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Territorial Inequalities, Ecological and Material Footprints of the Energy Transition: Case Study of the Cantabrian-Mediterranean Bioregion

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Abstract: This study develops a methodology to assess the energy transition's territorial, ecological and material impacts on regions. As a case study, the methodology is applied to the Cantabrian-Mediterranean Bioregion, a geographical area constituting eight autonomous communities located in the north of Spain. Two energy demand scenarios for 2030 and 2050 were assessed. The 2030 scenario is based on the Spanish government's planning, and the 2050 scenario constitutes a net-zero emission economy based on electrification. Energy dependence between autonomous communities, energy and raw material needs, and availability are obtained for both scenarios. Results show a high imbalance between energy producer–consumer autonomous communities and an ecological and critical material deficit for the Bioregion. Two alternative scenarios are proposed, one based on self-sufficiency to ensure a balanced energy transition and another based on energy and material efficiency seeking that the ecological and critical material footprints do not surpass the planet's carrying capacity. The indicators and methodology proposed can be easily replicated elsewhere and help develop more equitable and sustainable territorial planning strategies.

Keywords: energy transition; renewable energy; socio-environmental impacts; territorial planning; energy colonialism; critical raw material footprint; energy self-sufficiency

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1. Introduction

During the 21st United Nations Framework Convention on Climate Change in Paris it was internationally agreed to keep global warming well below 2 °C [1]. In this respect, the European Union aims to be climate-neutral by 2050, with net-zero greenhouse gas emissions [2]. This means a shift from fossil fuels, which are greenhouse gas emitters, toward less polluting renewable energy sources (RES), where electrification plays a key role [3]. This shift is also called decarbonization as it reduces the carbon dioxide equivalent emissions which is the metric for greenhouse gases [4].

The way to achieve economic decarbonization with 100% renewables systems is being extensively studied (i.e., at a global [5], regional [6], national [7], territorial [8], or city level [9]). In general terms, such studies mainly focus on the associated feasibility, reliability, and costs. Social aspects that may arise from this transition are usually omitted, and environmental ones rarely go beyond reducing the carbon footprint through the shift from fossil fuels to clean technologies. Indeed, there is a lack of studies that jointly analyze the energy transition and the other impacts it may entail, both locally and globally, in a holistic way.

It is a fact that RES technologies imply large occupation space, impacting rural areas and biodiversity [10], highlighting the importance of linking spatial planning to energy planning [11]. Furthermore, decarbonization implies the requirement of vast amounts of raw materials used to produce clean technologies [12–17]. Raw material security of supply raises global and European concerns [18] as mineral shortages may put at risk the very development of the energy transition.

For these reasons, there is a need to use alternative indicators and in-depth local studies to assess such usually unconsidered aspects regarding the sustainability of the energy transition.

This paper tries to fill that gap by proposing indicators to evaluate energy unbalances, environmental and material footprints associated with energy transition scenarios. The main aim is to provide local and global decision-making tools to reduce social, ecological, and material impacts.

The methodology is applied to the case study of the so-called Cantabrian-Mediterranean Bioregion, hereafter referred to as the Bioregion, comprising eight autonomous communities located in the north-east of Spain. The Bioregion is an optimal case study to show the proposed methodology. This is because the Bioregion includes highly populated and unpopulated territories, highly industrialized autonomous communities and others mainly dependent on the tertiary or primary sectors, territories blessed with considerable wind resources and others richer in solar energy.

The paper is structured as follows. Section 2 presents three indicators to assess the sustainability of a given energy transition scenario. The first is the energy self-sufficiency indicator, evaluating the potential social impacts associated with the space consumption of clean technologies and extra-territorial energy dependence. The second is the well-known ecological footprint. The third is the critical global equivalent mineral footprint, which evaluates the limits of an energy transition due to potential material shortages and supply risks. The first and third indicators show foreign dependence and exposure to geopolitical instabilities, which are vulnerabilities with negative consequences. This has become evident in Ukraine's war, in which Europe's gas dependence on Russia is provoking severe economic consequences in Europe [19] and the world [20].

Section 3 describes the case study, scenarios and data used to apply the methodology for the Cantabrian-Mediterranean Bioregion. There are three temporary scenarios, 2030, 2050, and 2050 efficient. The first is based on the National Integrated Energy and Climate Plan (PNIEC) [21], which proposes to produce 74% of electricity with renewable generation and a 4% increase in electricity demand compared to the current energy situation due to the electrification of part of the energy demands. The 2050 scenario is based on replacing fossil energy sources with renewables, mainly through electrification in a 100% renewable electricity system. In the efficient scenario we consider additionally a reduction of energy and material demands trying to ensure that the ecological and global equivalent mineral footprints do not surpass the planet's carrying capacity. Finally, we present two technical scenarios: the trend scenario is based on the current trend of installing renewable nameplate capacity, and the balanced scenario is based on electricity self-sufficiency.

Section 4 presents the results, where we compare the proposed indicators for each main scenario and discuss the results, analyzing the implications, possible consequences, and solutions.

Finally, in Section 5, we show the main conclusions derived from the paper.

2. Methodology

The energy transition goal is to reduce fossil fuel consumption and greenhouse gas (GHG) emissions drastically using clean technologies. Therefore, the associated carbon footprint, expressed in tons of CO_2 equivalent, will significantly decrease since, at least in the use phase, clean technologies, including renewables or electric mobility, do not emit GHGs.

That said, clean technologies generate other impacts that cannot be measured through the carbon footprint alone. Important amounts of water, raw materials, and energy (most of which obtained from fossil fuels) are required to produce them. Moreover, the amount of surface used per MW produced is many times greater than their conventional counterparts, since renewable energies have a much lower power density than fossil technologies.

According to [22], the power density of photovoltaics and wind are 50 and 200 times lower than of natural gas, respectively. The result is that vast amounts of land are expected to be used for power generation, modifying landscapes, and intensifying global competition for land, thereby creating social tensions.

Strategies to implement clean technologies in the territories cannot forget these other aspects that go beyond accounting for direct CO_2 emissions. This is why we propose to evaluate additional criteria considering the environmental impact of technologies, their intensity in the use of materials and territory, and energy-dependence. To that end, we propose using three indicators: renewable energy self-sufficiency, ecological footprint, and what we call "global equivalent mineral footprint", as explained below.

2.1. Renewable Energy Self-Sufficiency

The first indicator is renewable energy self-sufficiency. We obtain it from the ratio between renewable energy generation and energy demand, as Equation (1) shows.

$$\text{Renewable energy self} - \text{sufficiency} = \frac{\text{Renewable energy generation}}{\text{Energy demand}} \times 100 \tag{1}$$

This indicator aims to show the degree of energy self-sufficiency of a territory with renewable sources. It has some interesting connotations since by comparing regions that form a unit, the interdependence between them can be seen. "Sacrifice regions", meaning net energy exporter territories making available more RES-devoted land than they need domestically, can be easily detected. This, in turn, is an indication of potential social conflicts. Moreover, it is an indicator of external energy dependency and consequential vulnerabilities in a 100% renewable system.

The ideal result would be a value slightly higher than 100%, with enough surplus to cover losses.

2.2. Ecological Footprint

The ecological footprint is an internationally recognized sustainability indicator used as a standardized measure of demand for natural capital. It compares how fast resources are consumed and waste is generated with the speed of nature to generate new resources and absorb waste measured in areas [23]. The calculation consists of converting the equivalent global biologically productive hectares to the direct and indirect consumption of energy, biomass, building materials, water, and other resources on a population basis. The per capita biological capacity available on Earth was estimated to be 1.6 gha in 2019, and the ratio of the humanity footprint to the per capita biological capacity was 1.75 [23], which implies humanity's total ecological footprint of 1.75 planet Earths.

Results are shown with the concept of "Planet Equivalent" [24]. However, instead of the ratio of an individual's (or country's per capita) footprint to the per capita biological capacity available on Earth, we used the ratio of the territory's ecological footprint to the territory's biocapacity. We named the result "Territory Equivalent". A value of 2 means that the Bioregion needs 2 times its territory biocapacity to compensate for its ecological footprint.

