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Just transitions to renewables in mining areas: Local system dynamics

Pablo García-García [a,c,*], Óscar Carpintero [b,c], Luis Buendía [a,c]

[a] Department of Economics & Statistics, Faculty of Economics & Business Studies, University of León, Campus of Vegazana, León, 24007, Spain
[b] Department of Applied Economics, Faculty of Economics & Business Studies, University of Valladolid, 6 Avenue Valle de Esgueva, Valladolid, 47011, Spain
[c] Research Group on Energy, Economy and System Dynamics, University of Valladolid, Paseo del Cauce, Valladolid, 47011, Spain

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ABSTRACT

In the field of just energy transitions, local scales have been relegated and limited to qualitative approaches with non-specific methods by observation. Local quantitative approaches have gained popularity but remain far from the topic of just transitions and elude rural areas, probably because of data scarcity. Amid the quantitative panoply, system dynamics is attracting greater attention to alleviate such data shortages. Yet, despite the claim for holistic approaches, its application is scarce in rural contexts. This research presents an intuitive, scalable, and easily adaptable modelling exercise through system dynamics to estimate the effects on net employment and land availability of restructuring towards renewable energy sources in the rural mining areas of León (Spain), presenting possible lessons and policy implications for local and rural just transitions. A partially just transition is feasible in the short term, but a properly just transition is three decades late. The most optimistic projections suggest the potential creation of around five thousand jobs per zone, which is significantly fewer than the approximately forty-five thousand jobs that were recorded during the peak years of coal mining exploitation. Renewables fail to keep a young, qualified population in the areas, therefore showing the need to potentiate alternative activities, as well as causing sensitive trade-offs between land requirements and potential net employment. Land reductions for renewable projects vary depending on the scenario, ranging from 6 % to 17 %. This range poses a threat to the ecological integrity of these areas.

1. Introduction

Just transitions have transcended their unionist roots during the last few decades [1] and recently gained momentum in political agendas worldwide as transversal frameworks to tackle social and environmental deterioration, especially fuelled by the Sustainable Development Goals [2] and the International Labour Organisation [3]. Hitherto, the notion of justice has been applied to a vast range of socio-ecological transitions, both politically and scholarly. Notwithstanding, energy transitions are currently congregating most of the attention due to the relevance of their socioeconomic impacts, notably regarding employment [4,5] and income distribution [6–8].

Political frameworks and studies frequently picture just energy transitions at a global, world-regional or national scale, mostly in the Global North. Despite their strategic role in mobilising resources and facilitating decentralised interventions to enable a bottom-up, efficient, and just reorganisation of the energy sector, local transitions have been relegated to a secondary position. Among the array of local transitions, rural cases have been neglected. Now, there is a call to emphasise the importance of rural energy transitions and contribute to their better understanding [9].

The mining villages in the province of León, in Spain, constitute a significant case study contributing to the examination of local, rural, just energy transitions. Historically specialised in coal and thermoelectric production since the 18th century, these villages have experienced a profound socioeconomic decline over the last three decades. This decline can be attributed to such factors as increased competition from energy imports, declining costs of renewable technologies, climate commitments, rising emission prices, and the terminal Spanish Coal Decree, which prioritised subsidies instead of a real restructuring [10].

This decay has motivated layoffs and early retirements, consequently leading to migrations, depopulation, ageing, dependence, and territorial polarisation. Local governments have lost their ability to act due to the subsequent decrease in public revenues resulting from reduced economic activity and property taxes. Similarly, the abandonment of facilities and mining developments, some of them on the surface, has caused damage to the natural environment and landscapes.

Recently, the European Union has established a Just Transition Mechanism [11–13] and Spain has created an Institute of Just Transition

* Corresponding author. University of León, Spain.
E-mail address: pagag@unileon.es (P. García-García).

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Nomenclature:

Notations/Symbols

AL	Available land
AW	Available qualified workers
B	Biomass
GU	University graduates
GV	Vocational training graduates
N	Direct labour demand
n	Employment factors
NN	Net employment
NR	Employments at risk
p	Standard commercial power
P	Working-age population
PV	Photovoltaic
r	Land use
R	Registry
RL	Required land
S	Stakeholder
SCEN	Scenario
U	User-defined
W	Wind

Units

Km2	Square kilometre
m	Metre
MW	Megawatt
w/m2	Wind density per square metre

within the Ministry of Ecological Transition and Demographic Challenge [14] to promote just reorganisations in areas like León. However, stakeholders are currently facing uncertainty regarding the specific measures required to advance this objective. This research examines the case of León and its implications for rural energy transitions from a justice perspective. Additionally, it provides a modelling tool for analysing the local socioeconomic effects of the restructuring, thereby contributing to addressing the uncertainty.

This research offers a novel contribution to the domain of just energy transitions by introducing a quantitative approach to the study of local energy transitions, an area that has received comparatively less attention in existing studies primarily focused on national and regional scales. Employing system dynamics modelling, the study provides an examination of this transition process, considering such factors as wind power tenders, biomass capacity, net employment, and land requirements. In addition to the quantitative modelling, this work provides policy insights, stressing the importance of cross-sectoral approaches, the role of education in retaining a qualified workforce, and the potential risks associated with partially just transitions. By acknowledging the distinctive challenges faced by smaller, localised areas and utilising quantitative methodologies to inform policymaking, this research bridges the divide between academic inquiry and pragmatic solutions aimed at achieving a sustainable and equitable energy future.

The analysis in León highlights the potential of renewable energy, especially wind power, to create jobs in rural mining areas, benefiting the renewable energy sector and suggesting the need for job creation efforts. Quantitative methods like system dynamics are crucial in data-limited cases, emphasising the importance of upskilling and reskilling programmes for affected workers. The most hopeful estimates indicate the possibility of generating approximately five thousand jobs per zone, a substantial decrease from the roughly forty-five thousand jobs seen during the height of the coal mining activity. Reductions in land usage for renewable projects vary, with scenarios ranging from 6 % to 17 %. This spectrum of land reduction poses a potential risk to the ecological health of these regions. Maximising local wind tenders through supportive policies is recommended. Diversifying the local economy with rural tourism, agro-industry, and a "silver economy" is also advised. Shifting to renewable energy aligns with Sustainable Development Goals, but requires balancing land use and employment for public trust and conflict resolution.

