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Title

Large-scale green grabbing for wind and solar photovoltaic development in Brazil

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Abstract

Large-scale wind and solar photovoltaic (PV) infrastructures are rapidly expanding in Brazil. These low-carbon technologies can exacerbate land struggles rooted in historical inequities in land ownership, lack of regulation and weak governance. Here, we trace how green grabbing, i.e. the large-scale appropriation and control of (undesignated) public lands, both formally legal and illicit, for the development of wind and solar PV, has developed in Brazil throughout 2000 to 2021. We find that global investors and owners, mainly from Europe, are involved in 78% of wind and 96% of solar PV parks, occupying 2,148 km^2 and 102 km^2 of land, respectively. We also show that land privatization is the prevalent land tenure regime for securing land, indicating significant transformations of prior (undesignated) public and common land. We conclude that green grabbing is a persistent, critical phenomenon in Brazil, requiring transparency and vigilant monitoring of land claims and tenure modifications.

Keywords

Green grabbing; large-scale land appropriation; global investment; wind power; solar PV; Brazil

Main text

Brazil has witnessed a rapid growth of wind power and solar photovoltaic (PV) installations, known as variable renewable energies (VRES), since 2010. During the period from 2011 to 2021[1], the installed capacity of wind power increased from 1.2% to 11.4%, while solar PV capacity rose from 0.1% to 2.6%. Future energy plans, including the Ten-Year Energy Expansion Plans (2029/2031) and the long-term National Energy Plan 2050, project significant further growth in wind and solar PV energy. By 2030, wind power is expected to double, and by 2050, it is anticipated to rise eleven-fold compared to 2021. Similarly, solar PV is projected to double by 2030 and increase forty-fold by 2050[1]. The expansion is driven by Brazil's energy and climate policies aimed at reducing reliance on hydropower, and diversifying low-carbon electricity sources[2]. However, the transition towards renewable energies requires a significant land footprint, which can further fuel competition for land and intensify large-scale land deals[3]. As a consequence, VRES projects, in Brazil and the Global South in more general, are often subject to competing claims over land and differentiated reactions on the ground, culminating also in social struggles against non-recognition and loss of access to common lands and communal land use rights[4–6]. In the context of land-climate interactions[7], addressing pervasive social inequities in land ownership, and in particular the risk of reproducing historical conflicts through insecure land tenure and illicit land acquisition, is therefore a pressing issue for achieving effective climate action and just transition.

The phenomenon of large-scale appropriation, commodification, and marketization of land and natural resources gained notoriety as land grabbing, global land rush, or new enclosures following the financial crisis and food prices spike in 2007-08[8–10]. In these earlier stages, research was primarily linked to transnational deals and large-scale investments in farmland for food and fuel crops[11–13]. In the Brazilian context, land grabbing has been strongly tied to the expansion of agricultural frontiers and illegal deforestation, land speculation, territorial disputes and violence, particularly in the Amazon region[14–16]. Refining the concept, green grabbing[17] specifically emphasizes how securing access to and control over land and natural resources for carbon sequestration[18], biodiversity conservation[19], or renewable energy production[20,21] is enabled by setting 'green' agendas and climate change mitigation imperatives[22].

The definitions of land grabbing and green grabbing are, however, controversial and politically contested. A recurring key element is the "control grabbing"[23] of relatively vast tracts of land and natural resources, often driven by the involvement of foreign actors and capital, with detrimental impacts on livelihoods, culture and ecosystems. Land acquisitions and deals associated with the implementation of low-carbon technologies and infrastructure, such as wind power and solar PV, show intricate and often subtle interconnections with climate change politics[22] that, in principle, raise the political legitimacy of land tenure transformations, or even contribute through legal loopholes and mechanisms to the amnesty of prior illegal land grabs[24,25]. Whereas these deals entail, but not necessarily, a wholesale transfer of land in sales and dispossession from existing claimants, they invariably lead to a comprehensive restructuring of legal rules and authority over land and resource access, use and management[17]. Green grabbing thus supports practices of enclosure and appropriation that fix or consolidate certain types of concession regimes, and modify or transfer ownership, possession and use rights over public and private land[26]. The emerging land tenure arrangements range from direct and forced to politically-institutionally regulated or market-based approaches, potentially leading to legally and socially accepted variants of land control and dispossession[27]. As a result, VRES investments can accelerate patterns of social differentiation by causing significant alienating effects and reinforcing unequal power relations within and across local spaces[28,29].

In Brazil, green grabbing has been linked to the production of biofuels such as ethanol and palm oil[30,31] but the nexus between VRES expansion, investment flows and alternating land tenure arrangements remains poorly understood. Global databases, such as the Land Matrix aim to monitor large-scale land transactions to promote transparency and accountability[32], however, the sparse availability of investment and land tenure data renders the empirical assessment of the impacts of green grabbing by VRES controversial, especially in terms of quantitative and spatially explicit analysis. In the Brazilian context, land tenure is marked by great insecurity and conflict stemming from historical inequities in land ownership, lack of land regulation and weak governance[33,34]. This is particularly prevalent on undesignated (or untitled) public lands (known as *terras devolutas*), which historically have been occupied and collectively used in part by traditional communities as common lands[35,36], but are also increasingly identified in energy provision forecasts and mapping initiatives with large geophysical potential for large-scale deployment of wind power and solar PV[37,38].

The complex land tenure setting, coupled with incomplete or outdated land ownership records and overlapping land tenure designations, present challenges when tracking and documenting land deals related to VRES projects. By combining several datasets from a wide range of sources, we are able to trace the evolution of green grabbing in Brazil from 2000 to 2021 in the context of the expansion of VRES. Our study provides a detailed assessment, both quantitatively and spatially, of the scale of green grabbing for wind and solar PV park areas. It analyzes the intricate relationships among international and domestic actors involved in the development and financing of these parks. Furthermore, we assess the land tenure situation of the parks to shed light on various control grabbing dynamics. To achieve this, we integrate publicly available geo-referenced data from the Brazilian Electricity Regulatory Agency (ANEEL), the National Property Certification System (SNCI) and the Land Management System (SIGEF), the Rural Environmental Registry System (SICAR) with global investment and ownership data from Bloomberg New Energy Finance (BNEF).

Our results characterize green grabbing by relating large-scale capital investment to the acquisition of land control through land tenure modification. First, we show European actors, such as the Italian Enel SpA and Actis LLP from the UK, are driving large-scale appropriation and control of land for wind and solar PV parks, acting as direct owners. While both national and international players influence financing and ownership in wind parks, 90% of owners and 74% of investors of solar PV assets come from abroad, and mainly from Europe. Second, our analysis reveals that 94% of solar PV park areas have been privatized, while this share is lower for wind parks at 64%. Particularly wind parks are also affected by illicit land claims, e.g., by the use of environmental regulation titles (CAR), which are controversial in Brazil as a means to legitimize land grabbing but do not provide definitive land ownership.

Results

Investment in and ownership of wind and solar PV assets

Measured by occupied area, foreign companies and organizations are involved, either as investors, owners, or both, in 78% of all wind parks and in 96% of all solar PV parks. This demonstrates the significant presence of international actors, either directly or through subsidiary relationships, in land appropriation of the renewable energy sector in Brazil. For an example of green grabbing in the context of a single wind park, see Fig. 3.

Our database reveals that wind parks in operation and in construction cover an extensive land area of 2,148 km^2, primarily located in the northeastern region of Brazil. The majority of wind park ownership is held by Brazilian entities (for a definition of owners and investors, see Methods). Specifically, direct ownership is predominantly Brazilian, covering 89% of the land area (Fig. 1). The ten largest owners are all Brazilian entities (Supplementary Fig. 1), seven as subsidiaries of foreign companies. As a result, a significant portion of parent owners can be traced back to foreign countries, encompassing approximately 68% of the total wind park area. The largest foreign parent owner is Enel SpA (Italy). Europe is the largest region with foreign parent ownership, being associated with 52% of all wind park areas. France emerges as the leading foreign parent owner country, holding a 12% share of the total wind park area, with Engie SA being the largest parent owner.

The majority of direct (88%) and parent investors (65%) originate from Brazil. Among the top 10 direct investors in Brazilian wind parks, all are of Brazilian origin (Supplementary Fig. 1). The investment landscape in Brazilian wind parks involves the public Brazilian Development Bank (BNDES), which accounts for 15% of the land area. This highlights the involvement of the public sector in the development and financing of the Brazilian wind power sector. 87% of the parks associated with the BNDES have some form of foreign ownership or investments, indicating that foreign companies benefit from state subsidized capital. Furthermore, certain Brazilian investors are subsidiaries of foreign companies. For instance, the second largest investor, Enel Green Power Brasil Participações, whose parks cover 7.5% of the land area, operates as a subsidiary of Enel Green Power SpA from Italy. While the largest parent investment company comes from Italy, Spanish parent investors are linked to 10% of the overall land area, being only surpassed by Brazil.

The land area occupied by solar PV parks is smaller compared to wind parks, resulting from a lower installed capacity and higher power density of solar PV in comparison to wind power. Specifically, 102 km^2 of land is utilized by 117 solar PV parks. Although the overall land area is lower, the land use intensity of solar PV parks is more intensive compared to wind power[39]. The land sharing potential of solar PV parks, e.g. for agricultural purposes, is therefore limited, as spacing between solar panels is constrained and restrictive access rules apply.