The ecological footprint is a powerful tool for explaining the demand for the regenerative capacity of biotic systems. However, it provides insufficient information when dealing with abiotic resources [25]. Indeed, the environmental impact of mining is hardly measurable in biologically productive areas, and this indicator is consequently insensitive to depletion problems. Therefore, the ecological footprint alone cannot assess the material impact of clean technologies and we need to resort to other indicators, such as the global equivalent mineral footprint as explained below.

2.3. Global Equivalent Mineral Footprint

In 1993, Schmidt-Bleek presented the Material Input Per unit of Service (MIPS), which aims to account for all materials moved to produce goods or a service from cradle to grave [26]. MIPS preceded the Planetary pressures–adjusted Human Development Index (PHDI), which considers the society's material footprint (defined as the global allocation of used raw material extraction to the final demand of an economy) and the ecological footprint in order to develop indicators of sustainability and wellbeing [27]. A drawback of MIPS or the PHDI is that as the materials are measured in kg or tonnes of material input, there is no discrimination in terms of quality and the problem of adding apples with pears arises [25,28]. For instance, they do not take into account the scarcity of these materials in the Earth's crust.

A thermodynamic approach to account for the mineral capital loss through extraction was proposed by Valero et al. [25,28] and applied to several case studies such as Latin America [29,30], Europe [15], or the USA [31]. In this same line, the concept of material debt is currently under development, unifying all materials into a single indicator, considering their respective qualities based on thermodynamic aspects of the resource [32].

Even if a rigorous thermodynamic assessment of raw material use is advisable, alternative indicators can be used to account for at least their individual scarcity degree in the crust. We propose the global equivalent mineral footprint where the material needs for the energy transition are compared to global mineral reserves for each material, which can be easily obtained from the United States Geological Survey (USGS) statistics [33]. Reserves refer to the known economically viable resources to be extracted.

As shown in Equation (2), the mineral requirements per capita associated with the material needs to deploy the clean technologies of a given region, multiplied by the ratio between the world's population and the world mineral reserves.

$$\text{Global equivalent mineral reserves footprint} = \text{Mineral requirement per capita} \times \frac{\text{World population}}{\text{World mineral reserves}} \quad (2)$$

The result shows the planet Earth's reserves that would be required to meet a global energy transition for each mineral if the same strategy were implemented worldwide. A result of 1 means that all currently available reserves would be required to meet the material demands if the same energy transition were to be performed globally. It is, therefore, a matter of extrapolating the requirements of a territory to the world as a whole and determining the scenario's viability by considering global justice. If resources are considered the result is the Global equivalent mineral reserves footprint.

3. The case of the Cantabrian-Mediterranean Bioregion

3.1. Description of the Bioregion

The Cantabrian-Mediterranean Bioregion is a natural geographical space with sufficient resources to constitute a unit of resilience that addresses, with a global vision in the medium and long term, the challenges posed by adaptation to the climate emergency, as well as the planning of a harmonious and sustainable balanced development [34]. The idea of the Bioregion is to agree on fundamental values that foster human dignity, respect for nature, and the protection of common goods beyond current generations [35]. The objectives should be achieved by promoting harmony between the ecosystem communities to reduce their joint ecological footprint, proposing organizational structures adapted to the territory's ecological, economic, and social environment, thereby maintaining the cohesion and harmony of its inhabitants [35]. The autonomous communities of Cantabria, the Basque Country, La Rioja, Navarre, Aragon, Catalonia, the Valencian Community, and the Balearic Islands satisfy the characteristics mentioned above and hence can be considered as a Bioregion. The so-called Cantabrian-Mediterranean Bioregion is shown in Figure 1, marked in green. It covers a surface area of 136 thousand km^2, 27% of the Spanish territory. It has 18.9 million inhabitants, 40% of the Spanish population, with a gross domestic product (GDP) of 543 million euros, 43.7% of the Spanish GDP [36].

Figure 1. Cantabrian-Mediterranean Bioregion in the Spanish map (in green).

The Bioregion current final energy consumption (energy consumed by end users) is shown in Figure 2 for 2018. This year has been considered as the reference scenario as it is the year with the most recent available data for most communities. The reference year for electricity demands corresponds to 2020 due to its low variation compared to 2018 and because the data is more recent. If energy sources for electricity production are considered, fossil fuels represent 78% of the final energy consumption, a strong energy dependence on fossil fuels, which is in line with the world's average [37]. This fact makes the Cantabrian-Mediterranean Bioregion a good case study whose conclusions may be globally generalized.

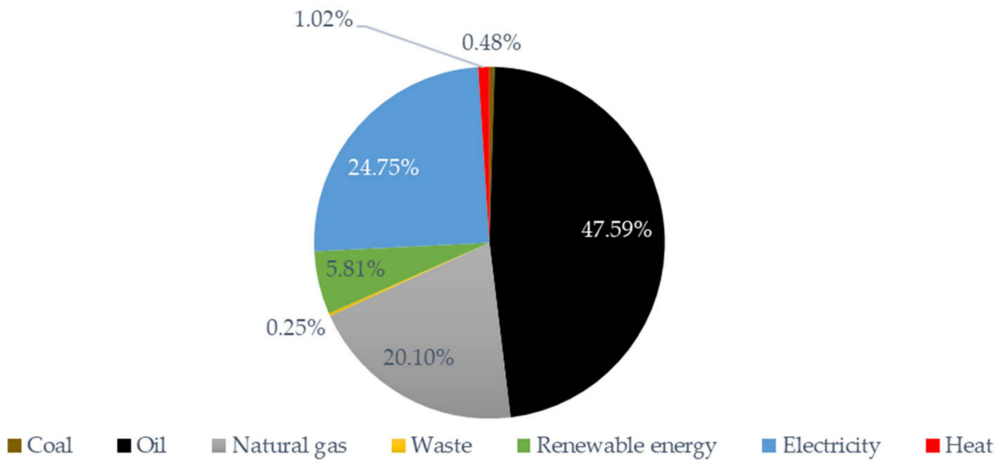


Figure 2. Energy sources in final consumption in reference scenario.

Table 1 shows other interesting data about the Bioregion in the reference scenario. It is highlighted that low-populated autonomous communities export electricity to high-populated ones.

Table 1. Bioregion characteristics.

Indicator	Aragon	Balearic Islands	Valencian Community	Cantabria	Catalonia	La Rioja	Navarre	Basque Country
Population density (people/km^2)	28	240	215	109	237	62	63	302
Area (km^2)	47,720	4992	23,255	5321	32,113	5045	10,391	7234
GDP per capita	28,727 €	23,206 €	23,206 €	24,383 €	31,119 €	28,200 €	32,141 €	34,142 €
Electricity demand (GWh)	10,109	4942	25,457	3906	43,840	1621	4844	14,955
Electricity imports (GWh)	−7997	1427	6347	2100	888	−171	−1767	8788

The Spanish electrical grid operator (REE) expects that by 2026 [38], most of the new renewable nameplate capacity will be installed in low-populated areas. Figure 3 represents renewable power generation capacity per inhabitant over population density. The most significant difference among communities can be found between the case of Aragon and the Basque Country. Aragon, with a population density 11 times lower than the Basque Country (27.75 to 301.62 inhabitants per km^2), has installed 92 times more renewable energy capacity per inhabitant than the Basque Country (8.7 to 0.1 kW/inhabitant). We used the same installation trend for the trend scenario explained below.