The work is organised as follows. The second section revisits the studies regarding the impacts of energy transitions in local and rural contexts, with special attention given to systemic modelling exercises. Subsequently, the socioeconomic status of the mining areas of León is delimited and contextualised in the third section. The fourth section describes the methodological approach and data sources, while the fifth section presents the results. In the sixth and seventh sections, respectively, the implications of the findings are explored and the conclusions are drawn.

2. Local energy transitions and system dynamics

In the field of just energy transitions, national scales have consistently dominated the discourse, primarily from quantitative perspectives grounded in national accounts and input-output analysis. National scales offer a comprehensive view of energy transitions, grounded in a macro-level perspective that is crucial for policy formulation and understanding broad trends. However, this scale can oversimplify the complexity of energy transitions by treating regions and localities as uniform. It may not capture regional variations, specific stakeholder interests, or localised dynamics.

In recent years, regional approaches have gained popularity in illustrating the asymmetric effects [15] and providing a more nuanced understanding of the process. Nevertheless, these scales may still lack granularity, failing to address the intricacies of energy transitions.

Conversely, local energy transitions, those at a sub-national level [16], have been relegated to a secondary position, notwithstanding their potential to provide insights into the particulars of grassroots energy transitions. These transitions can unveil distinct dynamics, stakeholder priorities, and governance challenges. Local-scale studies can face challenges due to limited data availability, resulting in a scarcity of research in this domain. Consequently, investigations at the local scale often adopt qualitative approaches, frequently characterising them as initiative-based learning studies [17].

Selvakkumaran & Ahlgren [16] demonstrated the relevance of quantitative techniques in local cases, yet these are dominated by the socio-technical theories of strategic niche management [18–20] and multi-level perspective [21–23]. Regarding strategic niche management, Coenen, Raven & Verbong [18] conducted a qualitative dissertation, while Hoppe et al. [20] supported this theory with a quantitative analysis based on qualitative data from interviews to illustrate its relevance, especially in conjunction with the leadership of public officials and community trust. Seyfang et al. [19] emphasised the role of mutual trust after exploring the functionality of networking and intermediary organisations in the British community energy sector. Among the works aligned with multi-level perspective, Beermann & Tews [23] presented an empirical analysis, using both objective indicators and survey results, to analyse the evolving role of decentralised renewable capacities after institutional shifts and transition progress, thus highlighting the need for greater systemic coordination. Fallde & Eklund [22] captured the interplay between the support from national levels and leadership of local actors in the development of sustainable projects in municipal transportation. Fudge, Peters & Woodman [21] identified possible specific factors linking local and macro goals in the British context through qualitative data from interviews.

As reviewed by Selvakkumaran & Ahlgren [16], these papers tend to explain and theorise past events as an extension of general transitions, a posteriori, without the needed specificity and emphasis on complex dynamics. This trend can lead to several significant problems and limitations in research and understanding, such as oversimplification, lack of contextual understanding, incomplete insight into stakeholder dynamics, limited policy relevance, missed opportunities for learning, risk of misleading conclusions, and an inadequate basis for predictions. The missed specificity of local energy transitions lies in five issues [16]: spatial scale, ownership of the transition, differing priorities among stakeholders, different institutional structures, and situative governance issues.

Regarding the incipient range of quantitative methods, local cases have increasingly applied system dynamics to model transitions due to its ability to allow systemic thinking, connect these specificities, and address complex multidisciplinary issues [24]. This methodology has been more frequently employed to analyse local energy transitions than any other local socio-technical transformation. It has covered not only the electricity sector itself [25–31] but also combinations with other sectors [32–35], as well as the entire energy sector and its relationships with non-energy sectors [36,37].

However, these local approaches based on system dynamics have little to do with the field of just transitions. Consequently, their utility in providing guidance for the topic under study remains severely constrained. Agnew, Smith & Dargusch [25] and Blumberga, Timma & Blumberga [32] focused on the adoption of balancing tools in local renewable systems; Capelo, Ferreira Dias & Pereira [26], Castaneda, Franco & Dyner [27] and Kubli & Ulli-Beer [28] modelled the impacts of policies and technologies on energy activities; Liu et al. [29], Selvakkumaran & Ahlgren [31], Matthew, Nuttall, Mestel & Dooley [34] and Brouwer et al. [36] analysed the effects of policy support or other social factors on the deployment of renewable technologies, endogenous electricity demand or resource efficiency; Hollmann & Voss [33] modelled the decentralisation of energy supply; Pruyt & Thissen [30] studied the European electricity sector from a local viewpoint; Pruyt [35] opted for smart transition management; and finally, Zhao et al. [37] modelled the sub-national implications of carbon trading mechanisms. While these studies are situated within the broader context of energy transitions, they overlook the aspect of justice implications tied to the restructuring of energy systems from the proper perspective of just energy transitions.

Delving further into localised contexts, rural energy transitions have highlighted the ability of sparsely populated areas to attract renewable facilities, particularly wind farms [38], and the subsequent potential to promote entrepreneurship [39] and foster innovation [40]. However, this research has not frequently documented social opposition to these rural renewable facilities [9,38,41–43]. While rural areas might be optimal locations for renewable energy due to their abundance of space and natural resources, the reality is more complex. Several factors contribute to this opposition, and they deserve consideration in the planning and implementation of local energy transitions. These include worries about environmental harm, noise and visual impacts, land use conflicts, perceived lack of community consultation and benefits sharing, and threats to cultural and historical sites.