Solar PV exhibits a higher level of foreign participation compared to wind parks (Fig. 2). Parent owners and investors largely originate from outside of Brazil, accounting for 90% and 74% of solar PV areas, respectively. Even 46% of areas associated with direct owners are non-Brazilian, while areas linked to direct investments are mostly Brazilian (85%). Similar to wind power, the majority of non-Brazilian parent investors and parent owners are from Europe (57% and 66%, respectively). Italy holds the largest area associated with parent ownership (27%), placing Brazil in fourth position (10%). Italy is also the top country in terms of parent investors, accounting for 30% of the land area, while Brazil ranks second (26%).

Unlike wind power, the primary investment in solar PV projects in Brazil is driven by private entities. Two companies, Enel Brasil Participações Ltda and Enel Green Power Brasil Participações, both subsidiaries of Enel Green Power SpA from Italy, dominate the sector, being involved in 30% of the land area occupied by solar PV parks (Supplementary Fig. 3). The second-largest player is the public Brazilian bank Banco do Nordeste do Brasil SA (12.5% of total land area). Similar to wind power, the top 10 direct investors are Brazilian, with the exemption of Engie Solar SAS from France. However, all private Brazilian investors, apart from one, are subsidiaries of international companies. In stark contrast to wind parks, the 10 largest direct owners of solar PV parks are predominantly from abroad. For instance, the second-ranked company, Actis LLP (12.5% of land area) is from the UK, while CGN Energy International Holding from Hong Kong holds 10% of the land. With one exemption, all parent owners are foreign, the largest of which is Enel SpA from Italy (26% of land area).

As changes in national and international policies may have changed the participation of different countries, we assessed temporal trends in regional participation, which could however not be confirmed neither for wind nor for solar PV parks (Supplementary Fig. 2 and 4).

Wind and solar PV park areas by land tenure category

In this section, we analyze the prevailing modes of land appropriation in VRES park and respective control areas (see Supplementary Table 1 for a definition of land tenure categories, and Methods for a more in-depth description including the definition of control areas). The majority of land regulation in wind and solar PV parks consists of private land with legal property titles (64% and 96%, respectively) (Fig. 4). For both technologies, the total share of legal private property titles is substantially higher than in the control groups. Note that the share of control areas covered by legal private property titles is higher for solar PV areas (47%) than for wind power (21% and 28% for *Control random* and *Control match wind resource* respectively). This indicates that solar PV parks are located in municipalities with higher shares of legal private property titles than wind parks. Also note that the two control areas for wind parks have different shares of legal private property titles. We identify two potential reasons: first, control areas of type *Control match wind resource* are placed closer to existing wind parks, as they are found in locations with high wind speeds. Spillover effects of privatization from existing wind parks may cause higher shares of private land there. Furthermore, these areas may contain assets for future investments in wind parks and therefore already see higher rates of privatization.

Statistical tests (see Supplementary Fig. 5, Supplementary Table 3, Supplementary Table 4, Supplementary Information 2.1) show that the control groups have significantly different types of land regulation patterns. Our findings confirm that VRES park development generally targets private legal property titling over other forms of land tenure regulation. For wind parks, the composition of land tenure regimes is more diverse: 36% of the wind park area is not covered by private legal property titles. 28% of the land area is only covered by CAR titles, i.e. by self-declared titles submitted to the rural environmental registry, which are commonly used as claims for controlling land, but are legally not binding (Fig. 3 illustrates an example for green grabbing in the context of a single wind park). Furthermore, 8-9% of the total wind park area has no information on private ownership, and overlaps with some form of public land (2%) or undesignated public land (7%). In contrast, only very minor shares of solar PV parks are not covered by legal private property titles (4%).

Furthermore, we examined land regulation for wind turbine locations only, excluding spacing areas of wind parks. We found that only 55% of all turbines are situated on land with legal private property titles, while 38% are located on private land with CAR titles only, and the remaining 7% overlap with public or undesignated public land.

While we observe that VRES parks are built on higher shares of private land with legal property titles than in control areas, does this imply that public or undesignated public land has been privatized for that purpose? We therefore also assessed the timing of land privatizations in relation to the first closure date of an investment in a park as a proxy of development activities (Fig. 5) to determine the temporal proximity between investment and privatization activities. We find that for both technologies, 75% of land privatizations took place later than 5 years before the first closure date of the financial transaction. Land privatizations have picked up speed in the years near the closure date, indicating that large shares of land privatizations are directly linked to VRES park development. In particular, almost half of all privatizations in wind park areas and one-third of all privatizations in solar PV park areas occurred after the first investment, further strengthening the case that land areas have been privatized due to renewable energy park development.

Discussion

Major networks of governments, and corporate entities are the primary source of funding and investment in wind and solar PV parks in Brazil, being involved in 78% of all wind parks and in 96% of all solar PV parks. These VRES projects are driving the appropriation of vast tracts of land by large-scale financial capital, confirming the hypothesis of green land grabbing. We found no discernible evidence of differences in foreign capital inflow into VRES projects between Brazilian governments, which points to a political continuity in setting policy conditions for attracting foreign investment and public-private partnerships in the renewable energy sector. Our analysis confirms that the provision of high-quality finance by BNDES has played an integral role in financing VRES, benefiting both national and international actors by de-risking low-carbon investments[40].

There is, however, a striking difference in shares of foreign investment depending on technology: international participation in solar PV parks is significantly higher compared to wind power projects. One hypothesis explaining the difference is that technology-specific auction mechanisms[41] and governmental incentive programs (e.g. PROINFA)[42], the BNDES' higher local content requirements for wind power than for solar PV to obtain low-cost financing[43], as well as high import tariffs on foreign wind turbines[44], have specifically incentivized the participation of national actors in wind park development. Developing domestic competitiveness in wind technologies, while also attracting international corporations through long-term, low-cost financing, however, shows continuous tension between government interests.

Furthermore, we show that for solar PV parks the predominant form of control capture is rooted in private property titles. This is also true for wind power, but in this case different modes of land acquisition and control overlap, including the use of CAR titles to illicitly claim private land possession, or the construction of wind turbines directly on public or undesignated public land without any form of tenure regulation. In principle, the choice of land tenure regime is linked to large-scale investments in infrastructure, which creates incentives to secure the park area with legally binding private property titles. The fact that wind power needs more spacing area than solar PV, i.e. the ratio of directly occupied to spacing area is 1:140 for wind power and 1:3 for solar PV on average globally[45], and that land tenure security of spacing area may be of less relevance to investors, does however not explain differences in land tenure regulation between the technologies. Roughly 40% of all wind turbines are placed directly on land without private property titles. One reason may be that solar radiation is far more uniform than wind resources and project developers therefore have greater spatial alternatives for building solar PV parks, including the choice of regulated private ownership of land.

The lower land-use intensity of wind parks, which include substantial spacing areas, could in principle allow for co-utilization of land. However, it is well documented that access to the wind park area is in many instances highly restricted by the erection of roadblocks, fences, gates, armed security and watchtowers[5,46]. Both wind power[6,47] and solar PV park deployment[4,48] have also been cited at international level in the context of multifaceted dynamics of dispossession by controlling access to marginal public and common lands, but a detailed analysis of the commonalities and differences between these technologies with respect to their impact on – prior – land-users is still lacking.

Our quantitative approach cannot analyze the specific dynamics of interaction with competing land claims and use rights, nor the impact of land acquisition for VRES development on livelihoods. We also recognize the need to consider not only the precise geographic area of operational land deals, but the broader implications, in both quantitative and qualitative terms, of non-operational or 'failed' land deals[49]. In any case, our results show that land privatization increases in close temporal relation to investments in VRES parks, indicating that VRES development is linked to driving the modification of land tenure regimes, particularly the privatization of public and undesignated public land (see Methods for methodological limitations in pinning down the direction of causality). The exact procedures of how land is formally appropriated and who, consequently, benefits locally is highly context specific. For northeastern Brazil, qualitative and fieldwork-based assessments by scholars and civil organizations have extensively shown that land acquisition for VRES frequently involves irregular claims and appropriation of public and common lands, falsification of land titles and notary fraud. Also documented are the lack of advocacy and due process in licensing, dysfunctional elite intervention to obtain royalties and leases, as well as physical expulsion, co-optation and deception of local community leaders[5,50,51]. New government agreements, such as the Normative Instruction No. 01/2020 in the state of Bahia[52] with its aim to secure legal access to land for corporate interests by specifically providing "procedures for land regularization on state vacant lands with wind power generation potential" of common lands[53]. To protect marginalized rural communities and prevent land conflicts, including threats to sensitive ecosystems with low conservation status such as the Caatinga biome[54,55] governments and companies must recognize these negative socio-ecological impacts related to VRES.

Addressing green grabbing in the context of VRES expansion as a complex form of large-scale investment promoting private appropriation and subsequent dispossession of undesignated public and common land is crucial for guaranteeing socially just low-carbon energy pathways. Improved land governance is also essential, including the development of transparent and accountable systems that integrate information from various land tenure sources. Based on the experiences on land grabbing and agricultural production in the Brazilian Amazon, there is also an urgent need to address land ownership inequities and improve land governance in the Northeast. This requires the acceleration of CAR validation and the removal of illicit registrations from the SICAR system, and the creation of a national territorial management system that effectively manages land and resource data, including the recognition of the rights of traditional peoples and communities, as set forth in the ILO Convention 169 of 1989 ratified by Brazil on 25 July 2002. Strengthening international standards, such as the International Finance Corporation's Performance Standards, are further means of enhancing responsible land use, especially as Brazil's ambitions to boost the production of green hydrogen, synthetic fuels and gases[56] will further increase the pressure on competition for land.

