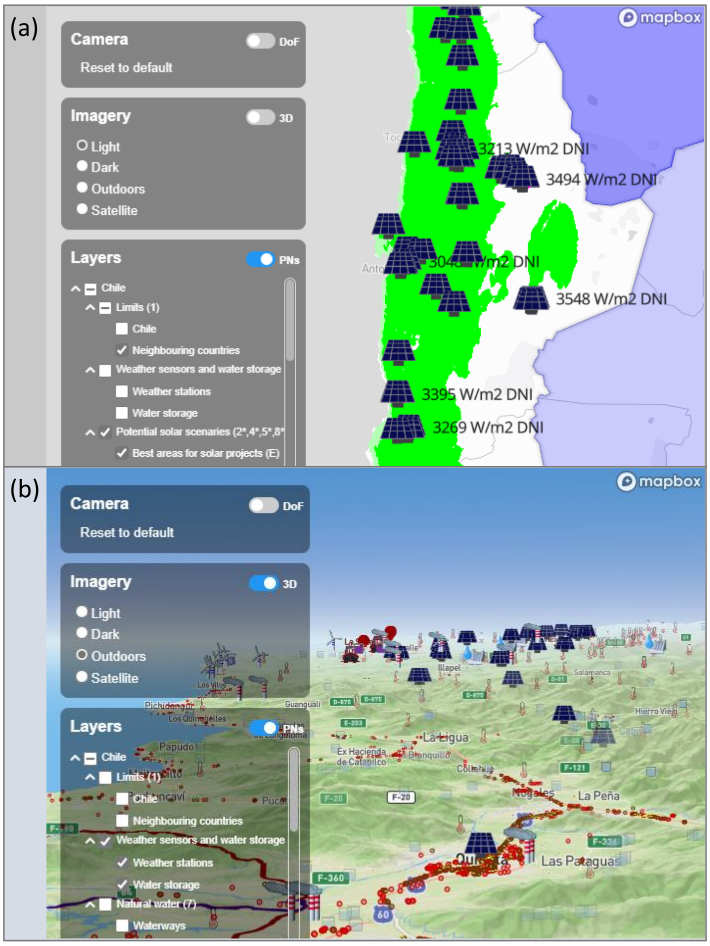


Figure A.2: *Example views: (a) 2D, and (b) 3D projection.*

A.2.1 Target users and target questions

Our design process requires the development of different views of data for different users. Each user is associated with different questions, and has different background knowledge so can understand different information. For instance, while a school student might benefit from simply recognising the existence of different types of infrastructure, an engineering student might be more interested in how the locations of the infrastructure relate to industrial centres of the country. A designer might be more interested the technological and economical effects of the allocation and design of renewable energy infrastructure with respect to geographic constraints. Finally, a politician might like to have a quick overview and develop a general understanding of demand, supply, advantages, and disadvantages.

We chose to prototype four visualisations for three user personas who are interested to understand the renewable energy potential and infrastructure in Chile in different ways, starting from simply looking at the data and progressing to increasingly complex inferences. We formulated a set of basic questions for each persona, each reflecting a different level of sophistication. Using the tools provided by The World Avatar (TWA) project [65–67], we were able to develop an appropriate visualisation for each user.

- **Basic user**. Defined by a school student persona. Questions include: What power plants are near me? What climate infrastructure (*e.g.*, weather stations) do we have? How are the power plants distributed over the country? What do they look like? Which areas are connected to the electricity grid? How does energy reach the city? Where are the ports? The visuals are simplified to aid identification of the elements.

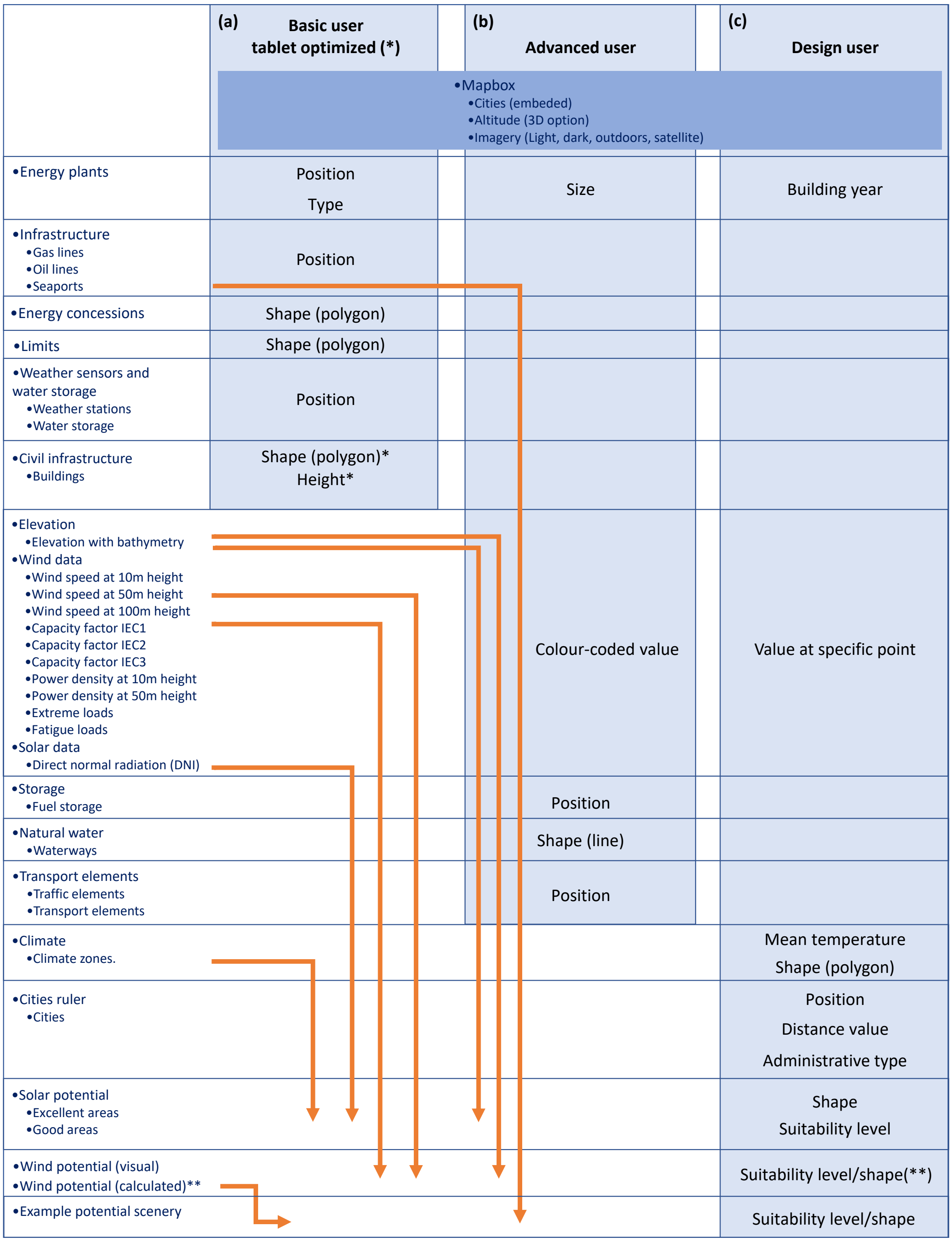
- **Basic user (Tablet optimised)**. Defined by a school student persona who enjoys exploring and/or flying drones. Answers previous questions, with the addition of 3D terrain and building data. It is recommended to use the “Outdoors” imagery.