The research into rural energy transitions has also often avoided quantitative techniques because of the limited availability of small-scale data. However, the studies about local system dynamics suggest the suitability of this technique in contexts with limited data, as it allows the integration of data directly from local stakeholders as primary sources of information [24]. Simultaneously, the research into rural areas demands more systemic thinking and greater precision to ensure accuracy [9]. These coincidences point to a path for advancing the state of the art. Rural studies call for a tool that has a growing background in local studies, albeit on a larger scale.

Therefore, in this novel contribution on the case of León, it is desirable to leverage the strengths of system dynamics, such as holistic thinking and the ability to include data from stakeholders on the ground, to present an a priori analysis. Hence, this research proposes looking to the future while navigating the methodological challenges of the rural scale.

3. Delimitation and context

The Spanish Institute of Just Transition is currently promoting processes of just transition in the most affected areas of León, El Bierzo-Laciana, and Montaña Central-La Robla through five interventions of the total thirteen implemented at a national level. These endeavours are directed towards attaining the Sustainable Development Goals by the year 2030. The concept of just energy transition is a multidimensional idea [15] and the Institute has set subsequent criteria to delimit the area of intervention and therefore translate its conceptual implications to reality through a tool called the agreement of just transition ("Convenio" in Spanish or abbreviated "CTJ"). These agreements bring together such stakeholders as workers, unions, companies, local and regional administrations, local social and environmental groups, among others [44]. These delimitation criteria under usage are impact, coherence, and territorial cohesion [45].

The minimum area of intervention is the municipality. Under the criterion of impact, if there are mining developments or coal plants in the municipality, it is immediately included in the area. Subsequently, the impact criterion also provides coverage for a municipality if it accommodates coal workers, whether own or outsourced, whose unemployment and reduction of wages would cause an impact on the working-age population and income, respectively, greater than the average impact on all the municipalities where the workers live. At the end of the delimitation under the impact criterion, 85 % of workers must be covered. Otherwise, municipalities below the average impact must be included to reach the target.

The criterion of coherence dictates that the covered municipalities must be adjoining. If this is not the case, those municipalities that are located between the selected territorial entities must be included. The criterion of territorial cohesion orders the inclusion of a whole subregion or group of rural development if the population of the covered municipalities surpasses 70 % of the total subregional or group population.

The impact criterion was challenging from the beginning of the intervention. The problem lay in the measurement of impacts in terms of current employment and wage income in areas that have suffered a process of decline for three decades. Leonese mining employed forty-five thousand two hundred and twelve workers in 1990; while current figures only report nine hundred and sixty workers at risk of losing their jobs (one thousand and fourteen workers before recent adjustments) [46–50]. To correct the resulting unrealistic delimitation, the Institute introduced two additional nuances after the process of revision and public consultation [51–55]. First, it is covering the municipalities that accommodated at least two miners in 2011. Second, it is also covering strictly rural municipalities that belong to the area of the mining basin and accommodated workers, regardless of number, in 2001.

Fig. 1 presents the resulting areas of intervention, El Bierzo-Laciana and Montaña Central-La Robla. El Bierzo-Laciana includes a whole subregion based on the criterion of territorial cohesion, but four critical areas can be distinguished: Fabero-Sil, Bierzo Alto, Laciana-Alto Sil and Cubillos del Sil-Ponferrada.

Table 1 presents the socioeconomic situation of the areas compared with the province [51–57].

The decline of mining has reinforced depopulation, ageing, loss of industrial fabric, and unemployment. Cubillos del Sil-Ponferrada stands out positively in all demographic indicators, as it shows a better situation than the rest of the areas and even the province. However, economic indicators display worse results: it registers the second-highest unemployment rate and the third greatest destruction of the industrial network. This behaviour is due to the role that the town of Ponferrada plays in the area. Ponferrada, the capital of the subregion of El Bierzo, is the second biggest town of the province and relies on diversified economic activities with a high relevance of services. Amid the process of deterioration in the surrounding areas, the town has acted as a pole of attraction to hundreds of unemployed miners and their families. The criteria of the Spanish strategy for a just energy transition are only

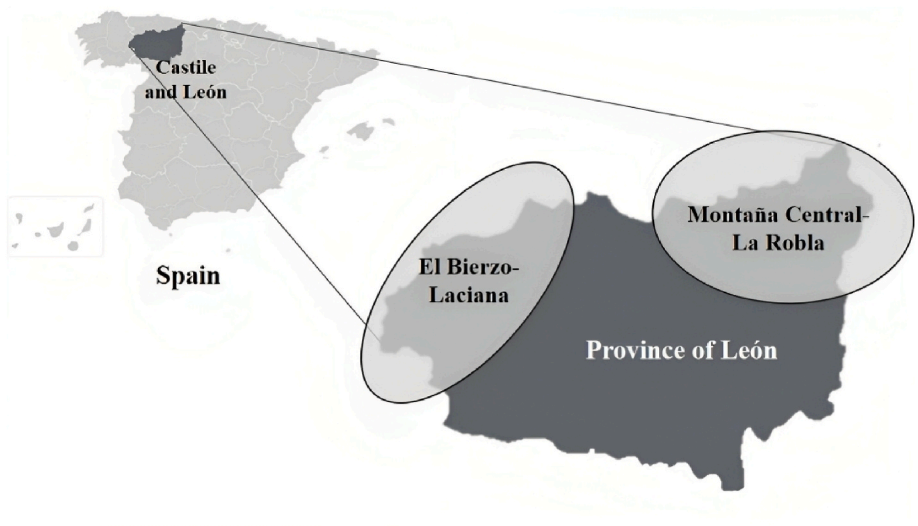

Fig. 1. Location of the province of León in Spain and the areas of just transition in the province. Source: Own elaboration.

Table 1
Socioeconomic situation of the areas of just transition compared with the province. N/A: Not available. Source: Own elaboration based on Ministry of Ecological Transition and Demographic Challenge [51–54] and Spanish National Institute of Statistics [56,57].