Methods

We conceptualize green grabbing as the large-scale appropriation of land and tenure control, both formally legal and illicit, for the expansion of wind and solar PV projects involving large-scale national or international capital. To understand the green grabbing dynamics of VRES projects, we rely on spatial information of wind and solar PV infrastructure, ownership and investment data, and digital land registries. We conducted all analyses using R Studio Server version 2023.23.0, except for the merging of land tenure data, which was performed using QGIS 3.28.

Study area. Our analysis covers the national scale of Brazil and focuses on implemented wind and solar PV parks in regions of the Northeast (Bahia, Ceará, Maranhão, Rio Grande do Norte, Sergipe, Paraíba, Pernambuco, Piauí), Southeast (Minas Gerais, Rio de Janeiro, São Paulo) and South (Paraná, Santa Catarina, Rio Grande do Sul) (Supplementary Fig. 6).

VRES area. The spatial allocation of wind and solar PV parks is based on data provided by ANEEL, the National Agency for Electric Energy, dated 04/02/2022. For both technologies only facilities with status 'operating' and 'in construction' are considered, solar PV parks only above 5 MW installed capacity are included. The georeferenced information on the wind park area is completed with wind turbine and power plant attributes. For solar, the ANEEL data is limited to point features. The spatial PV area information was therefore derived from OpenStreetMap Northeast Brazil and manually validated and completed using imagery from Google.

Ownership and investment data. We rely on the global investment and ownership dataset from Bloomberg New Energy Finance (BNEF) that reports transactions on wind and solar assets from 2000-2021. Three BNEF datasets were merged for this analysis:

1. The *projects* dataset contains details of wind projects. It provides key project information such as project capacity, commissioning and completion date, financing date, direct owner, parent owner and location.

2. The *organisations* dataset contains details of companies and organizations involved in developing and financing wind projects, such as their country and business description.

3. The *transactions* dataset contains details of transactions on projects such as the transaction date, type of finance, equity investors and debt investors.

Combined, this data set provides information on project owners and investors associated with each asset, providing detailed insights into the actors involved directly in green grabbing. 'Direct owners' are typically renewable energy companies responsible for owning and operating a specific asset. They oversee the entire project lifecycle, starting from an initial feasibility study, and progressing through planning permissions, site design and preparation and finally installation and commissioning. The direct owners or project developers can also be subsidiary companies affiliated with 'parent owners'. International parent owners may choose to develop and operate an asset through a regional branch to more effectively access local services and supply chains and leverage the knowledge and expertise of local personnel. For example, the Spanish energy company Iberdrola operates in Brazil through its subsidiary Neoenergia. More generally, parent owners often operate under limited liability, which protects them from financial losses incurred by their subsidiaries. While parent owners hold the controlling interest (greater than 50%) in the asset, additional investment is often sought by selling equity or raising debt through corporate bonds or loans. Equity and debt investors, holding a non-controlling interest in the asset, are typically not involved directly in project development but will conduct their own risk assessment of the project's viability prior to a final investment decision. These 'strategic investors' may enter the project at different stages of its life cycle, depending on their risk-appetite. These 'direct investors' may themselves be subsidiary companies of larger 'parent investors' that operate through regional branches. For example, an international bank such as the Arab Banking Corp BSC may extend a loan to a Brazilian renewable energy company through its subsidiary Banco ABC Brasil SA. In this way, international investors with expertise and experience in renewable energy financing can better access new and emerging markets such as Brazil[57].

The final dataset reports 25.5 GW of wind and 8.6 GW of solar capacity compared to the 21.2 GW of wind and 13.1 GW of solar capacity reported by IRENA[58]. The greater wind coverage reported in the BNEF data as compared to IRENA data is likely because the BNEF data includes information on wind assets that have secured finance but are not yet operational. The greater solar coverage reported by IRENA as compared to the BNEF data is likely due because BNEF does not report on projects less than 1 MW in size, which excludes rooftop solar installations accounted for by IRENA.

Merging ANEEL and BNEF data. To analyze park specific ownership and investment composition, we merged ANEEL solar and wind parks, dated 30/03/2022, with the BNEF dataset. Data merging is based on (a) fuzzy string matching on park names, (b) spatial locations, and (c) manual completion, in case that the spatial match and the string match did not agree or if there was no match at all. Finally, all matches were manually validated using public information on the internet. From 602 wind parks contained in Bloomberg, we could identify 574 matches in the ANEEL dataset. For solar PV, for the 120 solar PV parks listed in Bloomberg, 117 could be matched with ANEEL. However, these 117 parks are linked to only 44 shape files, as many parks were built in several phases, i.e. one large panel area (identified from satellite imagery) is possibly linked to several projects in the BNEF and ANEEL data sets. Each park is therefore allocated the same share of the total area, when several parks share one common area.

Areas were linked to investment following the following rules: for direct and parent owners, the share in land areas was equal to the share in ownership, given in the Bloomberg dataset. As not in all cases, the shares add up to one in the dataset, we determined a new share s_i^{new} as the fraction of the share given in the database s_i relative to the sum of all shares $\sum_j s_j$ for that particular park, i.e. $s_i^{new} = \frac{s_i}{\sum_j s_j}$. For direct and parent investors, no detailed information about the share in investments is given. We therefore first split the area between equity and debt providers, according to a gearing ratio known on a national level (58% and 70% for debt providers, for solar PV and wind power projects respectively). Within these categories, land areas were split evenly between all investors.

We have assessed how installed capacities in our combined BNEF and ANEEL dataset compares to ANEEL data alone, and have further compared it to the IRENA global capacity database[59], an independent dataset reporting installed renewable energy capacities (see Supplementary Fig. 8). The combined BNEF-ANEEL capacity data is lower than capacities reported by other institutions, while ANEEL data shows higher capacities than IRENA. We therefore underestimate the impact on land occupation by renewables as we do not capture all facilities, but with the exception of single years, deviations in capacity estimates are below 20%.

Land tenure analysis. In addition to identifying international and domestic actors involved in financing and owning assets, we also assess different schemes of land appropriation and claims for the expansion of wind and solar PV parks. Land tenure insecurity is a key issue in Brazil's low-carbon energy transition, as competing claims and poorly defined as well as enforced tenure rights characterize the situation, particularly on public and undesignated public lands. Several attempts have been initiated to organize land appropriation by private and public interests, but there is still a lack of a comprehensive national territorial management system that integrates key land institutions and land databases for regulating public and private land claims at various scales. The institutional framework for land regulation involves multiple widely ramified entities, including Federal and State governments as well as local notary systems, often prone to inconsistencies and uncertainties in land possession and ownership[33,60]. Rural areas, in particular, face systemic challenges in land tenure management, with overlapping land claims from different interest groups – affecting 50% of the registered territory in Brazil[34]. Legislative revisions by the Federal and State governments further contribute to an environment conducive to land speculation and illicit appropriation with widespread risk of volatility in the land market. The increasing digitization, particularly through georeferenced determination of land tenure using digital cadastres and land registries, has contributed to further data conflicts caused, e.g. from overlapping land claims due to illicitly forged land titles or mapping errors[34].

Due to the lack of reliable nationwide integral dataset of rural properties[33], the land tenure analysis builds on various publicly available datasets. The National Institute for Colonization and Agrarian Reform (INCRA) provides the most comprehensive information on formal land tenure, including private and public land. We cluster the following core tenure regimes for this analysis: (1) Private land, (2) Public land, (3) Undesignated public land (Supplementary Table 1 for details on the digital land tenure system). Private land is further distinguished between 'licit' private property titles, and private claims in the form of rural environmental registries, known as CAR titles. The former are issued by INCRA and registered in the Federal digital land tenure systems SNCI-SIGEF[61], and may involve privatization of previously public or undesignated public land. In contrast, the CAR provides self-declared environmental information from rural private properties and land claims related to land use and land cover[62]. The Brazilian Forest Code (Law 12,651/2012) requires landowners to submit CAR titles, including property boundaries and land use types, to the public electronic registry SICAR, however, the subsequent validation process by state environmental agencies has been exceptionally slow to date (2% of 618.8 million ha property area validated by 2022[63]). This situation increases the potential for fraud, which is why the CAR has been criticized also as a tool for land grabbing, especially since the legislative change by MP857 (now Law 13,465/2017) for enabling the legalization of prior illicit claims on public and undesignated public lands (known as *grilagem de terras*)[14,15,64]. Public land covers two types of conservation units – Integral Protected Areas, with very limited use options such as research and tourism, and Protected Areas for Sustainable Use, which allow e.g. renewable energy development within the subcategory Areas of Environmental Protection (APA). In addition, public land compromises Indigenous lands, Afro-Brazilian Quilombola areas, and rural settlement areas. Undesignated public land in our analysis refers to the residual area not covered by private or public land. According to the Federal Constitution (Art. 183, 191), undesignated public lands, cannot be privately appropriated. However, the approval of multiple modifications and amendments to regulate private property have favored the legitimization of illegal appropriation and use of these areas at the expense of agrarian reform[33]. This phenomenon has been widely studied in the context of deforestation in the Brazilian Amazon[14,65], but the issue of undesignated public lands is increasingly linked to the loss of common lands and threats to collective use rights of traditional populations posed by the expansion of VRES[35,50,53].