- **Advanced user**. Defined by a engineering student persona who is able to understand colour-coded graphics and has a basic understanding of energy systems. Answers previous questions plus: What types of power generation infrastructure exist in Chile? Where are they located? How big are they? How are the electricity concessions (areas with access to an electrical grid) distributed? How are hydroelectric plants distributed in relation to the elevation of the Andes and natural waterways? What is the distribution of solar farms in relation to solar irradiation? What is the distribution of wind farms in relation to wind characteristics? How far are the power generation systems from populated areas? Where are the industrial neighbourhoods?

- **Design user**. Defined by an engineering persona who needs more quantitative information. Answers previous questions plus: What are the relative distances? What is the solar irradiation at a specific solar plant? What is the wind speed value at 10, 50 and 100 m height at a specific wind farm? What is the elevation of a specific hydroelectric plant? What are the best areas for solar projects? What are the best areas for wind projects? What types of plants have been built in a specific time period?

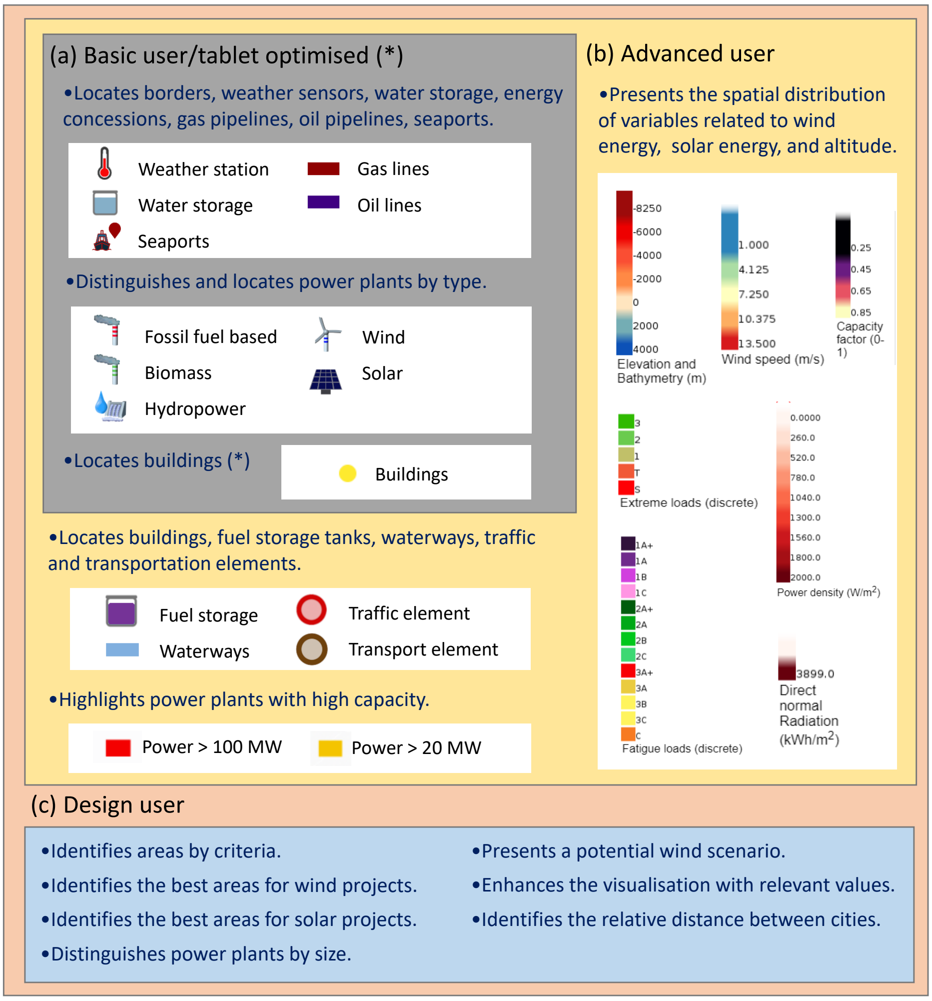
A.2.2 Selected data

Figure A.3 lists the data used by the visualisations to address the questions associated with each target user. **Figure** A.4 summarises the aim and shows the legend associated used by the visualisation for each target user.



	(a) Basic user tablet optimized (*)	(b) Advanced user	(c) Design user
	•Mapbox •Cities (embeded) •Altitude (3D option) •Imagery (Light, dark, outdoors, satellite)		
•Energy plants	Position Type	Size	Building year
•Infrastructure •Gas lines •Oil lines •Seaports	Position		
•Energy concessions	Shape (polygon)		
•Limits	Shape (polygon)		
•Weather sensors and water storage •Weather stations •Water storage	Position		
•Civil infrastructure •Buildings	Shape (polygon)* Height*		
•Elevation •Elevation with bathymetry •Wind data •Wind speed at 10m height •Wind speed at 50m height •Wind speed at 100m height •Capacity factor IEC1 •Capacity factor IEC2 •Capacity factor IEC3 •Power density at 10m height •Power density at 50m height •Extreme loads •Fatigue loads •Solar data •Direct normal radiation (DNI)		Colour-coded value	Value at specific point
•Storage •Fuel storage		Position	
•Natural water •Waterways		Shape (line)	
•Transport elements •Traffic elements •Transport elements		Position	
•Climate •Climate zones.			Mean temperature Shape (polygon)
•Cities ruler •Cities			Position Distance value Administrative type
•Solar potential •Excellent areas •Good areas			Shape Suitability level
•Wind potential (visual) •Wind potential (calculated)**			Suitability level/shape(**)
•Example potential scenery			Suitability level/shape

Figure A.3: *Data incorporated in the visualisations: (a) basic user, (b) advanced user, (c) design user. The arrows indicate the interdependence of the inferred data.*



- Locates borders, weather sensors, water storage, energy concessions, gas pipelines, oil pipelines, seaports.
- Distinguishes and locates power plants by type.
- Locates buildings (*)
- Locates buildings, fuel storage tanks, waterways, traffic and transportation elements.
- Highlights power plants with high capacity.
- Presents the spatial distribution of variables related to wind energy, solar energy, and altitude.
- Identifies areas by criteria.
- Identifies the best areas for wind projects.
- Identifies the best areas for solar projects.
- Distinguishes power plants by size.
- Presents a potential wind scenario.
- Enhances the visualisation with relevant values.
- Identifies the relative distance between cities.