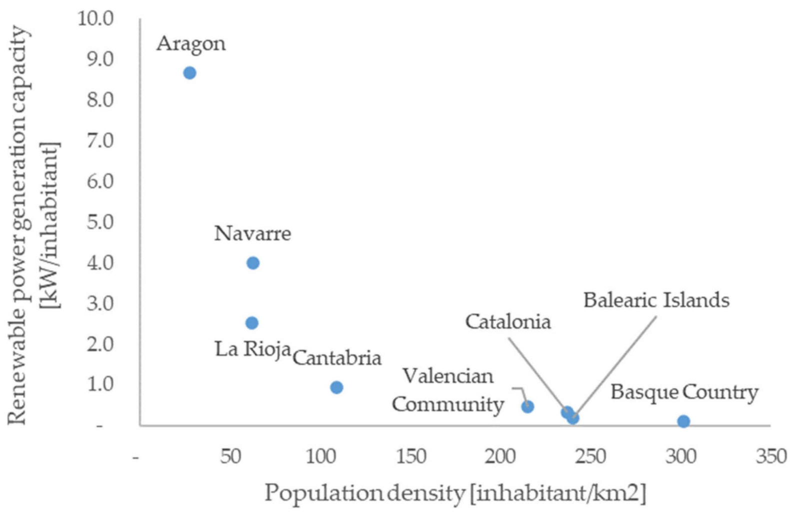


Figure 3. Renewable power generation capacity and population density relationship by 2026, elaborated with data from [38].

3.2. Energy Transition Scenarios for the Bioregion

The methodology described in Section 2 is applied to the following main energy transition scenarios for the Cantabrian-Mediterranean Bioregion. Results are compared with the reference scenario that represents the current situation in the Bioregion.

- The 2030 scenario is based on the National Integrated Energy and Climate Plan (PNIEC) [21], which proposes to produce 74% of electricity with renewable generation and a 4% increase in electricity demand. This should be achieved by replacing conventional boilers with heat pumps and by electrifying combustion vehicles. With additional energy efficiency measures, a reduction of 15% in the final energy consumption is expected. Furthermore, PNIEC plans to install 57 GW of renewable nameplate capacity and deinstall 16 GW nameplate capacity of conventional power plants in Spain.
- The 2050 scenario is a zero-emission economy, based on replacing fossil energy sources with RES, mainly through electrification, in a 100% renewable electricity system.
- The 2050 efficient scenario considers a reduction in energy and material demands but maintains the predictions of increased activity thanks to greater use of public transport, shared mobility [39], shared road freight transport [40], and train transportation

instead of road freight transportation [41]. In addition, greater energy efficiency in buildings due to isolation is considered (20% energy demand reduction for heating).

The main scenarios explained above are complemented with the following technical scenarios:

- The trend scenario considers the current new renewable nameplate capacity installation trend by territory.
- The balanced scenario is an alternative option in which the renewable nameplate capacity installation by autonomous communities is estimated according to their domestic energy needs. When an autonomous community does not have enough renewable resources, the neighboring autonomous communities provide the necessary renewable resources. The installed nameplate capacity is equivalent to the trend scenario but differs in the distribution among autonomous communities.

For all the scenarios, we evaluated the availability of renewable natural resources to satisfy demands. The model assumptions are explained in the following section.

3.3. Model Assumptions

The electrical system model is based on an energy balance to meet energy demands. We considered full load hours for each technology and territory. We considered a power density installation between 4 to 8 MW/km^2 to estimate the polygonal surface area occupied by wind farms based on [42,43]. There is no resource scarcity for ground photovoltaics (PV) in any scenario, considering the polygonal area occupied by PV of 70 MW/km^2 [44].

We modelled the 100% renewable electrical system with a constant monthly overproduction of 38%. The model is mainly based on wind and solar photovoltaics considering global technological trends [3], with support from concentrated solar power as well as hydro, biomass, and biogas power plants, in line with the studies of Jacobson [5] and the European Commission [45], but with a higher overproduction together with storage. Storage needs have been estimated at 11% of installed renewable power due to interconnections [5].

Table 2 shows the assumptions for the sectorial transformation for the 2050 scenarios. We considered an increase in consumption linked to the expected population and GDP growth [46].

Table 2. Assumptions for 2050 scenarios.

Sectorial Transformations	Assumptions
Transport electrification	Combustion cars replacement by battery electric vehicles as this is the lowest cost solution [3,47,48]. Electrification of existing diesel railroads [49]. Maritime and air transport have not been assessed.
Zero-emission industry	Replacement of fossil fuel energy sources considered on the 2050 European Commission Reference Scenario for industry [50] by biofuels (mainly biogas) and hydrogen. An 80% electrolysis efficiency for hydrogen production.
Electrification of household and service sectors	Electrification of heating, domestic hot water, and cooking [51] as it is the highest efficiency solution [3]. Residential consumption increases linearly to population growth, choosing an income elasticity value of 0.2 between GDP and consumption increase [52].
Primary sector	Energy consumption in the primary sector does not change in 2050. Consumption reduction offsets the primary sector growth thanks to efficiency [45]. On the other hand, there is a greater need for a modal shift to reduce its emissions [53].

Cost constraints have not been considered because we would incorporate considerable uncertainty in the model due to the recent high price volatilities of raw materials [54] and renewable technologies [13].

It is necessary to point out some limitations of our simulations. We assume a perfect electricity transmission with no congestion or frequency regulations and perfect matching between energy generation, energy storage, and energy demand. Furthermore, there are uncertainties in extreme weather events where energy demands and production may vary. Obviously, this is a best case scenario because such aspects may worsen the system requirements in terms of more renewable power installations, storage capacity, grid infrastructure, etc. To address this uncertainty, we assume an energy overproduction to guarantee that energy demand can always be supplied. We also considered distribution and transmission line material requirements that guarantee an appropriate interconnection and electricity distribution.

We assume that these limitations do not change the results significantly, since we compared the electrical power system of the Bioregion for the 2050 scenario with others already proven for Spain. More detailed information is shown in the Supplementary Material.

Disruptive technological changes, which were not considered in our model, can occur during the energy transition, requiring fewer materials or space resources. In this respect, it is not our goal to predict the future but to guide future policies based on the available technologies and existing global plan trends.

We gathered the data with the most recent available reports, there may be some data uncertainties or recent changes in activity or demand predictions, but these uncertainties do not change the conclusions of this paper.

3.4. Data Gathering

We analyzed the energy balance reports disaggregated by each autonomous community's economic sector and energy source. Table 3 and the Supplementary Material show the data gathered with the corresponding information sources.

Table 3. Data gathering.

Scenario	Information Gathered	Autonomous Community or State	Reference
Reference scenario	Energy balance reports and sectorial energy demand.	Aragon Balearic Islands Catalonia Valencian Community Basque Country Navarre Spain	[55] [56] [57] [58] [59,60] [61] [62–64]
Reference scenario	Electricity mix, electricity demand, and nameplate capacity	All autonomous communities	[65,66]
Reference scenario	Renewable capacity trend installation	All autonomous communities	[38]
Reference scenario	Final energy consumption by mode of transport	All autonomous communities	[63,67]
Reference scenario	Vehicle fleet	All autonomous communities	[68]
Reference scenario	Km travelled by mode of transport and activity forecast	All autonomous communities	[50,69]
Reference scenario	Final energy consumption by uses in residential and service sectors	All autonomous communities	[70]
2030 Scenario	Energy demands	All autonomous communities	[21]
2030 Scenario	De-installation of conventional thermal plants	All autonomous communities	[21]
2050 Scenario	Sectoral decarbonization	All autonomous communities	[3,53,71]
2050 Scenario	2050 zero-emission industry demands forecast	All autonomous communities	[45,50]
2050 Scenario	Growth and activity forecast	All autonomous communities	[45,50,72]
All scenarios	Renewable technologies capacity factor	All autonomous communities	[42,66,73]
All scenarios	Renewable resources (biomass, wind, biogas . . .)	All autonomous communities	[42,74–77]

As no report was available for the autonomous communities of Cantabria and La Rioja, we estimated their final energy consumptions for oil and coal according to their contribution to national GDP, considering the link between GDP and energy consumption [78,79].

We obtained the material requirements for the evaluated technologies. For electric mobility, estimations for heavy and light trucks, motorbikes, and electric bikes were obtained from [80]. Data for battery storage technologies, electric mobility, and market forecasts for 2050 were obtained from [13]. The material demand for each technology is presented in the Supplementary Material based on [12,13,38,80–85]. We considered two material intensity ranges. The lower range assumes the minimal material requirements found in the bibliography for each technology and a 1% annual improvement in using critical materials in electromobility and batteries. The upper range assumes the maximum material requirement found in the bibliography. Results show the mean value of both ranges, but more detailed data are shown in the Supplementary Material.