We aligned our methodological approach with Imaflora's land tenure dataset provided by the Brazilian Agriculture and Ranching Atlas (Atlas da Agropecuária Brasileira, or ATLAS, v202105). The ATLAS dataset combines multiple public data sources and uses an expert-vetted system to systematically resolve data conflicts resulting from, e.g., overlapping land claims due to illicit land title fraud or mapping error[34]. However, the ATLAS dataset lacks information on the date of land claim registration in SIGEF/SNCI and CAR registries. We therefore use rural property information from the public SIGEF and SICAR systems, dated 12/1/2022, but similar procedures to clean the original data, outlined in Supplementary Information 2.2. Furthermore, we applied a similar prioritization scheme based on the level of legal security of the rights, geospatial precision, and the likelihood of transition from public to private status, whenever overlapping land tenure information is found (Supplementary Fig. 9): On private land, licit private property titles registered in SIGEF and SNCI have highest priority and override CAR titles. CAR titles have the second highest priority, i.e. private property titles are erased from CAR titles. Private claims to rural properties, both registered in the SIGEF and SICAR systems, also override public land classification. Public land, including rural settlements, Afro-Brazilian Quilombola lands, Indigenous lands, and conservation units in both the Integral Protected Area, and Protected Area for Sustainable Use categories has the lowest priority: both private property and CAR titles are erased from the respective shape files of public land categories. Finally, any area in the municipalities of interest, i.e. the ones with wind or solar PV parks installed, which is not covered by any of these three land tenure categories, is classified as undesignated public land. The respective procedures have been implemented in Q-Gis 3.28.

To understand if land tenure regimes are different from control areas without wind or solar PV parks, we extracted control areas for comparison. For each park, we randomly sampled 100 points from the same municipality where the respective park is located. We then rotated the shape of the park 100 times randomly and moved one shape to one of the 100 random points. Those shapes which did not overlap with existing wind or solar PV parks and which were spatially completely contained in the municipality, were selected subsequently. In total, we had 124,000 km^2 to sample from for wind parks and 72,400 km^2 for solar PV parks. From the set of available parks, one was chosen randomly as control area (*Control random*). However, areas with strong wind resources may differ structurally from other areas, even if no wind parks have been built there (e.g., areas on mountain ridges). As a simple matching procedure for wind parks, we therefore created an additional control group (*Control match wind resource*), controlling for wind power density: from the sample of available control areas, we chose the area with the lowest absolute difference in wind power density to the reference wind park area. Wind power density is calculated from the Global Wind Atlas version 2.1[66]. We did not control for solar radiation for solar PV parks, as it is very uniformly distributed within municipalities. Supplementary Fig. 7 illustrates the procedure.

Limitations Our analysis here has some limitations related to data availability, as neither SIGEF nor CAR provide details on legal title holders and therefore we cannot provide information on royalty payments between landholders and wind park investors. In particular, the CAR dataset lacks a breakdown of registrations over time, which hampers our ability to accurately assess the temporal relationship between investments and private land claims. The short time period and clustered nature of these privatizations and investments further contribute to the limitations of our evaluation. Finally, our assessment relies on publicly available datasets, which are primarily based on digital tenure systems at the national level in Brazil. In addition, other overlapping land claims may exist. Besides the Federal digital land tenure systems, there are also State cadastres and local notary systems (known as *cartórios*) that maintain records of non-digitized private land possession and ownership claims. However, Brazil still lacks a comprehensive national territorial management system that fully integrates this detail of land tenure information and public access to this property-specific information in digital format is not available. Many of these legally disputed cases also lack regulatory verification, which delays inclusion in the national SIGEF land tenure system and, subsequently, were not considered in our analysis.

Furthermore, while we have shown temporal proximity between investment activities and land privatizations, we cannot statistically identify causality between these two processes as our proxy for the start of VRES park development, i.e. the date of the first investment into the park, is of limited capability: park development and activities to secure land control may have begun well before investments, as strategic investors may be unwilling to commit resources to negotiation and due diligence resources until a project has been fully ‘permitted’, i.e., including site control through regulated forms of land ownership[67]. The permitting phase, however, is the most time-consuming stage in the project development cycle, lasting between 2 and 8 years[68]. Various forms of acquisition of public or undesignated public land may have occurred prior to the initiation of investment activities, and temporal attribution of explicit land privatizations to VRES development is therefore complex.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Full data availability statement

The ownership and finance data that support the findings of this study are available from Bloomberg New Energy Finance (BNEF) but restrictions apply to the availability of these data, which were used under license for the current study and so are not publicly available. All other datasets are publicly available from government institutions, but under non-sharing licenses. We can therefore not provide a repository with the original data, however we uploaded processed data to the Zenodo platform[69]. In addition, we point to the download sources in Supplementary Table 1.

Full code availability statement

The R-Code used to analyze the data can be found at https://github.com/inwe-boku/green-land-grabbing

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Author contributions statement

M.K. and J.S. designed the empirical analysis, performed the data analysis and wrote the paper; N.A. provided data, and discussed and revised the paper. J.R. contributed with data analysis rules, and revised the paper.

Competing interests

None of the authors have to declare competing interests.

Figure Legends/Captions (for main text figures)

Fig. 1: **Ownership and investment of wind power assets**. The Sankey diagram shows the distribution of wind park area per region and company for wind park owners (top) and wind park investors (bottom). Countries included in "Other regions" can be found in Supplementary Table 2. Abbreviations are explained in Supplementary Table 5.

Fig. 2: **Ownership and investment of solar PV assets**. The Sankey diagram shows the distribution of solar PV park area per region and company for solar PV park owners (top) and solar PV park investors (bottom). Countries included in "Other regions" can be found in Supplementary Table 2. Abbreviations are explained in Supplementary Table 5.

Fig. 3. **Green grabbing in the context of a wind power park.** Wind park 'Primavera' (blue polygon) and turbines (blue dots) located in the municipality Morro do Chapéu, State of Bahia. Investors and owners (left above), temporal analysis of financial transactions and private land claims (left below), map with park boundaries and overlapping land tenure composition (right). Two different modes of large-scale land appropriation are shown: Private land with legal property titles (A)-(D), and the use of a CAR title (E) to illicitly claim private land possession. The registered submission/approval dates from the SIGEF land tenure system reveals that the area was formally privatized in the years 2015-2016 after the first investment in the wind park (in 2012).

Fig. 4: **Land area by type of land tenure regime.** Left: wind park areas. Right: solar PV park areas. Control areas are sampled from the same municipality with the same shape. Control match wind resources are areas with similar wind resources as wind park areas.

Fig. 5: **Cumulative land privatizations for wind parks**. Left: wind park areas. Right: solar PV park areas. Comparison to control areas as function of the difference in time to first investment. Control areas are sampled from the same municipality with the same shape. Control match wind resources are areas with similar wind resources as wind park areas.

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Supplementary Information 1 - tables and figures

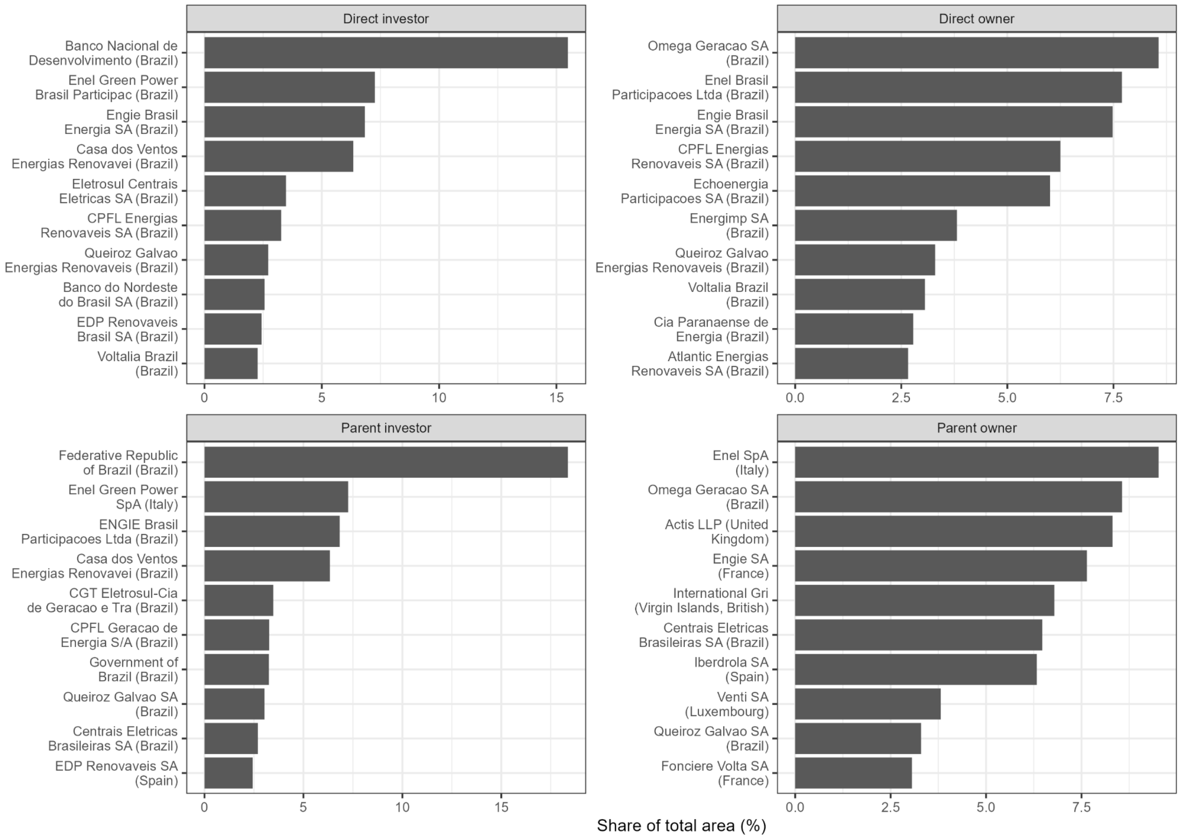
Supplementary Table 1. Dataset of digital land tenure systems and VRES infrastructure