Figure A.4: *Aims and legends for the visualisations: (a) basic user, (b) advanced user, and (c) design user. In the case of the latter, only the aims are provided.*

A.2.3 Corrections to data

Table A.1 summarises the corrections that were made to the data. The data on power plants come from government websites in two distributions. The first one contained information until 2018 [35], and the second one until 2023 [29]. We used the more consolidated 2018 data when possible.

Table A.1: *Data corrections by source.*

Dataset	Source	Corrections	Year
Power plants	[35]	Latin to UTF-8 re-encoding.	2018
	[29]	Coordinates transformation. At least 18 plants were deleted after the coordinate transformation due to incorrect transformation. Location data not provided for some plants in the *Austral* macro-zone.	2023
Energy concessions	[35]	Latin to UTF-8 re-encoding.	2010

A.2.4 Derived insights

The "design user" visualisation contains additional artefacts. These take the form of things that enhance the presentation of existing data, and things that involve additional data processing. Examples of artefacts that enhance the presentation of data:

- **Multi-criteria colour theory area identification**. This is achieved through the superposition of coloured layers and has the advantage of a faster rendering compared to calculation-based methods. **Figure A.5** shows the method. The results are exemplified the *Wind potential* visualisation[1] to highlight wind project suitability.
- **Icon superposition**. This is used to add additional information according to a data criterion. This is exemplified in the *Wind potential* visualisation[1], where yellow and red cards distinguish power plants by capacity.
- **Time-frame filtering through layers**. This is exemplified in the *Investment progress by type* visualisation[1], where the layer configuration provides interactivity to examine Chile's energy transition progress.

Examples of artefacts that involve additional data processing:

- **Raster point values**. This is exemplified in the *Solar potential* visualisation[1], which incorporates irradiation data from rasters to solar plants in the map. **Figure A.6** shows an example query.
- **Raster-raster intersection**. This identifies areas land areas that match criteria in multiple sets of raster data, for example, the areas that match all criteria ranked as excellent (E). This is exemplified in the *Solar potential* visualisation[1]. **Figure A.7** illustrates the steps involved in the calculation. **Figure A.8** shows an example query.
- **Lateral ruler**. This is exemplified in the *Cities ruler* visualisation[1], which highlights the capital and regional capitals, and annotates the north-south distance between cities.
- **Example scenarios**. Artefacts are used to show information about potential scenarios. This is exemplified in the *Potential scenarios* visualisation[1], where the best

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[1] Available online at https://theworldavatar.io/demos/chile.

areas for wind projects close to existing ports are highlighted. Figure A.7 illustrates the steps involved in the example.

Other examples of artefacts are shown in the *Investment progress global*, and *Grid analysis* visualisations[1]. The success of the artefacts in the "design user" visualisation prototype is critically assessed in Section A.3.

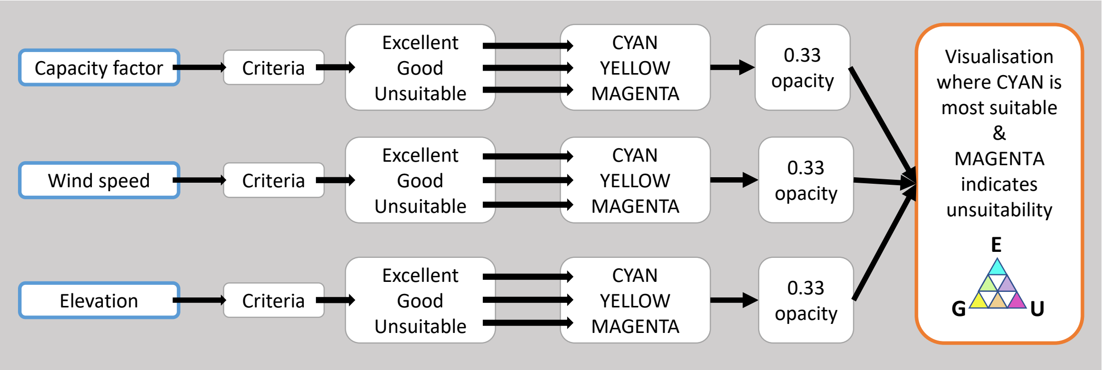

Figure A.5: *Multi-criteria colour theory superposition method.*

Step 1: Information required.

Raster file: `"windchile_raster"`

Vector (points) file: `"plant_points"`

SRID of `"plant_points"`

Step 2. Run SQL query.

```
SELECT rid,
    ST_Value(rast, geom, true) AS value,
    ST_X(geom) AS lon,
    ST_Y(geom) AS lat,
    nombre,
    tipo
FROM
    "windchile_raster", (
    SELECT
        nombre,
        tipo,
        ST_Transform(ST_SetSRID(ST_Point(coord_este, coord_nort),
        32719), 4326) AS geom
    FROM "plant_points"
) testpoints
WHERE
    ST_Value(rast, geom, true) IS NOT NULL
```

Step 3. Download CSV file and upload results with data uploader.

Figure A.6: *Raster point value SQL code.*

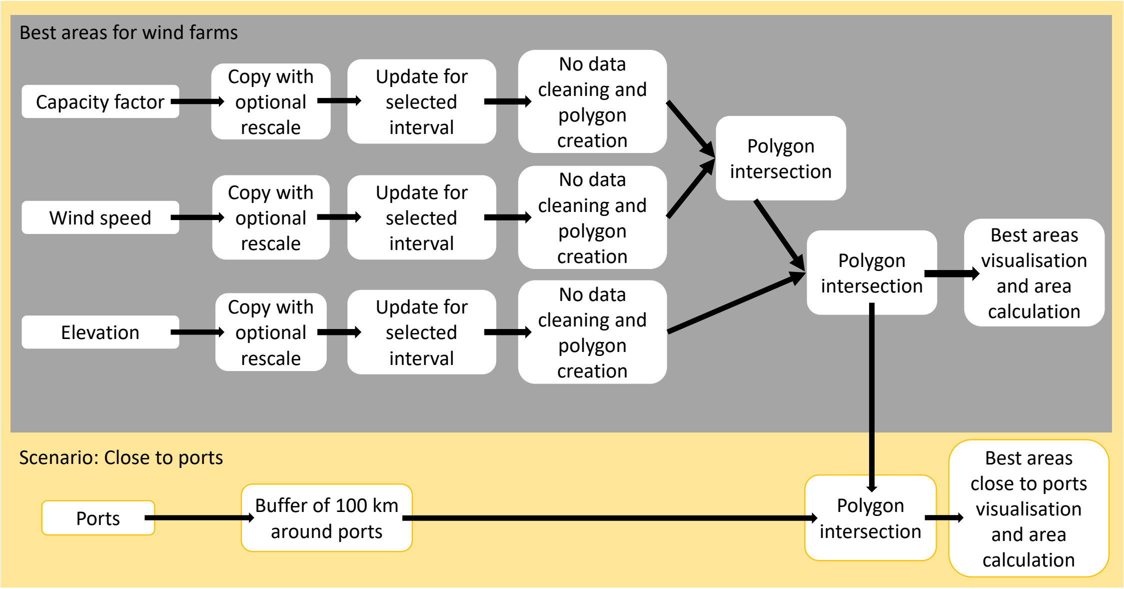

Figure A.7: *Steps in raster-raster intersection calculation.*

Step 1. Define rasters:

Wind speed: `raswind50m`

Elevation:`ras_elevationwithbathymetry`

Capacity factor:`ras_capacity_iec1`

Step 2. Define criteria:

Wind speed: 7.5000000001-12.5, elevation: 20-500, capacity factor: 0.5000000001-0.95.

Step 3. Run SQL queries:

```
CREATE TABLE wcl4 AS (SELECT * FROM "raswind50m");
CREATE TABLE wcl4neg AS (SELECT * FROM "raswind50m");
UPDATE wcl4neg SET rast = ST_Reclass(rast,1,'0-4.5:0-0,4.500000001-7.5:0-0,7.5000000001-12.5:5-
5,12.50000000001-100:0-0 ', '32BF'::text,NULL);
UPDATE wcl4 SET rast = ST_Reclass(rast,1,'0-4.5:0-0,4.500000001-7.5:0-0,7.5000000001-12.5:5-
5,12.50000000001-100:0-0 ', '32BF'::text,0);
CREATE TABLE wcl4added AS (SELECT ST_MapAlgebra(a.rast, b.rast, '[rast1] * [rast2]') rast
FROM wcl4 AS a , wcl4neg AS b );
CREATE TABLE wcl4addedpoly AS ( SELECT (ST_DumpAsPolygons(rast,1, TRUE)).geom as geom,
(ST_DumpAsPolygons(rast,1, TRUE)).val as value
FROM "wcl4added");
CREATE TABLE wcl4addedpolydis AS SELECT ST_UNION(ST_MAKEVALID(geom)) AS geom
FROM "wcl4addedpoly"

CREATE TABLE elevation4 AS (SELECT * FROM "ras_elevationwithbathymetry");
CREATE TABLE elevation4neg AS (SELECT * FROM "ras_elevationwithbathymetry");
UPDATE elevation4neg SET rast = ST_Reclass(rast,1,'-5000-4.5:0-0,20-500:5-5,12.50000000001-7000:0-0
', '32BF'::text,NULL);
UPDATE elevation4 SET rast = ST_Reclass(rast,1,'-5000-4.5:0-0,20-500:5-5,12.50000000001-7000:0-0 ',
'32BF'::text,0);
CREATE TABLE elevation4added AS (SELECT ST_MapAlgebra(a.rast, b.rast, '[rast1] * [rast2]') rast
FROM elevation4 AS a , elevation4neg AS b );
CREATE TABLE elevation4addedpoly AS ( SELECT (ST_DumpAsPolygons(rast,1, TRUE)).geom as geom,
(ST_DumpAsPolygons(rast,1, TRUE)).val as value
FROM "elevation4added");
CREATE TABLE elevation4addedpolydis AS SELECT ST_UNION(ST_MAKEVALID(geom)) AS geom
FROM "elevation4addedpoly"

CREATE TABLE capacity4 AS (SELECT * FROM "ras_capacity_iec1");
CREATE TABLE capacity4neg AS (SELECT * FROM "ras_capacity_iec1");
UPDATE capacity4neg SET rast = ST_Reclass(rast,1,'0-0.33:0-0,0.3300000001-0.5:0-0,0.500000001-
0.95:5-5,0.950000000001-1:0-0 ', '32BF'::text,NULL);
UPDATE capacity4 SET rast = ST_Reclass(rast,1,'0-0.33:0-0,0.3300000001-0.5:0-0,0.500000001-0.95:5-
5,0.950000000001-1:0-0 ', '32BF'::text,0);
CREATE TABLE capacity4added AS (SELECT ST_MapAlgebra(a.rast, b.rast, '[rast1] * [rast2]') rast
FROM capacity4 AS a , capacity4neg AS b );
CREATE TABLE capacity4addedpoly AS ( SELECT (ST_DumpAsPolygons(rast,1, TRUE)).geom as geom,
(ST_DumpAsPolygons(rast,1, TRUE)).val as value
FROM "capacity4added");
CREATE TABLE capacity4addedpolydis AS SELECT ST_UNION(ST_MAKEVALID(geom)) AS geom
FROM "capacity4addedpoly"

CREATE TABLE intersection_ee AS (SELECT ST_Intersection(a.geom, b.geom) as geom
FROM "capacity4addedpolydis" AS a, (SELECT ST_Intersection(a.geom, b.geom) as geom
FROM "elevation4addedpolydis" AS a, "wcl4addedpolydis" AS b) AS b)

SELECT ST_Area(geom::geography, true)/1000000 as km2
FROM "intersection_ee"
```

Step 4. The polygon "intersection_ee" can be downloaded and uploaded with the Data Uploader to be visualized.

Figure A.8: *Raster-raster intersection SQL code without re-scaling and single criteria for each raster.*

A.2.5 Styling principles

It is useful to abide by some aesthetic considerations to create attractive visualisations that motivate users. In particular, recent research on the links between beauty and science emphasises that there is not only a motivational connection [11], but also pragmatic and epistemic connections [55]. According Ivanova [55], key aesthetic elements that scientists appreciate in their work are clarity, simplicity, proper planning and good performance, alongside more personal experiences such as using their creativity.

We consider the attributes identified by Ivanova [55] to be desirable, with clarity and simplicity prioritised as the most desirable. The prototype visualisations have been designed to be as clear as possible, with simple elements that can be easily read. The whole has been organised to emphasise clarity and simplicity, while maintaining an agile user experience (*i.e.*, good computational performance). The following guidelines were adopted:

- Icons should look like the items they represent.
- Layers addressing a topic are organised by group.
- Most relevant information is more visible.
- Less relevant information is less visible.
- Final adjustment of the layer order is made to improve cross-domain interactivity.

A.3 Evaluation

A.3.1 Outcomes for the different prototypes

Basic user prototype The "basic user" prototype prioritises identification of energy-related elements such as power plants, gas pipelines and weather stations. Information is presented via easy-to-read icons as per Figure A.4(a). The icons are intended to resemble key aspects of the real objects, and their perspective is chosen so that they are intuitively understood in a 3D projection.