We did not consider technology lifetimes and recyclability, so the results show the minimum material requirements for an energy transition.

4. Results

Based on the model assumptions and data provided in the previous section, we first estimated the energy demands and consequences of economic electrification for the 2030 and 2050 scenarios, as shown in Figure 4.

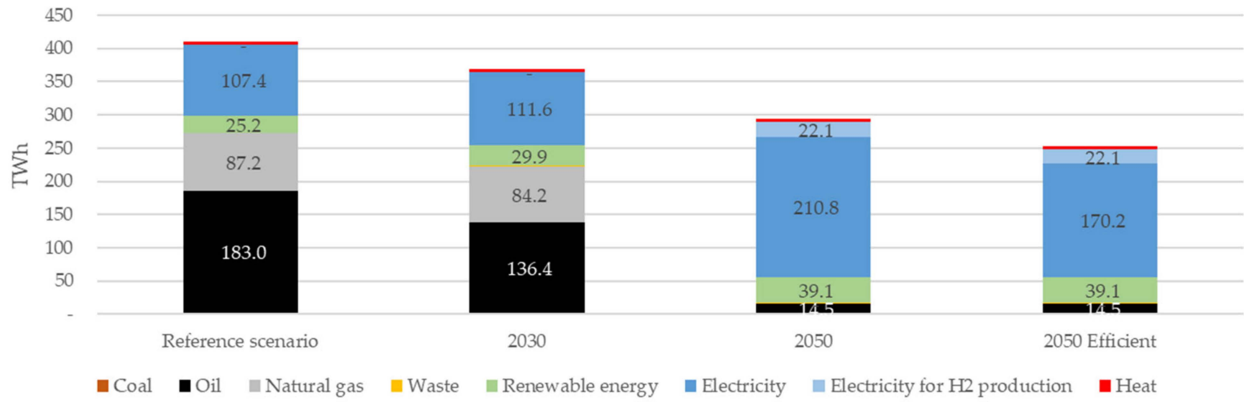


Figure 4. Bioregion final energy consumption in TWh.

Total energy demand decreases in all scenarios without reducing economic activity thanks to electrification, which is more efficient. Due to partial transport electrification, 2030 oil demands decrease, increasing electricity demand.

By 2050, as most of the economy is electrified, electrical energy represents 79.37% of the final energy consumption, 233 TWh, doubling the current electricity demand. Electricity demand for hydrogen production accounts for 22 TWh. A small oil-dependent fraction (4.75%) is still considered for difficult to decarbonize sectors, such as primary sector and part of the industry sector. The 2050 efficient scenario achieves a greater electricity demand reduction of 40 TWh thanks to land transport efficient measures and building insulation.

Figure 5 shows the Bioregion's renewable nameplate capacity for the reference, 2030 and 2050 scenarios. Thermal represents the conventional thermal power plants fueled with conventional fuels in 2020 and 2030. In 2050 thermal refers to biogas and biomass power plants. Comparing energy demands with renewable resources for the 2050 scenarios, the Bioregion has sufficient energy resources, except oil, to be self-sufficient.

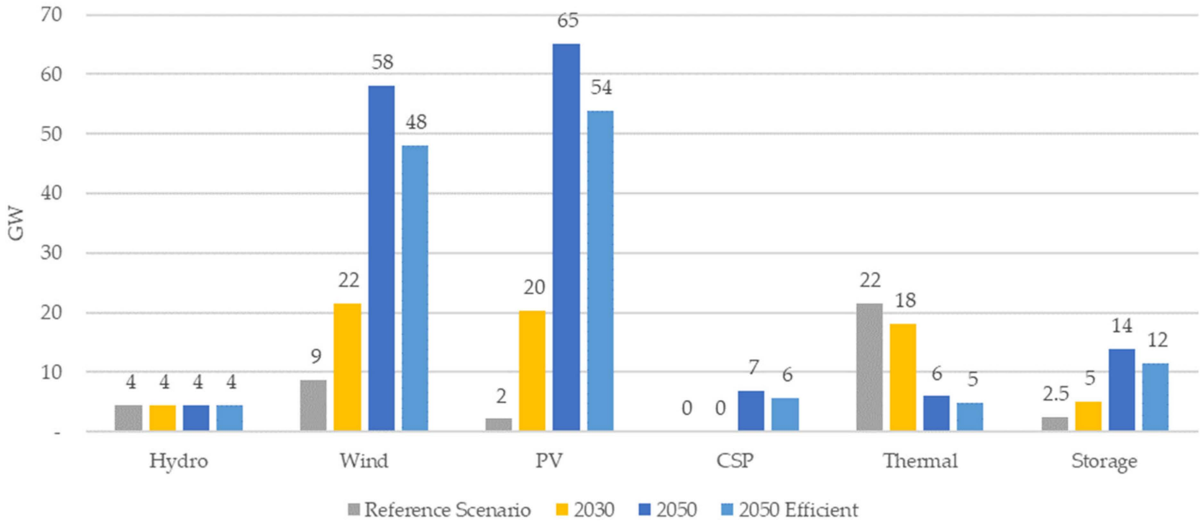


Figure 5. Power capacity in the Bioregion for the electricity system.

4.1. Renewable Energy Self-Sufficiency

We evaluated the renewable electricity self-sufficiency as explained in 2.1 for every autonomous community of the Bioregion 2030 and 2050 scenarios, considering the trend and the balanced scenarios.

Figure 6 shows the renewable electricity self-sufficiency in the reference scenario. The low-populated autonomous communities have the highest share of renewable production, which indicates that low-populated autonomous communities are closer to energy transition targets than high-populated ones.

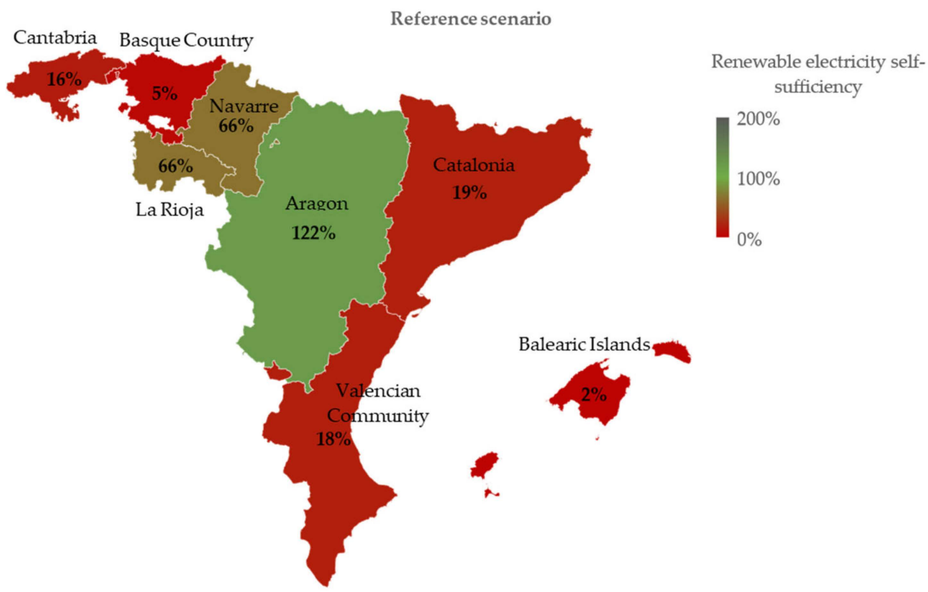
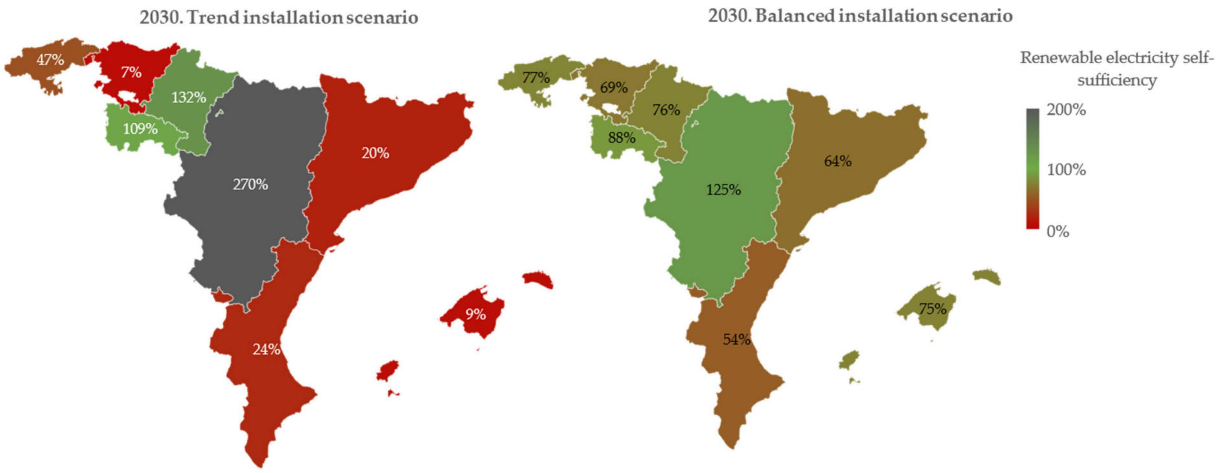