Indicator (Time)	Province of León	El Bierzo-Laciana				Montaña Central-La Robla
		Fabero-Sil	Bierzo Alto	Laciana-Alto Sil	Cubillos Sil-Ponferrada	
Variation of the population, % (1996–2020)	−11.75	−31.54	−29.49	−43.83	5.01	−34.47
Ageing index, % (2019)	255.37	418.49	352.75	392.36	196.86	461.07
Unemployment rate, % (2019)	12.99	17.85	14.01	11.56	17.23	14.34
Impact of coal closure on the working age population, % (2020)	Not applicable	2.45	0.41	0.53	0.5	1.63
Variation of registered local businesses, % (2012–2020)	−4.78	−4.59	−8.16	−3.47	−5.54	−12.18
Variation of gross annual income per capita, % (2013–2017)	3.42	2.64	3.75	1.92	6.47	5.39
Impact of coal closure on the local public budget, % (2017)	N/A	−46	N/A	N/A	−61	−31

applicable to rural areas because of the higher diversification of urban municipalities. Ponferrada has been included as an exception due to its high impact and its historical role as an alternative for miners [52].

The challenge is to mobilise investment in the areas through focused public interventions. While the areas have the potential for tourism, agroindustry, and a "silver economy", the most immediate option for them is to accomplish a restructuring towards renewable energies, as energy infrastructures, e.g., grids set up for thermoelectricity, are still in place, and their geography secures quality renewable resources. Their wind density at 100 m ranges between 1000 and 1300 W/m2; whereas in Spain, the 10 % windiest areas register an average of 717 W/m2 [58]. Their altitude and proximity to the Atlantic Ocean generate oceanic and mountain climates, with higher rainfall and numerous locations with high gradients, required for hydropower [59]. Likewise, residual biomass is easily accessible thanks to the proximity of vast forests and agricultural uses [60], and it has gained greater institutional support in the past years; although some analyses find more convenient uses of biomass as a nutrient in countries in the process of desertification and soil degradation like Spain [61].

From a human viewpoint, their population is skilled in technical fields because of the historical specialisation in mining [46–50]. Besides, the areas accommodate two Universities (the University of León and the National University for Distance Education in Ponferrada) [62,63] and centres of vocational training [64]. These institutions educate hundreds of students in key disciplines for just restructuring, such as Engineering, Environmental Sciences, Construction, Electricity, Electronics, Maintenance, Transportation, Human Resources, and Sociocultural Services.

Nevertheless, a transition to renewables is not straightforward in the zone: even if the Leonese geography secures high-quality renewable resources, social movements of contestation are proliferating to protest the destruction of jobs in mining and the change in land uses that renewables require, especially causing conflict in the traditional communal woodlands of these areas. Furthermore, the increasing profitability of renewable technologies is incentivising higher land rents than those the lessee farmers can afford, consequently displacing them to unemployment or non-suitable jobs. Likewise, protesters complain about the landscape impact of the new renewable facilities over territory with tourist potential and a high biodiversity. These events are happening in a province that has already gone through three decades of socioeconomic deterioration.

Currently, there is uncertainty and a lack of precision among the stakeholders regarding measures to foster a just transition in León. To contribute to analysing the proposals for the local energy sector and explain the process of just restructuring from coal to renewables, there is a need to estimate the socioeconomic impacts of potential projects. This research explores the possibility of generating such estimations through a modelling exercise concerning two aspects of the Leonese case: land use and employment. Modelling is challenging at this local scale, especially in rural areas like the ones concerned here because of data scarcity. Yet, this research relies on the potentiality of system dynamics to bridge energy, land and human issues, while combining data from diverse sources, including stakeholders on the ground.

4. Methodology and data

Given the context, and the need to combine energy, land, and human variables, this research applies system dynamics to model the local transition of the Leonese mining areas and its implications for justice. The method's development necessitated the collection of pertinent variables and the representation of their interrelationships.

The selection of variables is based on three criteria: simplicity, relevance, and availability. Simplicity is mandatory, provided that just transitions are public participatory processes that involve diverse social agents. Simple choices promote an intuitive and achievable mutual understanding, thus incentivising transparency and active participation. Relevance ensures a fit between analytical choices and the identified hotspots, as reported by local stakeholders through the agreements of just transition. Last, but not least given the context under study, variables must be publicly available at a local level in rural areas, as well as in other possibly similar zones, to ensure replicability and methodological significance. Fig. 2 shows the relations between the selected variables under these criteria.

After the variables have been chosen and interconnected, the model's execution proceeds through a sequential chain of steps, operating concurrently across the two areas of just transition in León. The model's focus extends to the year 2030, aligning with the target timeframe for political programmes that advocate for a just transition in Spain. The steps are as follows:

First, the model reads the scenarios of new installed power capacity in wind (W), solar photovoltaic (PV) and biomass (B). Nuclear capacity is not being regarded as a possible alternative to coal in Spain due to the prevailing focus of the current national energy policy, which prioritises the gradual phase-out of nuclear power from the country's energy mix.

Secondly, in Equation (1), these new capacities are translated into required land (RL) by applying the standard commercial power of wind and photovoltaic infrastructures (p) and their associated use of land through the projection of elevations to the ground, as observed in satellite images of similar local installations (r). In Equation (2), land requirements are the unitary demand for land of each turbine and panel, so they progressively reduce the stock of available land (AL).

$$RL_t = \frac{W_t}{p_w} r_w + \frac{PV_t}{p_{pv}} r_{pv} \tag{1}$$

where W_t is the new wind capacity in each moment, p_w is the standard commercial power of wind infrastructures, r_w is the associated land use of wind infrastructures, PV_t is the new photovoltaic capacity at each moment, p_{pv} is the standard commercial power of photovoltaic infrastructures, and r_{pv} is the associated land use of photovoltaic infrastructures.

$$AL_t = AL_0 - \sum_1^t RL_t \tag{2}$$

where AL_0 is the initial stock of available land.