Category	Description	Source & download link	Date of acquisition	Period covered
Private land	Licit private property titles: Privately owned properties are registered in the Sistema de Gestão Fundiária (SIGEF) or Sistema Nacional de Certificação de Imóveis (SNCI). The certification of the georeferencing of rural property ownership, created by Law 10.267 of 2001, is carried out exclusively by Incra, and guarantees that the georeferencing complies with legal technical standards and specifications. We considered the names and boundaries of the rural properties as well as the date of submission and/or approval.	SIGEF and SNCI-INCRA (link)	12-01-2022	> 2022
	CAR titles: According to Brazilian Forest Code (Law 12,651/2012), geo-referenced private rural property information must be submitted to the public electronic registry Sistema Nacional de Cadastro Ambiental Rural (SICAR). We only considered property boundaries and submission dates.	SICAR-MMA (link)	12-01-2022	2022
Public land	Indigenous lands: georeferenced boundaries of studied, declared, demarked, homologated, and regularized areas	FUNAI (link)	12-10-2021	> 2021
	Quilombola areas: Rural properties occupied by Afro-Brazilian communities of descendants of fugitive slaves from the colonial period.	INCRA (link)	12-01-2022	> 2022
	Rural settlement areas: Agrarian reform areas composed of small-scale agricultural plots.	INCRA (link)	12-01-2022	> 2022
	Conservation units: Differentiation according to ecological protection status – i) Integral Protected Areas (strict protection); ii) Protected Areas for Sustainable Use (with options for anthropogenic land use).	ISA (link)	03-03-2021	> 2021
Undesignated public land	Vacant lands (known as *terras devolutas*): Undesignated or untitled public lands owned by the Union or States, but often historically occupied and used by traditional communities, as well as affected by land grabbing and resource extraction.	Estimated result based on the spatial analysis	n/a	2022

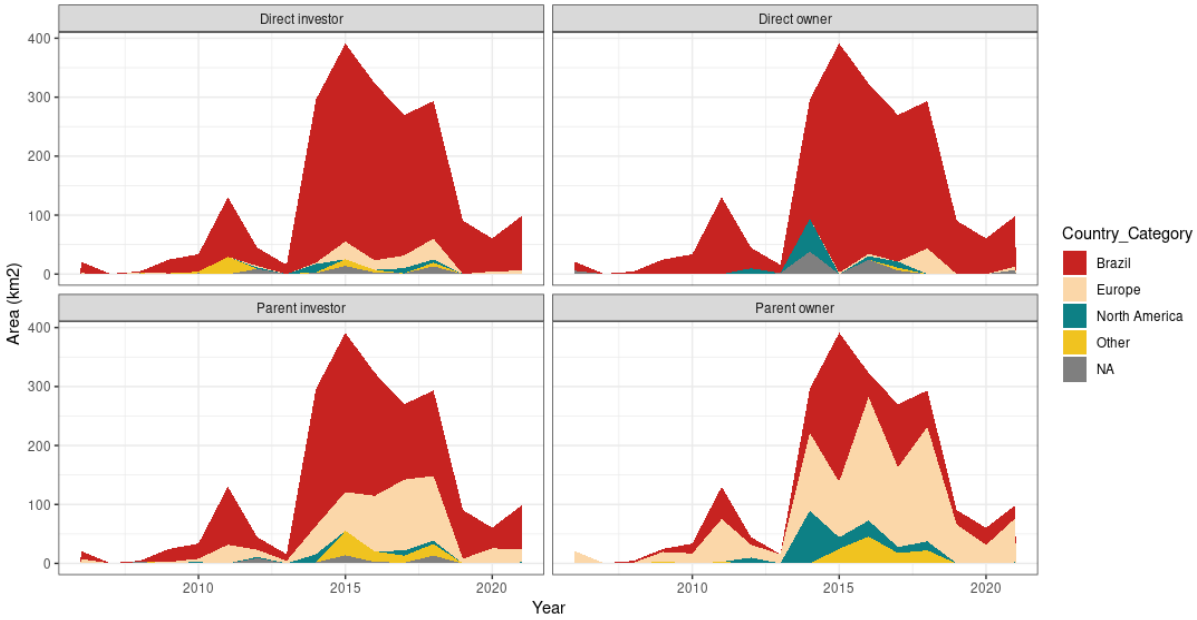
Land tenure boundaries	Georeferenced database covering public and private land holdings provided by the Brazilian Agriculture and Ranching Atlas (Atlas da Agropecuária Brasileira, or ATLAS, v202105).	IMAFLORA (link)	30-11-2022	> 2021
Administrative	Georeferenced information for municipality boundaries	IBGE (link)	18-01-2021	2020
	Georeferenced information for state boundaries	IBGE (link)	18-01-2021	2020
Wind power density	Spatial information on wind power density from the Global Wind Atlas (Version 2.1)	Global Wind Atlas by Technical University of Denmark (link)	10-02-2022	1987-2016 (average)
Wind and solar PV (VRES)	Spatial information for wind and solar PV (above 5 MW) parks with the status 'operating' and 'in construction'	Agência Nacional de Energia Elétrica (ANEEL) (link)	04-02-2022	2000 - 2021
Solar PV (VRES)	Spatial information and satellite photos for the detailed detection of solar PV park boundaries	GoogleSatellite EPSG:3857 (link); OpenStreetMap Northeast Brazil (link)	30-05-2022	> 2022
Wind power and solar PV capacity (VRES)	Statistical information for power capacity and generation from the IRENASTAT Online Data Query Tool	IRENA (link)	20-11-2023	2000 - 2021

Supplementary Table 2: Countries in regional groups

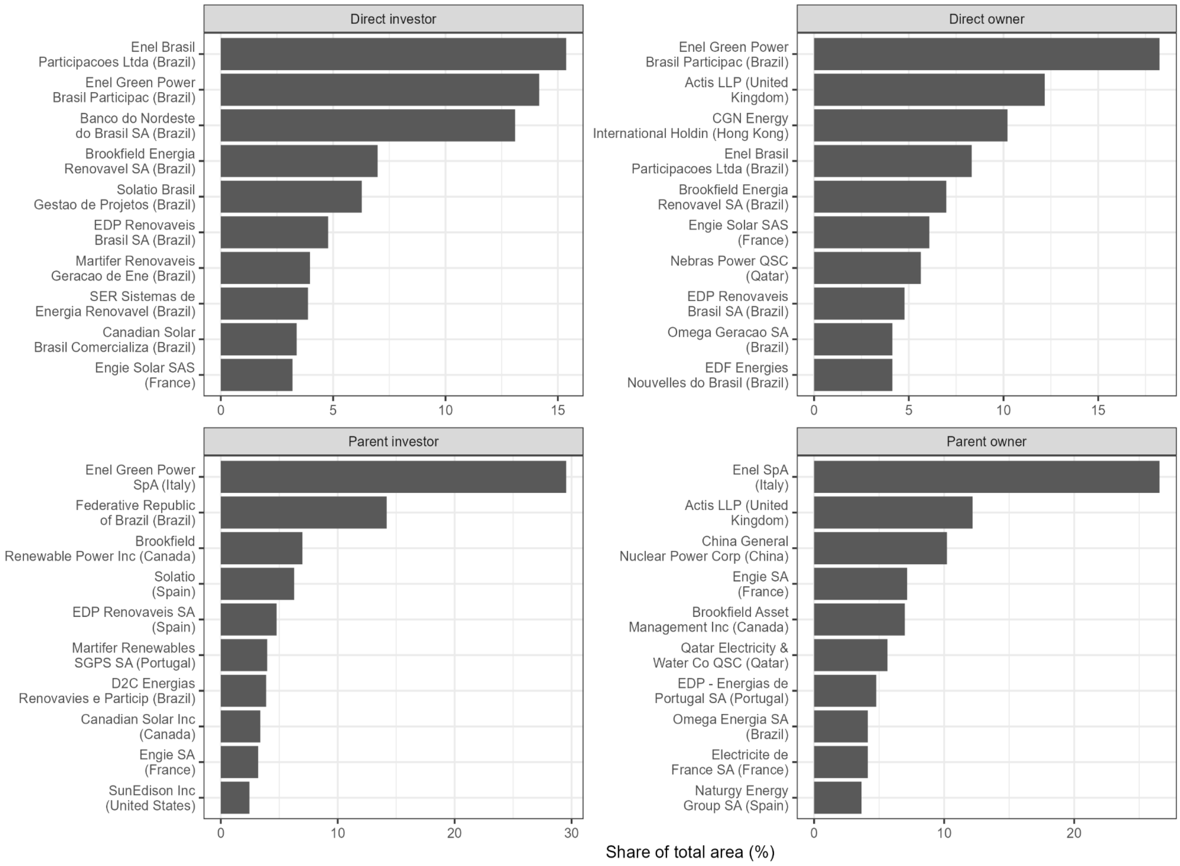
Technology	Region	Included countries
Wind	Brazil	Brazil
	North America	United States, Canada
	Europe	British Virgin Islands, Denmark, France, Germany, Isle of Man, Italy, Luxembourg, Portugal, Spain, Sweden, United Kingdom
	Other	Argentina, Australia, Bahrain, China, Colombia, Hong Kong
Solar PV	Brazil	Brazil
	North America	Canada, United States
	Europe	British Virgin Islands, Denmark, Germany, Hong Kong, Isle of Man, Italy, Luxembourg, Portugal, Spain, Sweden, United Kingdom
	Other	Argentina, Australia, Bahrain, China, Colombia, Hong Kong, Qatar