Figure 6. Renewable electricity self-sufficiency in the reference scenario.

Figure 7 shows the renewable electricity self-sufficiency of each autonomous community versus their electrical demand in 2030 for trend and balanced scenarios.



(**a**) (**b**)

Figure 7. Renewable electricity self-sufficiency in 2030. (**a**) Trend scenario; (**b**) balanced scenario.

The trend scenario for 2030, based on the current nameplate capacity installation trend and PNIEC goals, expects that the Bioregion imports 11.5 TWh of electricity by 2030, 9% of its demand, showing unbalances between electricity production and consumption. These unbalances are beginning to provoke protests in Spanish autonomous communities to defend their territory [86,87]. In addition, renewable generation concentrated in the same autonomous community is less stable and requires more storage than a distributed renewable generation.

On the other hand, the balanced scenario presents a Bioregion which does not import electricity and satisfies its electrical demand with 74% renewable electricity, avoiding the electricity generation concentrated in the same autonomous communities. The Valencian Community is the only autonomous community with a renewable generation-demand ratio lower than 60% due to its nuclear power capacity.

All autonomous communities have enough onshore wind resources and photovoltaic potential in the balanced scenario by 2030. The total polygonal surface area required for the new renewable installations in the Bioregion is between 1600 and 3200 km^2, around 2% of the Bioregion area. Adding the power already installed requires between 2500 and 5000 km^2 polygonal surface area. Energy planning and spatial planning are considered essential to reach a balanced scenario due to the following reasons:

1. Renewable energies require large surface areas. Even if they are polygonal areas, the territory is conditioned over an extended period of at least 30 to 100 years. Its installation must seek compatibility with traditional land uses and the maintenance of vital ecosystem services [88].
2. An emerging imbalance between electricity production and consumption in autonomous communities could lead to increased inequalities. The least populated autonomous communities would generate energy for the most populated ones, allowing its higher development and attracting more population.
3. To avoid renewable installation bubbles. By June 2022, the PNIEC targets for 2030 were doubled, adding together the power in service and the power with access permits [89].

Figure 8 presents the trend scenario and balanced scenario evaluated for the 2050 and the 2050 efficient scenarios; it shows the renewable electricity generation of each autonomous community versus its electrical demand.

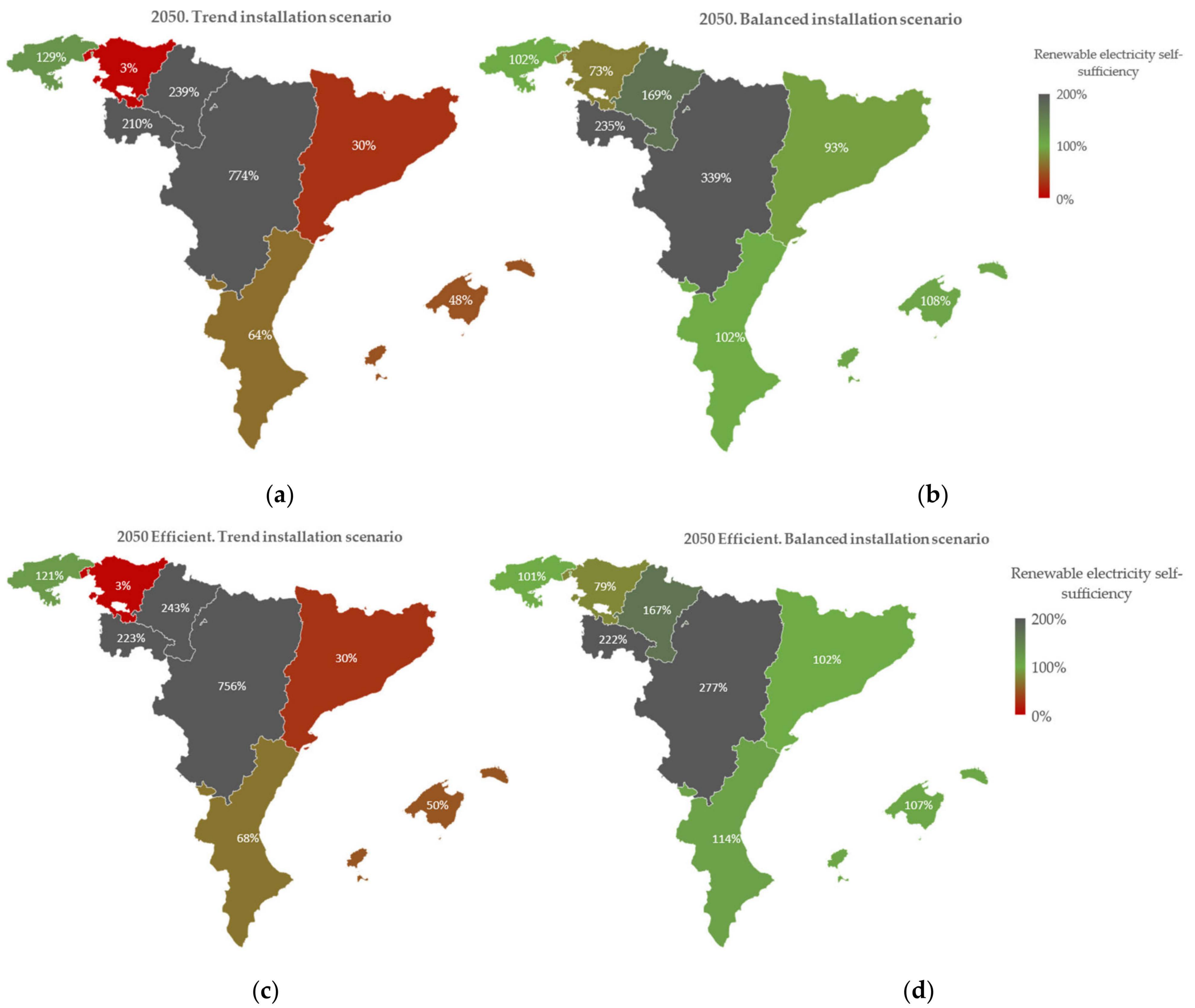


Figure 8. Renewable electricity self-sufficiency in 2050; (**a**) 2050, Trend scenario; (**b**) 2050, Balanced scenario; (**c**) 2050 Efficient, trend scenario; (**d**) 2050 Efficient, balanced scenario.

In the 2050 trend installation scenario, the largest renewable power installation occurs in Aragon, 62.5 kW/inhabitant, which is a mainly exporting energy community, as it has the highest ratio of renewable power installation compared to its demand, 3.69 MW/GWh, producing seven times its electricity demand. The second highest renewable power installation occurs in Navarre (20 kW/inhabitant or 1 MW/GWh, producing two times its electricity demand. On the contrary, there is hardly any renewable power installation in communities with a higher population density, which are mainly importing energy communities, such as the Basque Country (0.2 kW/inhabitant or 0.01 MW/GWh), and Catalonia (1.5 kW/inhabitant or 0.13 MW/GWh). The most significant imbalance occurs between the autonomous community of Aragon, with a renewable installation per inhabitant 314 times greater than the Basque Country. Furthermore, in the trend scenario, the power system is unstable as most renewable installations are concentrated in the same areas with the same full load hours, requiring more storage capacity than planned.