Thirdly, in Equation (3), capacities are translated through technology-specific employment factors (n) into direct labour demand (N), which increases the stock of net employment in energy activities (NN) in Equation (4). This increase is also offset by the destruction of jobs at risk in coal activities (NR) from a net employment perspective. Employment factors represent the ratios between registered local workers in renewable energy activities and the installed renewable capacity, based on the direct impact [65]. These factors exclusively reflect the employment opportunities per unit of capacity within the specific realm of renewable activities, without considering the broader job generation that may occur in associated sectors or throughout the economy because of ripple effects. The assessment of net employment prospects relies on the ongoing calculation of newly generated jobs in comparison to the number of jobs that have been eliminated. This approach allows for an examination of the specific impacts and their distribution.

$$N_t = W_t\, n_w + PH_t\, n_{pv} + B_t\, n_b \tag{3}$$

where n_w is the employment factor of wind technology, n_{pv} is the employment factor of photovoltaic technology, B_t is the new biomass capacity at each moment, and n_b is the employment factor of biomass exploitation.

$$NN_t = -NR_0 + \sum_1^t N_t \tag{4}$$

where NR_0 is the initial number of jobs at risk in coal activities.

Fourth, the availability of qualified workers (AW) is cross-checked with the educated working-age population (P) and the new graduates in local vocational training centres (GV) and universities (GU) in key technical fields to ensure a just transition in Equation (5). The goal is to determine whether there is sufficient educated population to meet the workforce demand, or conversely, whether shortages exist and to understand the nature of the said shortages.

$$AW_t = P_0 + \sum_1^t GV_t + \sum_1^t GU_t - \sum_1^t N_t \tag{5}$$

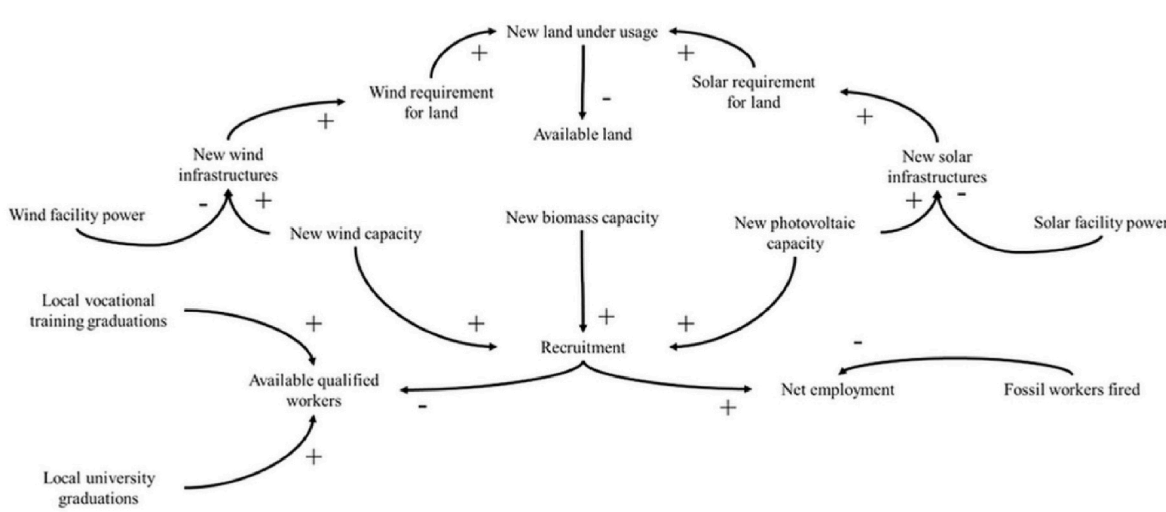

Fig. 2. Diagram of influences. Source: Own elaboration.

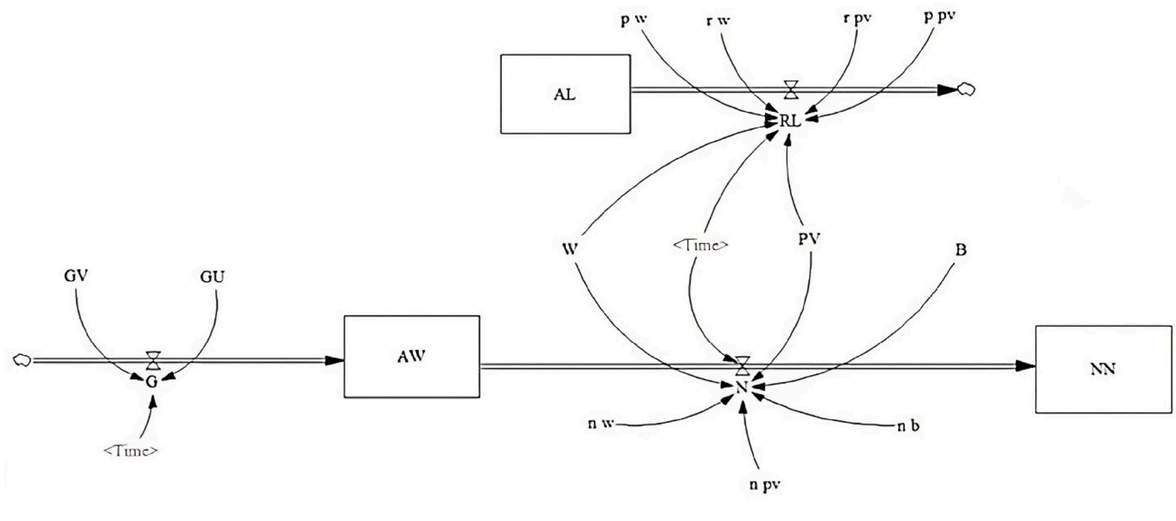

Fig. 3. Forrester diagram. Source: Own elaboration.

where P_0 is the initial educated working-age population, GV_t is the number of new graduates in vocational training at each moment, and GU_t is the number of new graduates in universities at each moment.

Fig. 3 presents the system dynamics structure of the model following this rationale and notation.