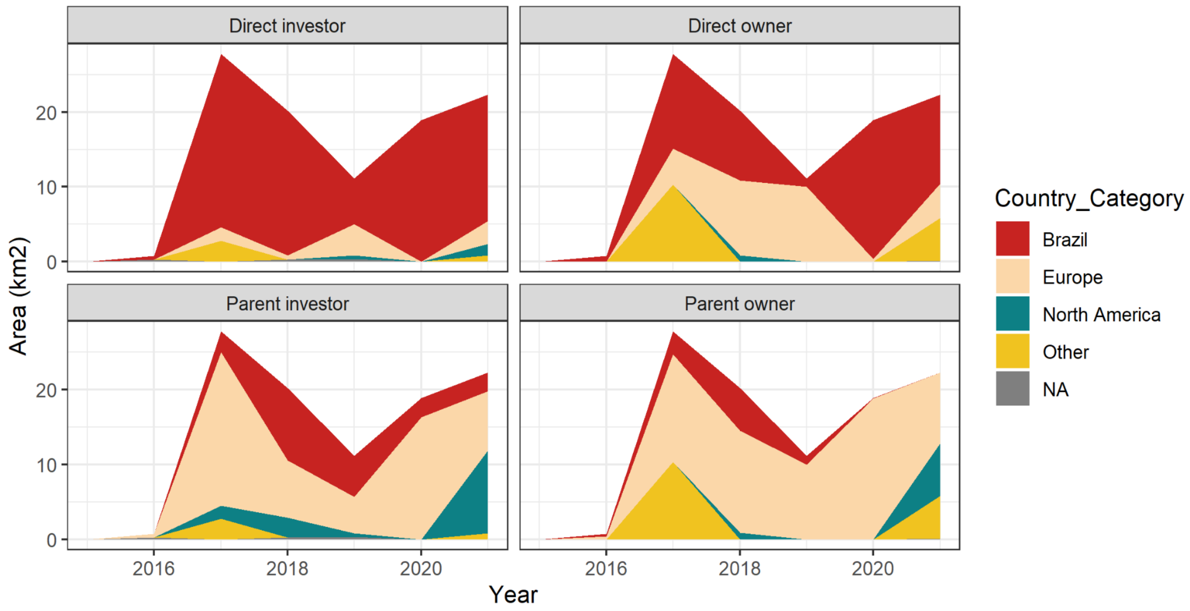
Supplementary Fig. 1: Share of total land area occupied by wind parks per company



Supplementary Fig. 2: Land area occupied by wind parks per investment and ownership country. Year indicates the start of park operation. Countries included in regions can be found in Supplementary Table 2.



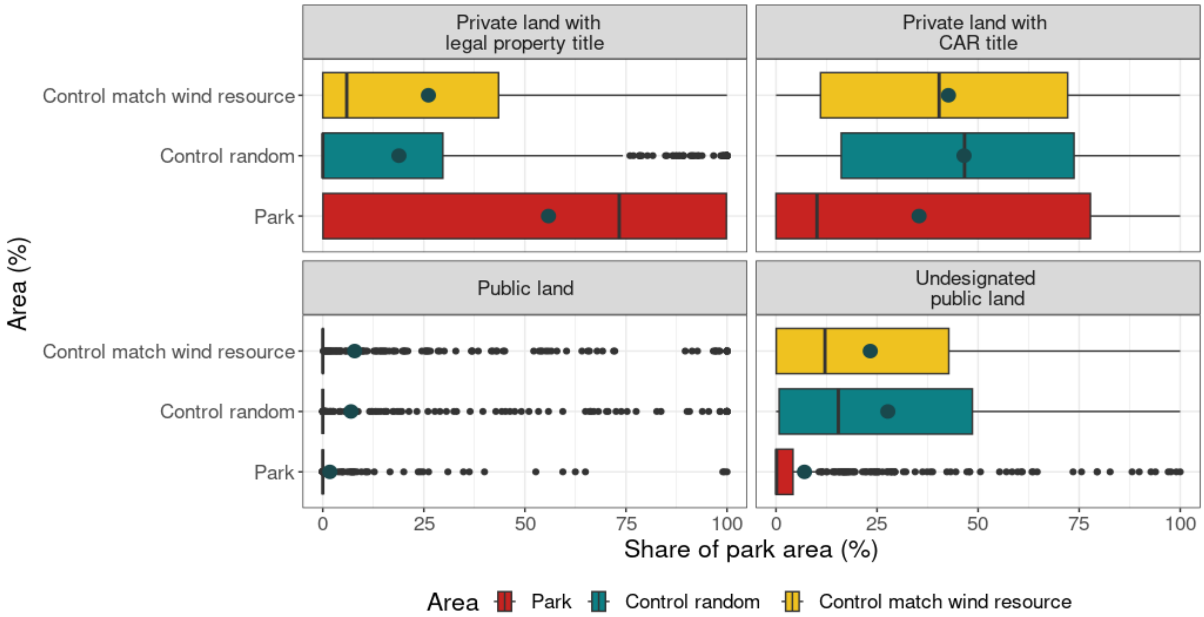
Supplementary Fig. 3: Share of total land area occupied by solar PV parks per company

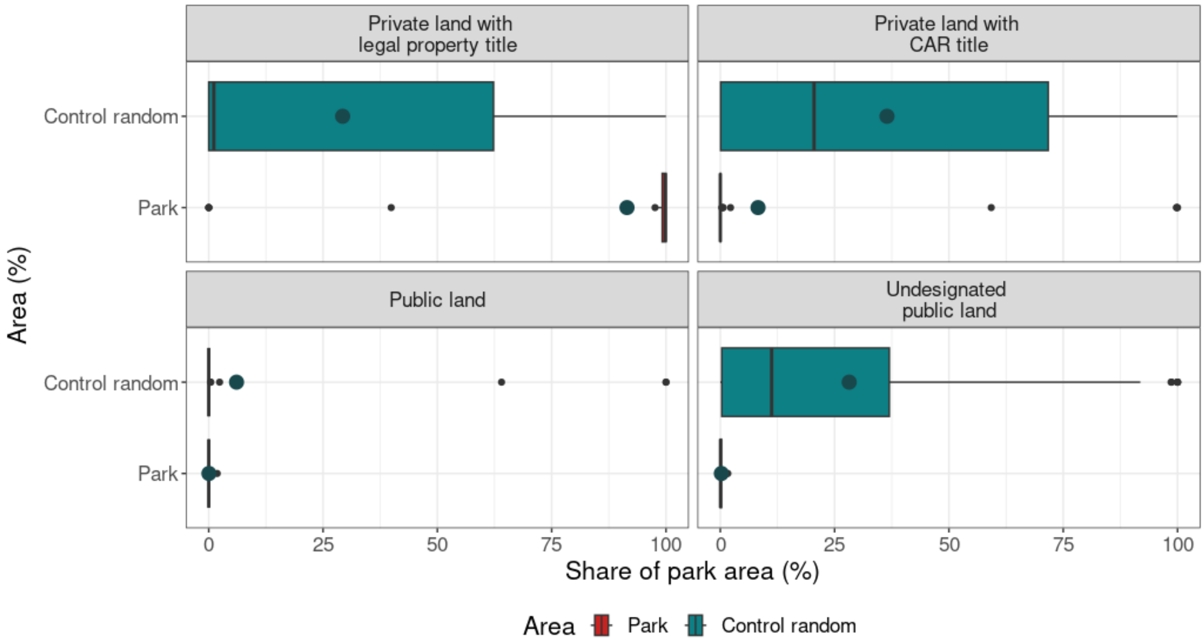


Supplementary Fig. 4: Land area occupied by solar PV parks per investment and ownership country. Year indicates the start of park operation. Countries included in regions can be found in Supplementary Table 2.

To statistically analyze, if a significant difference in land regulation patterns can be confirmed, we calculated the share of land regulation for each park and performed two-sided t-tests to compare the park areas with control areas for the four different land categories. Our analysis involved a sample of 574 wind parks and 44 solar PV parks, and the corresponding boxplots and results of the statistical analysis can be found in the appendix (Supplementary Fig. 5, Supplementary Table 3, Supplementary Table 4). The purpose of the t-tests was to determine if there were significant differences in the means between the control areas and the park areas for each land category (private land with legal property title, private land with CAR title, public land, and undesignated public land), for both wind parks and solar PV parks. With one exception, i.e. comparing public land in solar PV parks to control areas, the p values of the t-tests are well below 0.001 when testing differences in mean between the park areas of wind parks and solar PV parks compared to all types of control areas, confirming that the groups have different types of land regulation patterns.