In the proposed 2050 balanced installation scenario, all autonomous communities range between 24 kW/inhabitant to 5 kW/inhabitant or 1.42 MW/GWh to 0.39 MW/GWh. There are communities that cannot meet their demands as they do not have enough wind resources. Accordingly, the missing power is installed in the autonomous communities with spare wind resources. Another alternative is the development of offshore wind power. On the other hand, there is no shortage of photovoltaic resources. Moreover, PV potential installation on building roofs is between 30% [77] and 51% [76] of all PV power capacity needed in the 2050 scenarios.

Efficient scenarios show similar results to their non-efficient versions in the trend installation scenario. However, the balanced scenario shows that all autonomous communities may be self-sufficient (with the exception of the Basque Country), reducing unbalances among them. All the autonomous communities range between 17 to 4.3 kW/inhabitant and 1 MW/GWh to 0.34 MW/GWh.

Figure 9 represents the polygonal area required to install wind and PV renewable power for all the considered scenarios. We considered a power density of 6 MW/km^2 to obtain the polygonal surface area occupied by wind farms and 70 MW/km^2 for PV. The 2050 scenario requires 11,554 km^2 of surface area (8.49% of its territory) to decarbonize the economy through electrification, while the 2050 efficient scenario requires 8791 km^2 (6.46% of the territory).

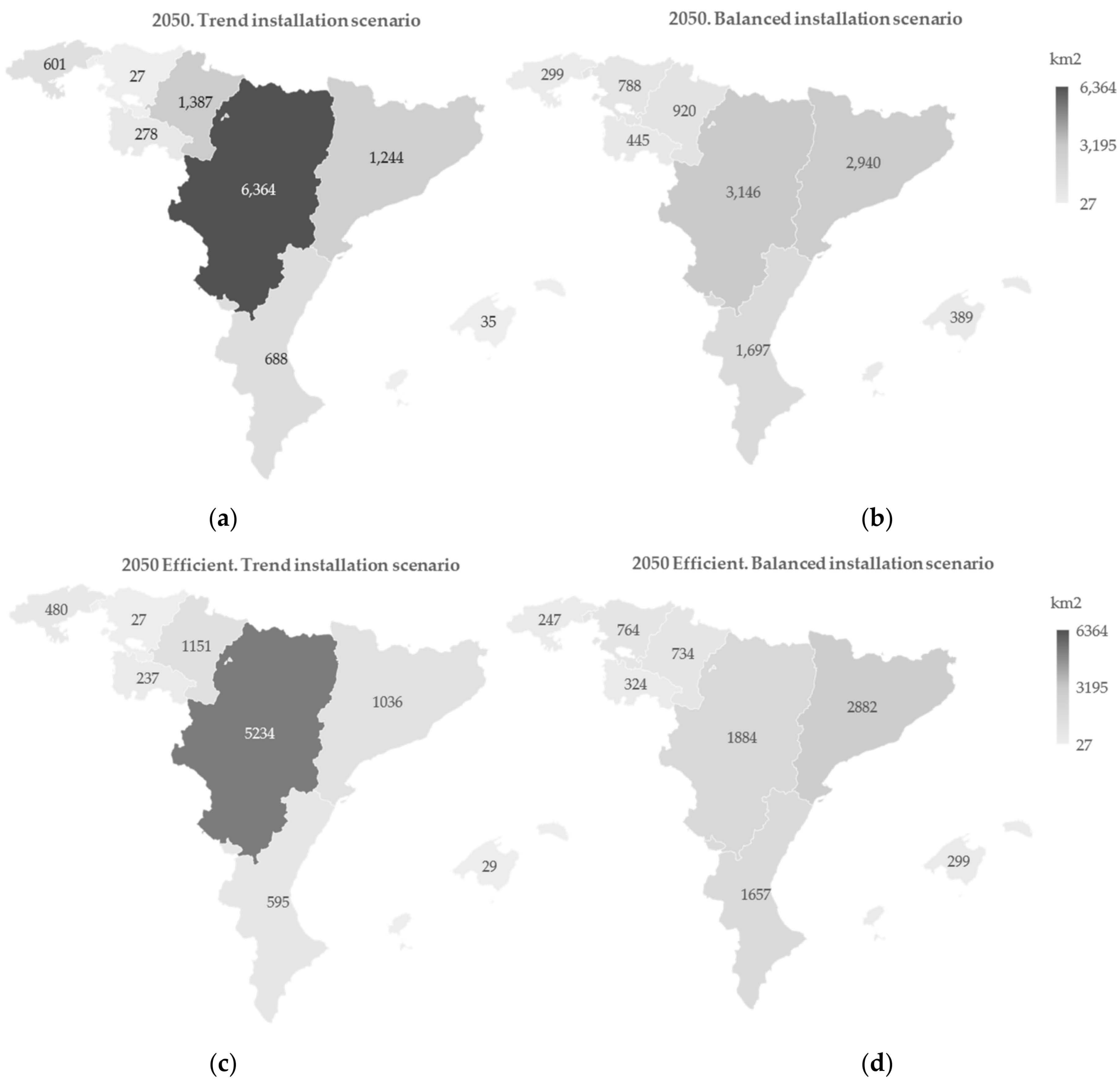


Figure 9. Wind and PV polygonal area occupation in km^2. (**a**) 2050, Trend scenario; (**b**) 2050, Balanced scenario; (**c**) 2050 Efficient, trend scenario; (**d**) 2050 Efficient, balanced scenario.

In the trend scenarios, most of the area occupied is in unpopulated autonomous communities. It implies that Aragon, the most depopulated autonomous community, has an area occupied by renewable energy installations equivalent to the size of autonomous communities such as the Basque Country, Navarre, Cantabria, or the Balearic Islands, to meet foreign electrical demands.

Suppose this installation trend is replicated elsewhere, with rural and unpopulated regions supplying energy necessities of urban and populated regions. In that case, it may cause significant imbalances between autonomous communities or territories, with serious social problems, as has already occurred in the mining case described in the Global Atlas of Environmental Justice [90], raising a global concern about energy colonialism in the energy transition [91]. On the other hand, these extreme energy dependences may lead to vulnerabilities and supply risks.

Should these populations be compensated in some way? Will the populations allow the occupation of the territory? Will the renewable energy protests limit the energy transition?

The proposed balanced scenario has lower regional imbalances, which may facilitate the population's acceptance of the energy transition. It should be highlighted that the lower space requirement in the 2050 efficient balanced scenario allows all autonomous communities to require below 3000 km^2. As mentioned before, energy planning policies linked to land use planning are necessary for this scenario. For that, the physical linking of demand with production is necessary, moving energy consumption points to energy production points thanks to different incentives, e.g., energy price. It may lead to industry movement to depopulate autonomous communities, thus improving population balance.

Some questions arise in the energy transition planning. Should unpopulated regions supply the total energy needs of populated regions? Or should a balanced energy transition be performed? At the same time, the same questions arise regarding the ecological footprint and biocapacity concepts. Is a society with a unitary territory equivalent but unbalanced between autonomous communities sustainable?

4.2. Ecological Footprint—Territory Equivalent

Based on the previous work performed by Valero and Torrubia [92], where the Bioregion's ecological footprint for the reference scenario was obtained, we estimated the Bioregion's ecological footprint for the proposed scenarios, considering the CO_2 emission reductions for energy sources and the emissions from the life cycle of renewable technologies [93], electric light duty vehicles [94], high duty vehicles [95], and motorbikes [96]. All other sectors and biocapacity were considered constant for the 2050 scenario.

As mentioned in the methodology, results are related to the concept "Planet Equivalent". However, instead of the ratio of a territory footprint to the per capita biological capacity available on Earth, we used the ratio of the territory's ecological footprint to the territory's biocapacity.