Selvakkumaran & Ahlgren [24] developed a classification of models for local transitions through system dynamics based on six criteria: sectorial focus, type of transition, modelling depth, objective, justification for the use of system dynamics, and the level of interaction with the local scale. Following this classification, this research focuses on energy, specifically on the mining and electricity sectors within the context of the energy transition. However, it also yields insights applicable to agriculture and other non-energy sectors. While it provides arguments rooted in systemic thinking and presents a causal loop diagram in Fig. 2, the core of the model consists of a stocks and flows diagram used for simulation, as represented in Fig. 3. The goal is both prescriptive and evaluative, as it aims to explore solutions and provide a tool for assessing potential projects. The reason for applying system dynamics is the need to incorporate energy, land, and human variables within the same modelling framework, bridging the gap between systemic thinking and the imperative to address these issues. Lastly, the level of interaction with the local scale is stringent: this modelling exercise does not consider landscape factors beyond the local focus, integrating information from local stakeholders through the agreements of just transition. This integration is both qualitative, helping to determine the concerns and relationships related to the transition in Fig. 2, and quantitative, yielding parameters for the simulation in Table 2.

Table 2 collates the necessary information for conducting the simulation, sourced from a variety of origins.

The simulation relies on the parameters r, p, and n to translate new energy capacity into new jobs and estimate the land requirements of renewable technologies. These parameters are grounded in data and assumptions. Concerning employment factors (n), this exercise calculates the ratio between the current number of employees in renewable energy companies and the current capacity. Current data can only lead to the estimation of the factors for solar photovoltaic, wind and biomass power, as jobs in hydropower are marginal and mixed up with other categories in the registries.

Table 2
Data sources. Source: Own elaboration.

Category	Variable	Sub-element	Source	
			Reference	Public registry (R), local stakeholder (S) or user-defined (U)
Energy	New renewable capacity (W, PV, B)	Current tenders	Secondary source: Union Institute of Labour, Environment and Health [66]. Primary source: local energy authorities.	S
		Territorial distribution	Scenarios	U
	Standard power of renewable infrastructure (p)	Wind turbines	Industrial standards	U
		Photovoltaic panels		
		Biomass	Own estimate based on current registers at a province level	
Land	Available land (AL)	Municipal surface	Council of León [67]	R
		Urban land	Land registry [68]	R
		Woodland	Forest Inventory of the Castile and León Regional Council [69]	R
	Land requirements (r)		Satellite estimates based on similar local facilities	U
Human	Qualified working-age population (AW)	New vocational training graduates	National Registry of Teaching Centres, Spanish Ministry of Education [64] & Castile and León Regional Council [70]	R
		New University graduates	Statistics and Transparency Bureaus of the local Universities [62,63]	R
		Educated working-age population	Agreements, Institute of Just Transition [46–50]	R
	Employment factors of renewables (n)		Own estimate based on: Secondary source: Union Institute of Labour, Environment and Health [66]. Primary source: Business registry [71].	R
	Jobs at risk in fossil activities (NR)		Secondary source: Agreements, Institute of Just Transition [46–50]. Primary source: affected local companies.	S

Table 3
Scenarios. Source: Own elaboration.

Scenario	Proportion of current tenders installed in the affected areas		New annual biomass capacity	Employment factors
	Wind	Solar PV		
SCEN 1	50 %	50 %	0 %	Current
SCEN 2	80 %	30 %	0 %	Current
SCEN 3	80 %	30 %	5 %	Current
SCEN 4	80 %	30 %	5 %	Current (2021) to average in previous works (2030)

Table 4
Current employment factors of wind and photovoltaic power in León and estimates in previous works. Source: Own elaboration.

Renewable technology	Employment factor (jobs/MW)	
	Currently in León	Average value in previous works
Wind	3.563	7.092
Solar photovoltaic	2.447	18.857

Regarding the land requirements of renewables (r), the focus is on wind and solar power. Based on satellite images, it is assumed that turbines with a diameter of 90 m will constitute wind power facilities with distances of 400 m between generators. For solar facilities, this exercise relies on standard panels measuring 13 × 8 m with a 20 m gap between them. Under these dimensions, considering industrial standards, turbines would add (p) 2 MW, and panels would add 0.0184 MW.

The proposed scenarios for input into the model are four, as shown in Table 3. In the first scenario (SCEN 1), the preferential installation of 50 % of the current renewable tenders at a province level is considered (769 MW of wind and 3647 MW of solar photovoltaic) in the affected areas, while maintaining the current biomass potential. The second scenario (SCEN 2) calculates the effects of a more realistic situation, in which 80 % of wind tenders and 30 % of photovoltaic tenders are placed in the affected areas due to their comparative advantage in wind speeds. Similar to SCEN 1, the biomass potential remains constant. In the third scenario (SCEN 3), the replication of SCEN 2 is performed with a year-on-year increase of 5 % in the biomass potential. Finally, SCEN 4 replicates SCEN 3 with employment factors that gradually converge with their average in previous works [65,72–75]. At the outset of the simulation, employment factors are initialised based on current registrations in the study area. As the simulation progresses, these factors evolve linearly, gradually converging with the average employment factors documented in the existing literature. Table 4 showcases this average value, which has been derived by aggregating the direct employment figures across manufacturing, construction, operation, and maintenance sectors.

León registers notably below average employment factors. However, these averages are predominantly derived from papers focused primarily on a national level. In light of this disparity, the estimates in SCEN 4 are considered a maximum or optimistic value, assuming all other factors remain constant, to encompass the range of possible developments over the decade. Consequently, the expected level of employment could fall between the outcomes of SCEN 1–3 and SCEN 4. Essentially, SCEN 1–3 comprise a set of business-as-usual scenarios pertaining to employment factors.

5. Results

In Table 5, the primary objective is to address the key concerns associated with the just transition in León. The attention centres on the pool of qualified workers (AW), net employment (NN), and the extent of available land (AL).