See Supplementary Fig. 5 on the next page:





Supplementary Fig. 5. Boxplots of wind (upper panel) and solar PV (lower panel) park areas related to land tenure categories. Horizontal lines in the boxes represent the medians, the upper and lower boundary of the boxes represent the 25th (bottom hinge) and 75th (top hinge) percentiles. The top/bottom whiskers reflect the maximum/minimum if there are no outliers; in cases of the existence of outliers (i.e. if there are values below the 25th percentile -1.5 times the interquartile range or values above the 75th percentile +1.5 the interquartile range), the whiskers represent the highest/lowest values within 1.5 times the interquartile. For wind power, n=575 parks, for solar PV, n=44 parks. For each park category, we have sampled the same amount of Control Match Wind Resource and Control Match areas, i.e. n=575 for wind power and n=44 for solar parks.

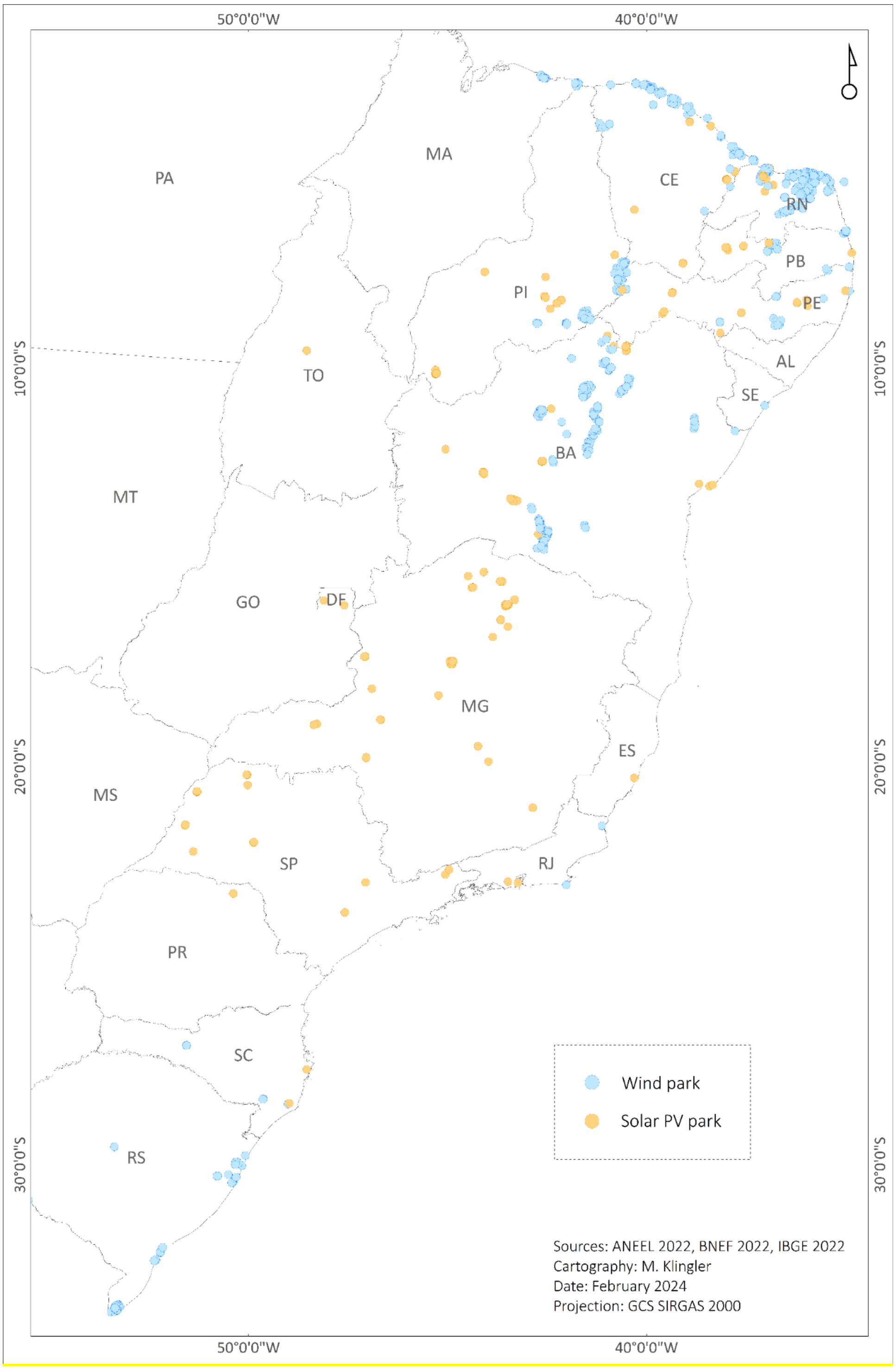
Supplementary Table 3. Means and standard deviations of land tenure categories for park and control areas.

Area type	Land tenure	Mean of area (km2)	Standard deviation of area (km2)
Wind power (n=575)			
Control match wind resource	Private land with legal property title	0.579	1.22
Control match wind resource	Private land with CAR title	0.264	0.731
Control match wind resource	Public land	0.805	1.39
Control match wind resource	Undesignated public land	0.276	1.14
Control random	Private land with legal property title	0.557	0.977
Control random	Private land with CAR title	0.297	0.922
Control random	Public land	0.976	1.75
Control random	Undesignated public land	0.322	1.22
Park	Private land with legal property title	0.833	1.93
Park	Private land with CAR title	0.32	0.878
Park	Public land	0.266	0.944
Park	Undesignated public land	0.104	0.758
Solar PV (n=44)			
Control random	Private land with legal property title	0.881	1.44
Control random	Private land with CAR title	0.276	0.478
Control random	Public land	1.64	4.26
Control random	Undesignated public land	0.24	0.618
Park	Private land with legal property title	1.14	1.96
Park	Private land with CAR title	0.106	0.304
Park	Public land	0.00805	0.0114
Park	Undesignated public land	0.00411	0.00985

Supplementary Table 4. Results of two-sided t-tests on the difference in mean between park areas and control areas.

Land tenure	Group 1	Group 2	Type	Value
Wind power (n=575)				
Private land with legal property title	Park	Control match wind resource	p value	0
Private land with CAR title	Park	Control match wind resource	p value	8,00E-04
Public land	Park	Control match wind resource	p value	0
Undesignated public land	Park	Control match wind resource	p value	0
Private land with legal property title	Park	Control random	p value	0
Private land with CAR title	Park	Control random	p value	0
Public land	Park	Control random	p value	0
Undesignated public land	Park	Control random	p value	0
Private land with legal property title	Control match wind resource	Control random	p value	1,00E-04
Private land with CAR title	Control match wind resource	Control random	p value	0.0469
Public land	Control match wind resource	Control random	p value	0.481
Undesignated public land	Control match wind resource	Control random	p value	0.0097
Private land with legal property title	Park	Control match wind resource	t statistic	12.8405
Private land with CAR title	Park	Control match wind resource	t statistic	-3.3628
Public land	Park	Control match wind resource	t statistic	-6.1169
Undesignated public land	Park	Control match wind resource	t statistic	-12.278
Private land with legal property title	Park	Control random	t statistic	16.667
Private land with CAR title	Park	Control random	t statistic	-5.1548
Public land	Park	Control random	t statistic	-5.3299
Undesignated public land	Park	Control random	t statistic	-14.486

Private land with legal property title	Control match wind resource	Control random	t statistic	-3.8492
Private land with CAR title	Control match wind resource	Control random	t statistic	1.9893
Public land	Control match wind resource	Control random	t statistic	-0.705
Undesignated public land	Control match wind resource	Control random	t statistic	2.5903
Solar PV (n=44)				
Private land with legal property title	Park	Control random	p value	0
Private land with CAR title	Park	Control random	p value	1,00E-04
Public land	Park	Control random	p value	0.0874
Undesignated public land	Park	Control random	p value	0
Private land with legal property title	Park	Control random	t statistic	8.8903
Private land with CAR title	Park	Control random	t statistic	-4.0618
Public land	Park	Control random	t statistic	-1.7494
Undesignated public land	Park	Control random	t statistic	-5.1108



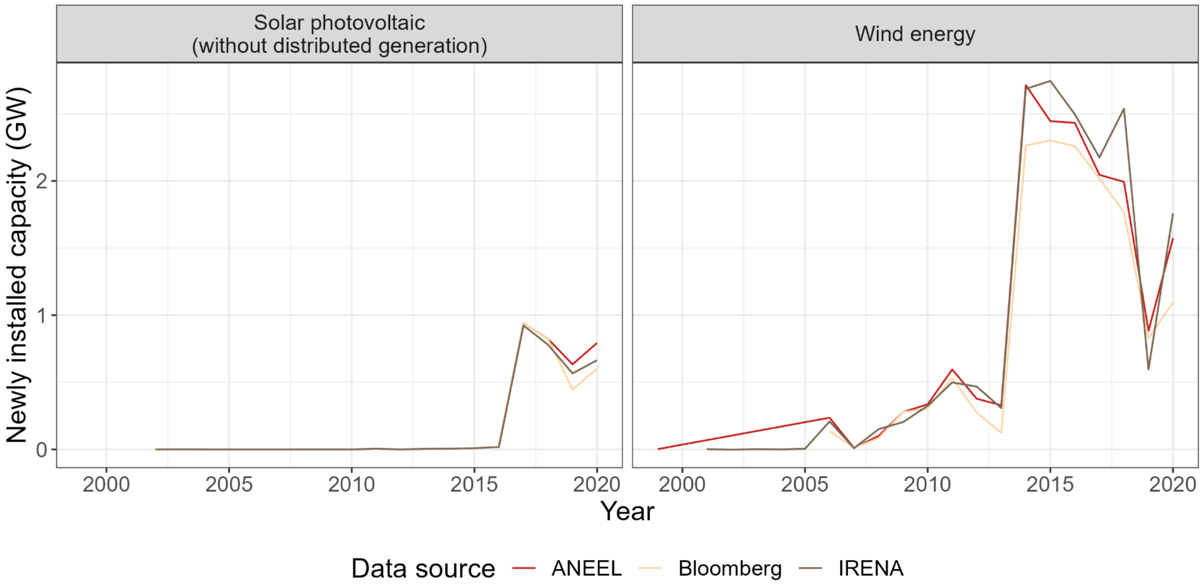
Supplementary Fig. 6: Spatial allocation of wind and solar PV parks in Brazil. For both technologies, only facilities that are included in both the ANEEL and BNEF datasets with status 'operating' and 'in construction' are considered. Only solar PV parks above 5 MW installed capacity are included.