Figure A.9 shows examples of the visual elements from the different prototypes. A light background is recommended to make it easy to identify visual elements without confusion or information overload. See **Fig. A.9**(a). Users can select different background map imagery and switch between 2D and 3D projections. If the satellite imagery is selected, users can study the physical appearance of the infrastructure. If a 3D projection is enabled, it is possible to deduce geographical implications between the altitude and the location of the power plants. Fig. A.9(b)–(f) provide examples of power plants highlighting the differences between the 2D and 3D projection views.

The "basic user" prototype could be useful for educational purposes. For example, to motivate students to pursue scientific careers, or to provide a basic and necessary understanding of where energy comes from.

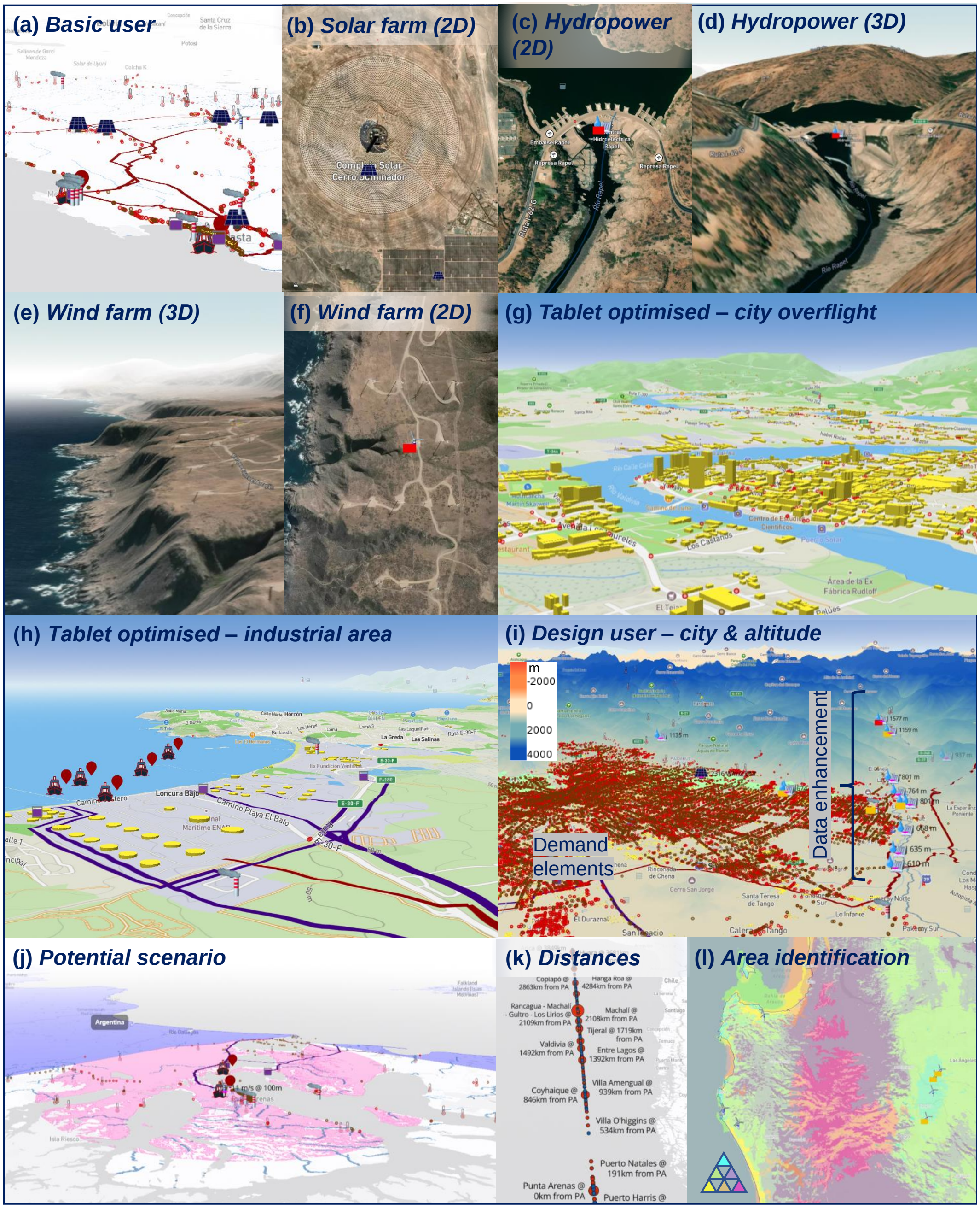

Figure A.9: *Applications of 2D/3D visualisations: (a) basic user, (b) "Cerro Dominador" concentrated solar power plant, (c) top view of "Rapel" hydroelectric power plant, (d) 3D projection of "Rapel" hydroelectric power plant, (e) 3D projection of "El Arrayán" wind farm, (f) top view of "El Arrayán" wind farm, (g) 3D projection of a city, (h) 3D projection of an industrial area, (i) design tool analysing the relationship between altitude and hydroelectricity in the surroundings of Santiago, (j) potential scenario with the best areas for wind projects within 100 km of existing ports, (k) distance tool, (l) colour method for area identification.*

Tablet optimised prototype The "Tablet optimised" prototype provides an alternative version of the "basic user" prototype that modifies the default options to show the power plants, gas lines, oil lines, seaports, fuel and water storage, weather sensors and buildings layers. It is recommended to used "outdoors" background imagery and 3D projection. These choices were considered desirable when using the visualisations via touchscreen devices. The buildings layer provides a block representation of buildings and makes the navigation more interesting. However, the concessions are expensive to render, so the layer that shows them is disabled by default, with the choice left to users to enable as and when they choose. Fig. A.9(g) and (h) show examples of aerial views of areas of interest such as city surroundings and industrial neighbourhoods.

Advanced user prototype The "advanced user" prototype provides additional information and assumes that the user has prior knowledge. A typical user would be an engineering student, who it is assumed would be able to comprehend concepts such as energy demand and be able to interpret technical information encoded using colour scales. New concepts included include colour-scaled data describing elevation, wind speed, capacity factor, power density, fatigue loads, DNI, and indicators of energy demand, water availability and industrial areas as per Fig. A.4(b). Yellow and red cards overlaying power plants were used to distinguish small, medium and large power infrastructure.

The additional data allows users to develop a deeper understanding of the relationships between infrastructure, demand, renewable energy, and geography. Access to satellite views and 3D projections, as per Fig. A.9(b)–(f), now has more meaning in the energy context. For example, Fig. A.9(d) illustrates how this might provide a better understanding of the relationship between the geography and hydroelectric infrastructure. Fig.A.9(e) illustrates how the user might develop a better appreciation of the relationship between the excellent wind conditions, the elevation and proximity to the sea.