The exclusive prioritisation of current renewable energy tenders is expected to yield positive short-term outcomes. Simulations indicate that the creation of direct jobs in renewables would offset the direct jobs at risk in fossil fuel activities (resulting in net employment) by 2023 in El Bierzo-Laciana and by 2022 in Montaña Central-La Robla. This outcome underscores the need for social agents to promote early reskilling and upskilling programmes so that affected workers can transition into the new employment opportunities as they arise.

However, even though renewables may mitigate the negative impact of phasing out fossil fuel facilities, they are unlikely to provide a significant share of employment. The pool of available qualified workers is expanding in SCEN 1–3, under business-as-usual employment conditions, as new graduates in key disciplines are entering the workforce at a faster rate than recruitment in renewable sectors. Only under optimistic assumptions, such as the average factors in SCEN 4, would recruitment progress at a higher pace. Nevertheless, this optimistic scenario either absorbs new graduates in El Bierzo-Laciana but fails to recruit experienced workers, or benefits experienced workers while neglecting newcomers, as the workforce remains at a similar level between 2021 and 2030. In Montaña Central-La Robla, it even leads to a shortage of qualified workers starting in 2029, as indicated by the negative level of the workforce stock, highlighting the workforce gap.

The average employment factor for wind power is feasible, implying a doubling of jobs per installed MW over the decade. This is likely due to the optimal conditions for wind power infrastructure in the area. However, achieving the average employment factor for solar photovoltaic is unlikely without a highly improbable revolution in these specific areas, which do not possess the optimal insolation and irradiance levels due to their geography and climate [76]. Therefore, the most realistic outcome falls between SCEN 1–3 and SCEN 4, closer to the former, particularly SCEN 3, due to the relatively lower potential of biomass power to generate employment. Consequently, the affected areas may experience short-term compensation for jobs at risk but may struggle to maintain a qualified workforce in the medium term. Even in the optimistic SCEN 4, renewables are unlikely to match the employment levels seen in these areas during the peak years of coal mining when there were more than forty-five thousand miners. Hence, a partial just transition is highly likely, but a complete just transition in the local energy sector appears to be unattainable. Alternative options, such as

Table 5
Results of the simulations, SCEN 1–4. Source: Own elaboration.

Variable (unit)	Area El Bierzo-Laciana					Area Montaña Central-La Robla				
	2021	2030				2021	2030			
		SCEN 1	SCEN 2	SCEN 3	SCEN 4		SCEN 1	SCEN 2	SCEN 3	SCEN 4
AW (people)	7365	11270	11700	11670	7640	1175	2717	3151	3135	−890
NN (people)	−714	1911	1477	1511	5536	−300	2325	1891	1907	5932
AL (Km2)	1552	1422	1458			742.9	613.1	648.7		

Table 6
Results of the simulation of SCEN 3 under the unequal distribution of tenders to balance negative land impacts (SCEN uneq). Source: Own elaboration.

Variable (unit)	Area El Bierzo-Laciana			Area Montaña Central-La Robla		
	2021	2030		2021	2030	
		SCEN 3	SCEN uneq		SCEN 3	SCEN uneq
AW (people)	7365	11670	11010	1175	3135	3792
NN (people)	−714	1511	2168	−300	1907	1250
AL (Km2)	1552	1458	1430	742.9	648.7	677

rural tourism, agroindustry, and a "silver economy" with enhanced social capacities and care [77], are highly recommended, though similarly limited.

Regarding land requirements, the difference between equalising wind and photovoltaic and prioritising wind can be observed in the gap between SCEN 1 and SCEN 2–4. In El Bierzo-Laciana, SCEN 2–4 would result in a roughly 6 % reduction in available land by 2030, while SCEN 1 would lead to an 8.4 % decline. Similarly, in Montaña Central-La Robla, SCEN 2–4 would require a reduction of approximately 12.7 % in 2030, whereas SCEN 1 would result in a 17.5 % decrease.

Given the larger surface area and the higher number of jobs at risk in El Bierzo-Laciana, energy companies and competent authorities are likely to concentrate tenders in this area rather than distribute them evenly between the two regions, given that both offer similar quality resources. However, they will face the challenge of balancing job creation without depleting the available land in El Bierzo-Laciana and avoiding disruptions to the timing of the energy transition; as well as preventing unequal impacts between the two regions that could foster mistrust. To illustrate the delicate balance that must be achieved, if stakeholders decide to pursue the scenario with the highest probability, SCEN 3, and allocate 65 % of tenders to El Bierzo-Laciana (resulting in SCEN uneq), it would lead to a similar reduction in land availability in both areas (7.86 % in El Bierzo-Laciana and 8.87 % in Montaña Central-La Robla) and would achieve net employment compensation around the same time frame. However, this would come at the expense of losing 34.45 % of net employment in 2030 compared to SCEN 3 in Montaña Central-La Robla, as demonstrated in Table 6.

Increasing the proportion of photovoltaic tenders comes at a greater cost in terms of land. The land requirement per installed MW of photovoltaic is approximately 46 % higher than in the case of wind under the current simulation parameters. This outcome reinforces the strategic need to prioritise wind power in León, as it offers a higher energy return and requires less land. If wind tenders are prioritised, the interference between renewables and land used for agriculture and livestock should be minimal, given that wind facilities are typically installed in higher fields, which are less suitable for cultivation.

Future studies could incorporate geographic information systems or more specific spatial transition analyses, which are beyond the scope of this analysis, to assess the optimal locations for renewable facilities, current land uses, and local preferences [78]. This would ultimately help forecast potential conflicts between energy production and farming activities, especially concerning communal woodlands.

6. Discussion

These findings and the proposed methodology have implications that extend to other rural mining areas in developed countries experiencing intense deindustrialisation over recent decades. Firstly, just energy transition plans often focus narrowly on net direct employment in the energy sector. As demonstrated in Table 1, a comprehensive just energy transition necessitates a cross-sectoral approach, because the phase-out of mining and thermoelectric production has indirect and induced effects on local economies. Table 5 indicates that renewable technologies alone cannot provide significant employment in such small-scale contexts.