Sources: ANEEL 2022, IBGE 2022

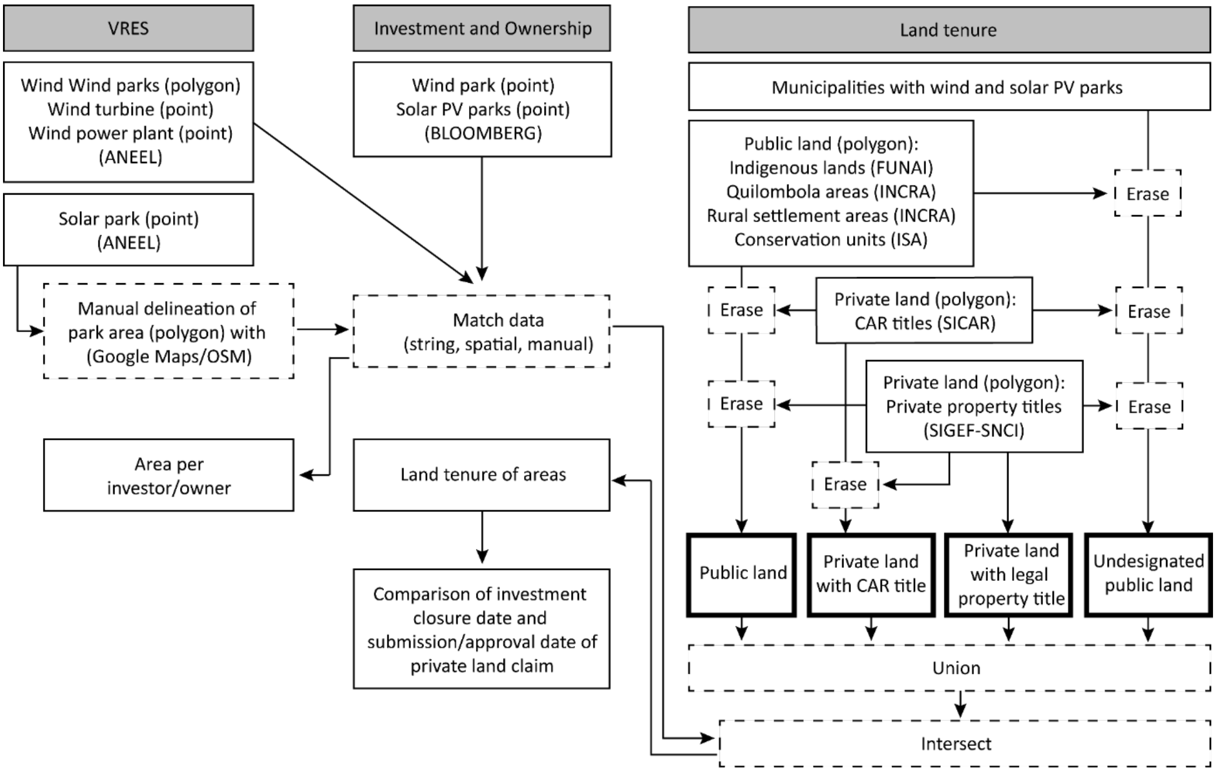
Supplementary Fig. 7: Example random sampling procedure for wind park Guirapá in the municipality Guanambi. The red shape is the original wind park. The green shapes are other wind or solar PV parks in the municipality. The points are 100 randomly chosen locations. The shapes surrounding the points are rotated and shifted shapes of the original wind parks on those points. Shapes which intersect with existing parks or which are not spatially fully contained in the municipality are removed. From the remaining shapes, a random shape is chosen (in orange) for the group of *Control random* areas. For the group *Control match wind resource* the shape is chosen, where the absolute difference between the mean wind power density of the original wind park in red and the mean power density of the shape is minimized.

Supplementary Table 5: Abbreviations in figures.

Abbreviation	**Meaning in Portuguese/Italian**	**English meaning**
Ltd|Ltda	Limitada	Limited liability company
SA|S/A	Sociedade Anônima	Public limited liability company
LLP	-	Limited liability partnership
CPFL	Companhia Paulista de Força e Luz	São Paulo Company of Power and Light
CGT	Companhia de Geração e Transmissão	Company for Transmission and Generation
SpA	Società per azioni	Company limited by shares
Inc.		Incorporated



Supplementary Fig. 8: Validation of ANEEL and BNEF (Bloomberg) wind and solar PV capacity data against independent data source IRENA.



Supplementary Fig. 9. GIS Model procedures for deriving information on land tenure. Applied to municipalities with wind and solar PV infrastructure ‘in operation’ or ‘in construction’.

Supplementary Information 2

SI 2.1 – Statistical comparison of land tenure categories

To statistically analyze, if a significant difference in land regulation patterns can be confirmed, we calculated the share of land regulation for each park and performed two-sided t-tests to compare the park areas with control areas for the four different land categories. Our analysis involved a sample of 574 wind parks and 44 solar PV parks, and the corresponding boxplots and results of the statistical analysis can be found in the appendix (Supplementary Fig. 5, Supplementary Table 3, Supplementary Table 4). The purpose of the t-tests was to determine if there were significant differences in the means between the control areas and the park areas for each land category (private land with legal property title, private land with CAR title, public land, and undesignated public land), for both wind parks and solar PV parks. With one exception, i.e. comparing public land in solar PV parks to control areas, the p values of the t-tests are well below 0.001 when testing differences in mean between the park areas of wind parks and solar PV parks compared to all types of control areas, confirming that the groups have different types of land regulation patterns.

SI 2.2 Cleaning GIS data

Land tenure data

We follow the methods introduced by ATLAS[55] to clean the GIS data, and inform here in detail about the performed steps. QGIS 3.28 and Python 3.9.13 with Geopandas were used to clean the GIS data. Although the data cleaning processes for CAR and SIGEF/SNCI data are very similar, the data quality of SIGEF and SNCI Data is by far better. Due to overlaps and erroneous geometries more than 50% of CAR area is lost during data cleaning, while the SIGEF/SNCI data set loses less than 5% of area.

CAR data

The Rural Environmental Registry CAR dataset was downloaded from the official Brazilian website at the end of 2022. As the dataset has to be downloaded for each district individually, only those from districts intersecting with the solar and wind plants were used (i.e. 132 municipalities). To clean the data, the 132 CAR shapefiles were merged to one large Geodatabase. The polygons that intersect with wind and solar parks were selected with *select by location* and duplicate geometry was removed. Furthermore, duplicates in the column COD_IMOVEL, i.e. the CAR registration code, were removed, prioritizing larger areas over smaller ones. To remove polygons with unnatural shapes, the CI (circularity index) was calculated according to the following formula: $CI = \frac{2\sqrt{\pi A}}{P}$, A being the area and P the perimeter. Polygons with CI smaller than 0.12 and polygons with a CI bigger than 0.98 were removed.

Furthermore, major polygons that contain more than 5 polygons within their boundaries were removed. The total CAR area resulting from our analysis is not sensitive to these rules, as total CAR area is reduced by less than 3% after excluding the above specified areas.

The CAR dataset was divided into poor and premium quality: premium polygons have less than 5% overlap with other CAR polygons and are therefore more trustworthy. Polygons with poor quality have more than 5% overlap with other CAR titles and therefore possibly lose a significant amount of area in the following cleaning process. If there are overlaps, premium CAR titles are prioritized over poor CAR titles. Within the two categories, overlaps were removed randomly. At the end polygons smaller than 1 ha were removed. Note, as we do not use CAR title specific meta-information, the order of prioritization of CAR titles does not affect our results - they are therefore insensitive to the particular choices made in these final steps.

SIGEF/SNCI data

SIGEF and SNCI polygons are both representing rural properties in Brazil. Therefore, they were merged, keeping the certification date. Duplicate geometry was removed. Again, shapes with unnatural CI (see above) were removed. Overlapping geometry was also removed, prioritizing titles with the most recent certification date.

Wind park data

Wind park data was of high quality in general, but a minor share of wind parks showed overlaps. We removed them, prioritizing the area of the wind park with the most recent operating date.