Figure 10 presents the Bioregion Territory Equivalent comparing all scenario results. No autonomous community is sustainable in the Bioregion in terms of ecological footprint in the reference scenario, but the ecological footprint of unpopulated autonomous communities is considerably lower than that of populated autonomous communities. As a whole the Bioregion needs more than four times of its territory biocapacity to compensate for its ecological footprint.

The CO_2 emission reduction of energy sources in the proposed scenarios shows how the ecological footprint decreases thanks to decarbonization. The 2050 scenarios indicate that some autonomous communities can be seen as "ecological reserves". This means that their biocapacity exceeds their footprint, absorbing more CO_2 than they produce. These autonomous communities are Aragon, La Rioja, and Navarre, the unpopulated autonomous communities. However, it is not enough to offset the ecological footprint of the populated autonomous communities: 2.3 times of the Bioregion territory's biocapacity is still needed to offset the total ecological footprint in the 2050 scenario and 2.1 times in the efficient scenario.

An energy transition is insufficient to match the Bioregion's ecological footprint to its biocapacity. It indicates the need for changes in the rest of the sectors and consumption patterns, mainly in the agriculture sector and food consumption as has been highlighted recently in Spain [97].

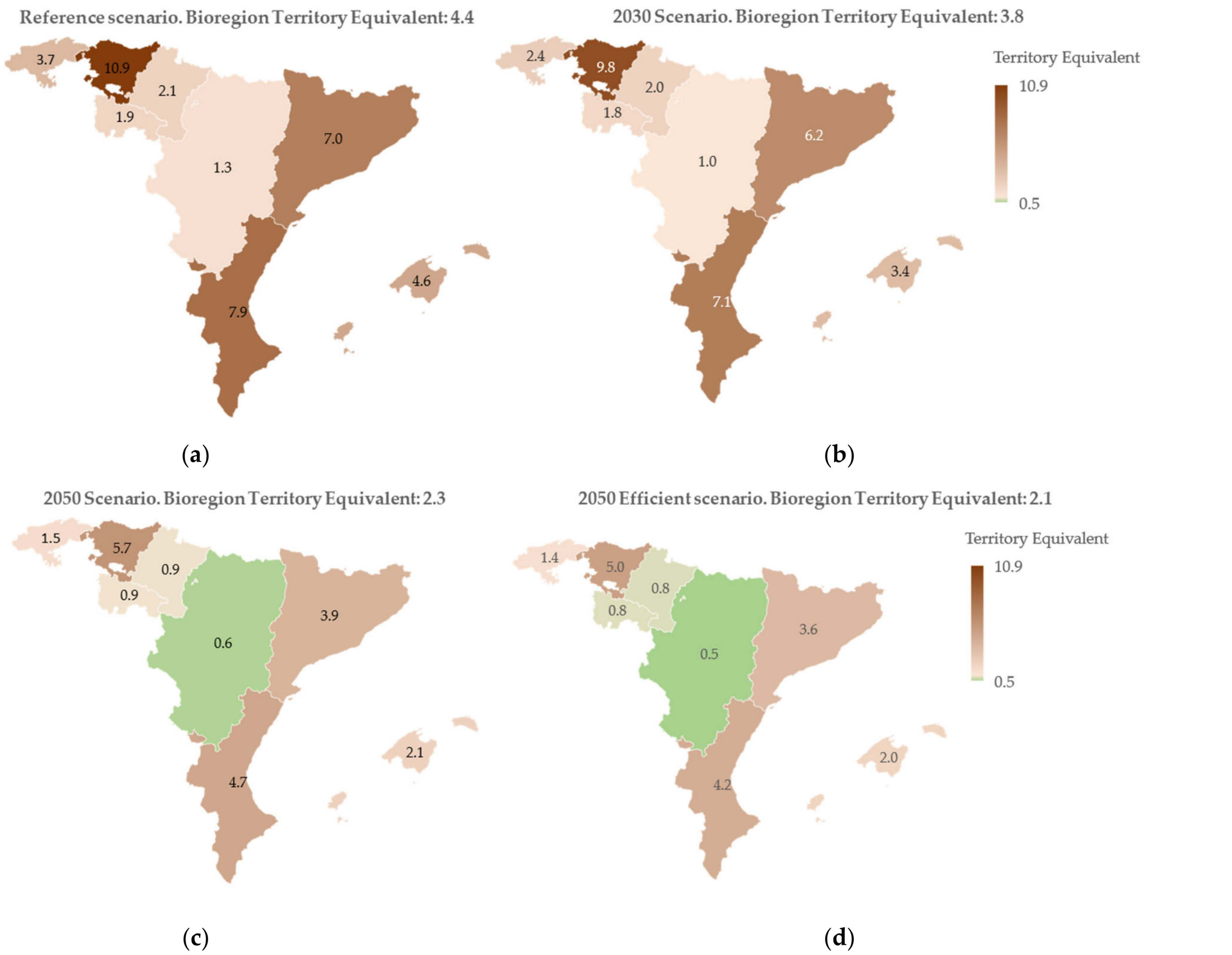


Figure 10. Bioregion Territory Equivalent. (**a**) Reference scenario. Data obtained from [92]; (**b**) 2030 Scenario; (**c**) 2050 Scenario; (**d**) 2050 Efficient scenario.

4.3. Global Equivalent Mineral Footprint

Material footprint results show that 37 million to 45 million tonnes of materials are needed to decarbonize the economy, representing a material footprint between 2.25 and 2.76 tonnes per capita.

What if the whole world were to make the same energy transition? We recalculated the material demand, assuming that the entire planet makes an equivalent energy transition, and then compared the figure with planetary resources and reserves to answer the question. We performed the comparison to understand the impact of a global energy transition with globally accepted technologies and current Bioregion lifestyles, considering the scenarios of world population [98] and bioregion population.

Figure 11 shows the global equivalent mineral reserves footprint for each temporary scenario. As the energy transition is at its beginning and there are no high material demands yet, the reference scenario is not shown.