The "advanced user" prototype provides the ability for virtual exploration of infrastructure. This has some advantages over a real visit. For instance, physically visiting power plants would require considerable time and resources. In contrast, the visualisation allows users to explore the distribution of different types of power plants, make general comparisons and inferences, and cross-reference what they see against other knowledge. Moreover, the flying object view is similar to a drone exploration, providing an intuitive way to explore, understand, and remember the information.

Design user prototype The "design user" prototype adds artefacts to support specialised engineering users to develop a more comprehensive understanding of the infrastructure. The artefacts provide insights about typical design parameters as per Fig. A.4(c). For instance, the representation of wind farms has been enhanced with wind speed information at heights of 10, 50 and 100 m above ground level. The representation of hydroelectric power plants has been enhanced with information about their elevation. The representation of solar farms has been enhanced with the addition of DNI values.

One consideration in the use of artefacts was the cost of the additional computations. For example, it was necessary to down-sample the underlying raster data when performing the calculations underlying Figs. 5 and 6 in the main text.

Fig. A.9(l) shows examples of artefacts that have been added to a 3D projection of Santiago. Traffic elements have been used as a proxy for energy demand and the representation of hydroelectric power plants has been augmented with elevation information. In Fig. A.9(j) and (k) we highlight the use of two calculated artefacts. The first shows the land within 100 km of a port, supporting the evaluation of scenarios relating to potential uses for this land. The second shows a tool that provides reference distances of cities from a given location. The red markers indicate significant cities, for example regional capitals, with the size of the marker reflecting the status of the city in the administrative hierarchy in Chile. The labels next to the markers appear dynamically depending on the zoom level. Finally, Fig. A.9(l) shows the use of colour theory to identify areas with particular properties without the need for additional (potentially expensive) computations. The artefacts allow improved interactivity and a way to provide additional quantitative information.

Additional artefacts could be added to perform more operations to analyse and explore the data. For example, public policy constraints or industrial energy demands would add new perspectives for users. However, this would require more effort on behalf of the user to understand and take advantage of these opportunities. The choice of which artefacts to include (or not include) was guided by the principle of prioritising clarity and simplicity as the dominant characteristics.

A.3.2 Comparison with other digital tools

Table A.2 lists the tools that were investigated as part of this work. A few tools provided information about the energy infrastructure in Chile. The Chilean Ministry of Energy provides a Geoportal [36] with data and a 2D visualisation. The Open Infrastructure Map from OpenStreetMap, provides information about power plants and transmission lines around the world [82]. While these tools are remarkable, they were insufficient for the analyses presented in the main text because they were unable to support the required data integration. With regard to other digital technologies, the ubiquitous nature of websites may provide advantages for visualising data over other methods. For example, virtual reality is less used due to effort required to integrate it into educational processes [48]. And while the use of augmented reality has increased in recent years [42], its use requires more complex devices that are expensive compared to accessing a website.

In a recent study, Chalal et al. [17] analysed the methods used in eco-feedback visualisation techniques in 1050 articles. The study highlights that the customisation of tools for target users is common practice. It further highlights the role of scenarios in planning and design. Finally, it recommends a list of desirable features for 2D and 3D geospatial visualisations. The following provides an abbreviated summary:

(a) Helps users make informed decisions.

(b) May be more effective when combined with discussions and public information campaigns.

(c) Can be more effective when reflecting changes over time.

(d) Considers the higher cost of 3D over 2D.

(e) Users can choose 2D or 3D.

(f) Uses block level instead of building level due to privacy issues/concerns.

We assess the visualisations developed in this work against these criteria.

- They can help users make informed decisions based on their own data exploration, but they do not suggest a path of action.
- They provide insight into the change of the energy landscape in Chile over time.
- Users can easily switch between 2D and 3D projections.
- Buildings have been included for advanced users only, given the graphical cost, and are presented in a way that does not infringe personal information. However, data are only available for some buildings as the source data [50] is incomplete.

We consider items (a), (c), (d), (e) and (f) to be addressed, leaving item (b) as a possible use for the visualisations.

Table A.2: *Tools investigated during the development of the visualisations.*

Tool	Description	Use in current work
Chilean Ministry of Energy Geoportal [36]	Contains data related to Chile's energy infrastructure consolidated until 2018. These include power plants by type, transmission lines, among others. The visualisation is 2D.	Source for power plant data, 2018.
PELP [71]	Contains data related to Chile's energy plans until 2050 using different scenarios. The visualisation is 2D.	Not used.
Open Infrastructure Map [82]	Contains world data on energy infrastructure. These include power plants by type and transmission lines. The visualisation is 2D.	Provided data for comparisons with the UK.
Global Wind Atlas [107]	Contains world data on wind energy. The visualisation is 2D.	Source for wind and elevation characteristics.
Global Solar Atlas [24]	Contains world data on solar energy. Data can by retrieved by year. The visualisation is 2D. Estimates specific power for fixed-angle solar panel systems.	Source for DNI and optimal solar panel tilt angle.
Photovoltaic geographical information system [30]	Contains world data on solar energy. Includes seasonal and daily parameters. The visualisation is 2D. Estimates performance for fixed-angle and tracking-angle solar panel systems.	Provided parameters for comparison with the solar potential calculation.

A.3.3 Validation

The veracity and utility of the visualisations can be validated at different levels.

User perspective The integration of the data from multiple sources provides opportunities for users to cross-check things. For example, the background satellite imagery was used to verify the locations of a selection of energy infrastructure, including power plants, oil tanks, industrial parks and buildings. Likewise, the consistency of inferred information can be cross-checked against the available data. Consistency between data from different sources increases the confidence in the information.

Developer perspective Tests with external users remain to be conducted.

Renewable energy potential The location of existing energy infrastructure was used to cross-check the analysis of the best areas for wind and solar projects. See Sections 2.2 and 3.1 in the main text.

Energy transition tool The visualisations enabled a better understanding of the renewable energy potential of Chile and the challenges posed by the expansion of its energy industry. We assessed the information through a chemical engineering lens and used it to propose for further assessment three opportunities to accelerate the energy transition. The insights that led to these proposals required calculations on top of geospatial data and would not have been apparent without a comprehensive overview of the information. We hope that the use of these methods may contribute to the energy transition.

A.3.4 Limitations and challenges for 2D and 3D visualisations

The following are requirements for a broader use of the approach described in this work.

- Highly skilled developers.
- Funding routes.
- Access to reliable data that allows adaptation.
- Facilitators who can educate users.
- Server capacity and reliability.

To overcome these limitations, we can formulate five challenges.

(a) **Developer capacity** The data flow through the stack used to host the visualisations is shown in **Figure A.10**. In the design process used in this paper, the data, style files and settings for the visualisations had to be provided by the developer. The role of the developer(s) is to create a visualisation as a communication tool. However, this is a complex task that requires multiple skills, including:

(i) Domain expertise to select the necessary information and use it correctly in calculations.

(ii) Communication and educational skills to communicate information to different audiences, ranging from experts in different fields to lay users.

(iii) Programming skills to configure the visualisation.

(iv) Design skills to understand the interactive behaviour of the users and make the visualisation attractive.

It is unusual to find all these skills in a single person. Routes to address this include improving the underlying digital tools (this is something we seek to achieve in The World Avatar project), and to fund multidisciplinary teams that can perform the tasks required.

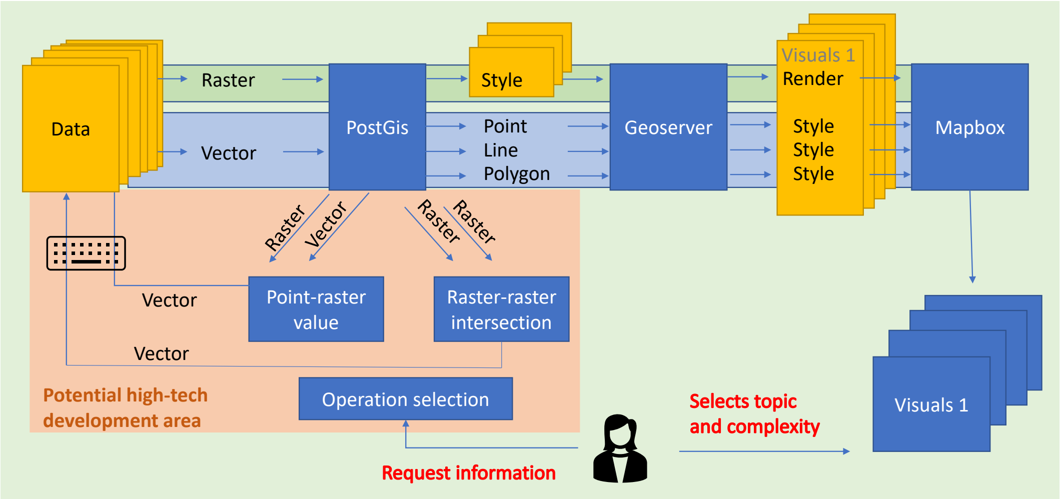

Figure A.10: *Data flow through the stack used to host the visualisations.*

(b) **Funding routes** The intended users of the visualisation tools are strategic focus groups. We have shown in the main text the types of insights that the visualisation might help develop. These potentially have large financial implications, yet the focus groups may not have access to funding or the ability to invest directly in such visualisations. One option may be to seed the development of tools for common purposes through specialised government funding. In the longer term, product-market fit and business case for such tools need consideration.

(c) **Access to data** Access to reliable data is essential. The platform must allow validation of the information and provide clear indications of the sources of information. The information could be referential or usable for other purposes, depending on the target audience. Privacy and security protocols may be necessary (and are possible) to protect sensitive information. This is a complex task that must be defined in each specific situation.

(d) **Target-user network** One way to increase impact and usage might be to incorporate local energy-related organisations. This could facilitate the introduction of the tool to potential users and provide a source of feedback. For example, following the approach of the gaming industry, which tests products and ideas on target communities.

(e) **Server capacity and reliability** It is anticipated that a distributed architecture will be required to host the necessary quantity of data and to provide a high-availability service. Standard solutions exist for this.

A.4 Opportunities

The possibility to explore the data from any location in an intuitive way offers many advantages. The flying object view allows users to be transported from one end of the country to the other in seconds. This visualisation can highlight things that are relevant to users, facilitating comprehension of the data. It offers a cheap, intuitive, accessible and extensible approach. This provides opportunities for businesses that can provide the necessary skills at a reasonable price. Although the tools that we have used to create the prototype visualisations lag the capabilities of gaming platforms, this is perhaps understood in terms of market, users and profitability, rather than technological limitation. In addition, the information required to develop strategic insights to guide the energy transition requires the integration and consolidation of reliable, interoperable data sources. These requirements add complexity to the product development.

Digitalisation has advanced slowly in the energy field. Digitalisation is at the heart of two of five challenges to create a new era for industrial strategy identified by WEF [108]. The first involves improving supply, transparency and resilience. The second aims to accelerate the scaling up and adoption of industrial technologies. But the effective use of existing digital tools could provide improved access to data. Such is the case of simple 2D and 3D online visualisations. These offer a practical route to disseminate information of general interest. Although they do not pose a technological challenge like the metaverse, they nevertheless achieve effective communication.

A further opportunity is the development of tools for scenario analysis. These should be a natural consequence of implementing user-targeted visualisations, as users will develop more specific questions that may require modelling or data analysis. Finally, at the bottom of Fig. A.10 we highlight the possibility of future developments that would make it possible to ask questions and retrieve answers via customised visualisations. For example, Mapbox have recently launched a MapGPT [63] that allows users to ask natural language questions and receive responses via information on a map. This could be combined with the use of natural language questions to retrieve data and, if necessary, trigger calculations to support artefacts. This type of approach has been demonstrated in the field of chemistry as part of The World Avatar project [99, 110].

A.5 Concluding remarks

The implementation of the visualisations to integrate cross-domain information to support the acceleration of the energy transition was an iterative process. We started by answering simpler questions on the first iteration, and proceeded to address more complex questions in subsequent iterations. The result is that the data can be explored in a intuitive way with the purposes of gaining insight into possible routes for the energy transition that far exceeds the scope of activities in the physical world. The use of 3D projection greatly improved our understanding of geographical constraints. Our study was limited to Chile, but further iterations could lead to incorporating information from other countries. Given access to sufficient data, the outcomes will be limited by the programming skills and imagination of the developers. Actions that could facilitate further development of these digital tools are suggested. There is an opportunity to generation information dynamically in response to requests from users (or machines).

B Supplementary images of the energy landscape in Chile

The following images provide additional insights from the visualisation with respect to infrastructure and renewable energy in Chile. **Figure** B.1 uses colour theory to show the classification of the different levels of land suitability for solar projects in Chile. **Figure** B.2 identifies the areas of Chile with most power infrastructure by type.