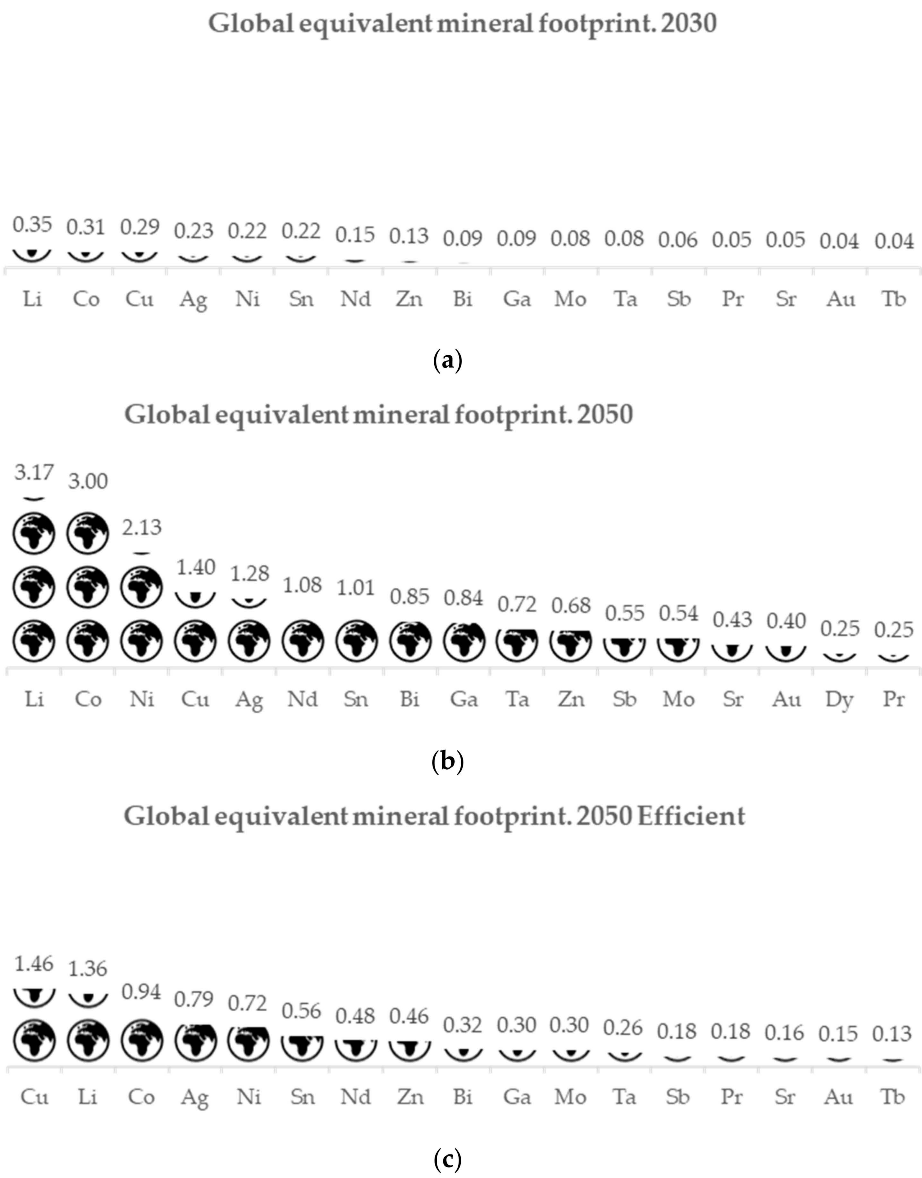


Figure 11. Global equivalent mineral reserves footprint. (**a**) 2030 Scenario; (**b**) 2050 Scenario; (**c**) 2050 Efficient scenario.

The global equivalent mineral reserves footprint for 2030 shows how the energy transition starts to demand materials requiring more than a third of global lithium reserves. However, in the 2050 scenario, 3.17 times the known lithium reserves are required, with more materials exceeding the planetary known reserves such as cobalt, nickel, copper, silver, and tin. On the other hand, the 2050 efficient scenario decreases the global pressure over mineral reserves, but there is still room for improvement, as 1.36 times the known lithium reserves are still required. Supplementary Material shows the results of the rest of the materials.

If we consider resources, the global equivalent mineral resources footprint shows that a high amount of the known resources of lithium (79%), nickel (68%), and neodymium (56.5%) among others are required to perform a global energy transition.

Suppose almost all resources of some materials and several times the planet's known reserves are required to meet a global energy transition. In that case, significant inequalities are expected between countries in achieving the energy transition due to the lack of access to materials. Together with the context of global warming, it can lead to severe geopolitical conflicts [99].

The results indicate the criticality of mineral materials, their scarcity relative to their consumption and the local supply risks they may entail. These supply risks may constrain the technological development necessary to achieve an energy transition at regional and global levels. The high pressure on critical materials also indicates the need to consider scenarios with a more significant reduction in consumption [100] and more efficient use of the mineral materials necessary for an energy transition. Furthermore, the global equivalent reserves footprint shows the minimum mineral requirements for an energy transition as the life cycle of the products and subsequent recycling rate are not taken into account. This also indicates the need to find more deposits that guarantee a global energy transition and a circular economy that minimizes waste materials.

The result of the global equivalent mineral footprint if everyone performs the same energy transition indicates the unsustainability of current lifestyles in the Bioregion. However, similar results are obtained compared with global north lifestyles. The result for European citizens performing the same energy transition indicates that one-third of lithium and cobalt reserves are needed, in addition to one-sixth of silver, nickel, neodymium, and copper reserves when Europe represents a tenth of the world's population.

5. Conclusions

This work is based on the novelty of analyzing the ecological, territorial, and critical materials footprint alongside energy dependencies in a case study of a Bioregion. Energy self-sufficiency, ecological footprint, and global equivalent mineral footprint analysis are proposed as additional indicators for the assessment of energy transition models and so to help in territorial planning. The analysis identifies social and energy imbalances, ecological, and material issues, facilitating the achievement of more balanced energy and territorial strategies at regional and global levels through successive iterations, thus reducing social, ecological, and material impacts.

The methodology was applied to the Cantabrian-Mediterranean bioregion transition scenarios for 2030 and 2050 as a case study. Both scenarios reduce consumption due to electrification without reducing activity. In a balanced scenario, by 2030, all the autonomous communities have sufficient wind and photovoltaic resources to cover their demands. In the 2050 scenario, final consumption is reduced by 29%, thanks to electrification, which accounts for 80% of final consumption in an electrified economy and has sufficient energy resources to achieve energy self-sufficiency, except oil. However, there is a lack of onshore wind resources to meet 2050 demands in the Basque Country, Catalonia, the Valencian Community, and the Balearic Islands. Thus, offshore wind, or energy imports from Aragon and Navarra are necessary and required. On the other hand, roofs may accommodate between 30% and 51% of the installation of photovoltaic power. The required surface area of a 100% electrical power system is between 7300 and 14,600 km^2.

According to the current trend, new renewable power will be installed in depopulated autonomous communities, increasing inequalities between energy-producing and energy-consuming autonomous communities, and aggravating rural depopulation and imbalances. This trend may worsen reaching imbalances in renewable installation of 62.48 kW/inhabitant in the most depopulated autonomous community versus 0.2 kW/inhabitant in the most populated autonomous community by 2050. The same trend observed in the Bioregion can serve as a global example of what happens when energy planning is not linked to the territory. These results serve to plan territories that have not yet begun to carry out an energy transition in other parts in a balanced way.

Therefore, adequate energy and land use planning are necessary to give renewable power installation in the Bioregion together with the high space requirements for renewable energies. First, we need to avoid falling into speculative bubbles fueled by the climate emergency, which could generate a negative opinion of renewable energies, as may be happening at present with recent demonstrations in rural areas. Second, we need to achieve a robust and resilient system with distributed renewable generation. Third, we need to achieve a balanced transition by avoiding imbalances between autonomous communities.

For this reason, this work proposes installing renewable power in accordance with the energy demand of each territory, seeking self-sufficiency as far as possible and avoiding energy colonialism practices or extreme energy dependences. When it is not achieved, the autonomous communities with high renewable resources will provide the remaining energy. The question arises as to whether energy-producing autonomous communities should be compensated with mechanisms that encourage their development, thus avoiding imbalances accentuated by a massive installation of renewables; for example, by incentives such as lower energy prices for the industry. A lower energy price would allow industry relocation to autonomous energy production communities, thus avoiding population loss.

Reducing the ecological footprint by decarbonizing the energy sources is insufficient to ensure the Bioregion's ecological sustainability, although it reduces the excess over its biocapacity by half. To achieve an ecological sustainable footprint, the energy transition should be accompanied by a modal shift in the agriculture sector with changing food diets to reduce consumption.

Regarding the material footprint, material demands of lithium, cobalt, nickel, silver, copper, neodymium, and tin are in some scenarios greater than the planet's reserves to guarantee an energy transition for the whole world. The pressure over the reserves is high in other materials such as bismuth, gallium, tantalum, zinc, antimony, molybdenum, strontium, gold, praseodymium, and dysprosium. The energy global equivalent mineral footprint raises the question of whether there will be enough materials at current prices to meet the entire demand or whether this energy transition is sustainable. Therefore, an efficient scenario has been proposed, reducing energy and material demands without reducing activity and growth. Although this scenario may reduce the material footprint and space requirement, it is not sufficient to guarantee a sustainable scenario in either its material or ecological footprint. It indicates the need to propose more efficient scenarios, find new mineral deposits that guarantee a global energy transition, a greater efficiency in using materials in each technology, and the establishment of a true circular economy linked to the recovery of the materials used.

Results obtained in this case study may be replicated for the entire planet, as the methodology developed has international use regardless of the specificities of the Bioregion. Future work is oriented towards analyzing the Bioregion water footprint and introducing the thermodynamic rarity indicator in the global equivalent mineral reserves footprint.

Supplementary Materials: Information regarding material intensity for each technology and reserves and resources considered can be downloaded at: https://www.mdpi.com/article/10.3390/land11111891/s1.

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