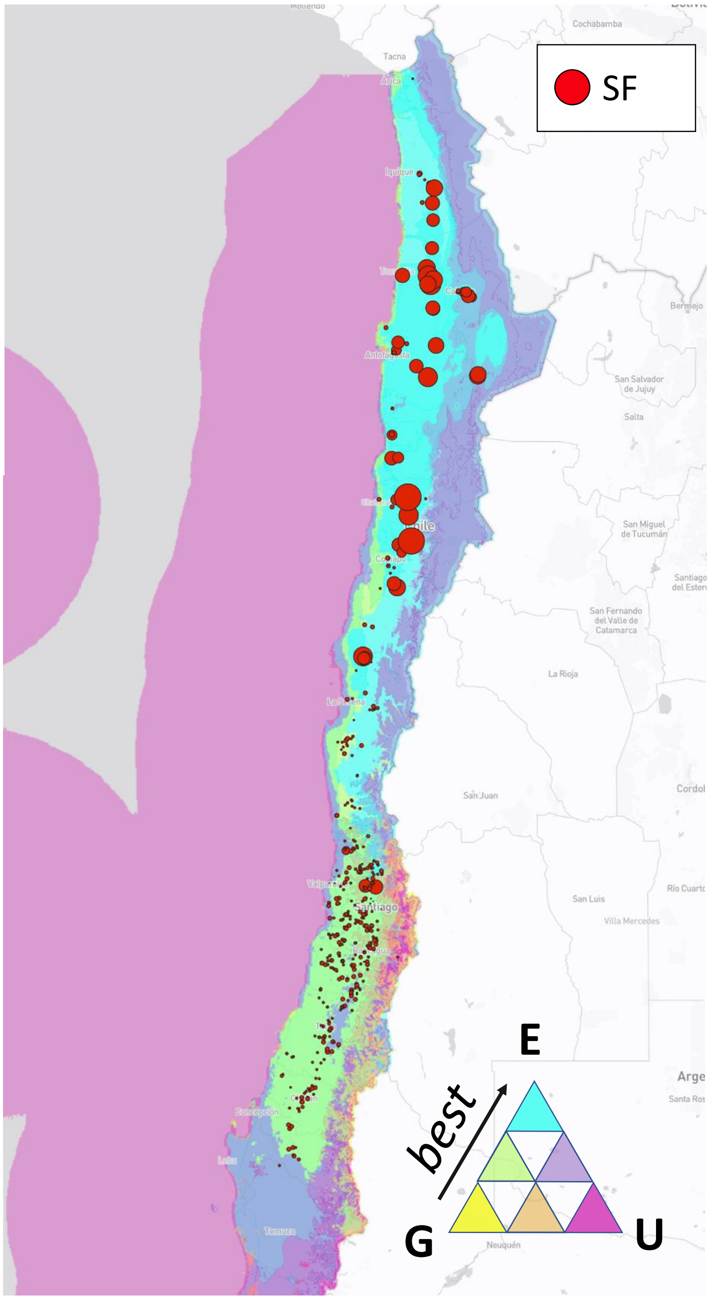

Figure B.1: *Classification of areas for solar projects using elevation, mean climate temperature and direct normal irradiation criteria. The temperature criterion is defined as* $\geq 11°C$*. Red circles indicate existing solar farms, with the area of the markers indicating their relative capacity.*

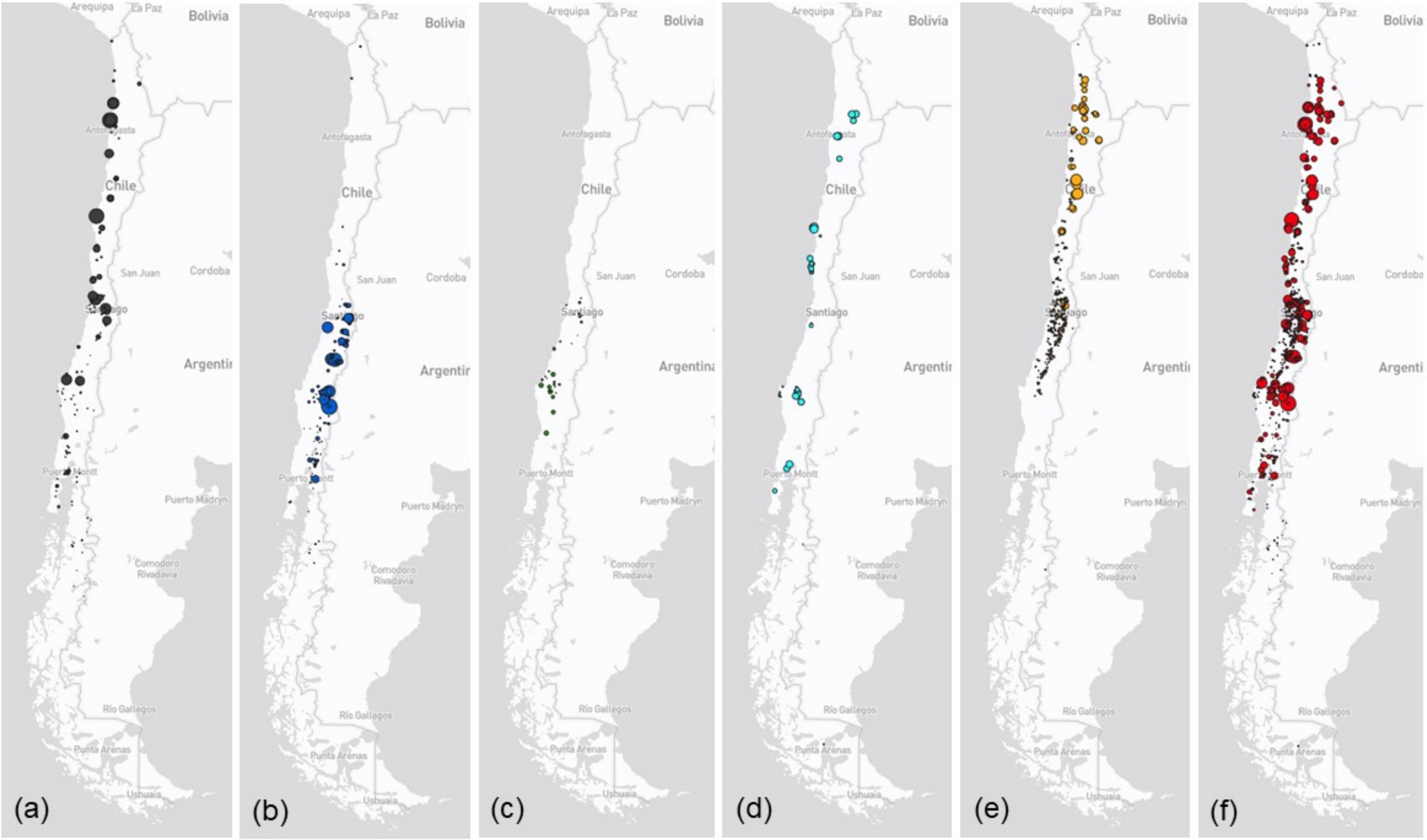

Figure B.2: *Installed capacity for electricity generation in Chile: (a) fossil fuel-based installations, (b) hydroelectric plants, (c) biomass plants, (d) wind farms, (e) solar farms, and (f) any type. The area of the markers represents the relative size of the plant. Data from [36], 2023.*

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