Simultaneously, just energy transition plans frequently address only the socioeconomic aspects of restructuring while neglecting environmental effects, despite their interconnectedness. Environmental impacts, job quality, and implications for land use, along with the landscape effects of coal phase-out, should not be treated as separate dimensions. As pictured in Figs. 2 and 3, human and land dynamics constitute the system of the just energy transition and interact concurrently, affecting justice and social contestation, as shown in Table 6.

Evaluating environmental effects, especially land dynamics, is crucial for promoting justice and addressing social contestation in nearby areas simultaneously undergoing a transition with similar socioeconomic circumstances. Potential asymmetries in Table 6 must be considered and managed to maintain social trust. Technological advancements in renewables and land use compatibility should play a pivotal role in this regard.

Secondly, just transition plans should place greater emphasis on education, especially in rural areas. Fig. 3 shows that education determines the flow of qualified workers and the efficacy of upskilling and reskilling programmes. In the context of rural places grappling with depopulation, local education centres are essential for retaining and incentivising a young and qualified population. Promoting vocational training, university studies, and lifelong learning in energy and non-energy fields should complement the required upskilling and reskilling programmes for the most affected sociodemographic groups.

Thirdly, public authorities and stakeholders must be prepared to assess whether a partially just energy transition suffices to achieve justice in afflicted areas. The decline of coal began in the late 20th century, but the push for a just transition gained momentum with the Sustainable Development Goals in 2015. Political plans (2021) are therefore applied after decades of socioeconomic deterioration, which may be irreversible, as seen in Tables 5 and 6 This partial outcome persists despite additional criteria introduced in political plans to account for the time gap. It poses a risk to social trust.

The analysis on just energy transitions in León provides insights and implications for various stakeholders. In terms of industry, the findings suggest that renewable energy, particularly wind power, can offset job losses in rural mining areas. This has implications for the renewable energy sector, highlighting opportunities for job creation.

Policymakers and industry stakeholders should consider the immediate implementation of upskilling and reskilling programmes to support affected workers during the transition. Regulatory implications indicate that maximising local wind tenders can be an effective strategy, calling for supportive policies in this regard.

This study recommends diversifying the local economy through such avenues as rural tourism, agroindustry, and a "silver economy". Environmental benefits are apparent in the shift to renewable energy, aligning with environmental, social, and corporate governance principles and contributing to reach the Sustainable Development Goals. However, in this direction, managing trade-offs between land use and employment is crucial for public trust and conflict resolution.

This analysis challenges the notion that quantitative modelling is unsuitable for local scales, advocating for its use to inform policies and provide political insights for decentralised solutions in energy transitions. Methodologically, local system dynamics offers mathematical and statistical advantages in studying energy transitions by capturing spatial and temporal variations more accurately, accounting for diversity among entities, simulating agent interactions to reveal complex feedback, integrating diverse data sources for accuracy, facilitating analyses to identify critical regions, enabling scenario testing, producing spatially explicit outputs, and informing location-specific policy design.

However, the methodology applied in this research also has some limitations and boundaries. First, it simplifies variables related to energy, land, and human factors, potentially oversimplifying the complexities. Second, the reliance on varied data sources, including secondary ones and local stakeholder input, can potentially introduce inherent biases. Third, assumptions, such as land requirements and employment factors, may not always reflect the actual conditions present in every location. The model's adaptability to evolving conditions may be constrained by static employment factors and the absence of sensitivity analysis. This limitation carries implications for policymakers and the scientific community, particularly in the context of climate change targets. In dynamic environments, where conditions are constantly changing, this restricted adaptability hinders the model's utility. Nonetheless, this limitation is partially mitigated by the relatively short time frame considered, derived from the political plan (2030). Employment factors generally exhibit stability unless subjected to extreme and unforeseen shocks, which are not currently evident. Fourthly, the emphasis on the energy sector might inadvertently neglect the intricate interplay between various sectors, potentially leading to oversights from the perspective of the induced impacts, even when drawing conclusions about agriculture based on interpretations of land impacts. Such external factors as market dynamics are not considered.

The limitations outlined in the research present opportunities for future investigations. To overcome the oversimplification of the variables related to energy, land, and human factors, advanced modelling techniques can be explored. Sensitivity analyses should be incorporated to gauge the impact of variable variations on model outcomes.

To mitigate biases introduced by diverse data sources, data fusion techniques could be employed. The validation of assumptions, particularly regarding land requirements and employment factors, can enhance the model's accuracy. This practice necessitates a medium-term observation of the case study.

To gain a more comprehensive understanding, it is necessary to incorporate market dynamics and extended time horizons when they become accessible in political plans. Addressing these considerations will enhance the adaptability, robustness, and practical relevance of the research findings, contributing to a more comprehensive understanding of the complex system under study.

7. Conclusions

This work focuses on the often-overlooked significance of local contexts in just energy transitions, advocating for the adoption of quantitative modelling, particularly system dynamics, as a tool to comprehend the multifaceted challenges encountered by rural areas undergoing energy shifts.

Examining the case of León, Spain, a province grappling with the decline of coal and thermal energy, this work examines two pivotal facets: net employment and land requirements. Four incremental scenarios are simulated, encompassing wind and photovoltaic power tenders, increased cumulative biomass capacity, and the convergence of techno-specific employment factors below the average.

Current tenders offset job losses by 2022–2023. Therefore, it is essential to initiate upskilling and reskilling initiatives that expedite the workforce's transition while concurrently managing the trade-offs between adverse effects on land use and favourable impacts on employment. In the most optimistic scenario, the transition may be unable to absorb the influx of newly qualified workers in the dynamic El Bierzo-Laciana area, potentially causing a labour shortage in the less dynamic Montaña Central-La Robla region. More realistic scenarios project that renewables alone may not be sufficient to retain a young, qualified population in these areas. Alternative avenues such as rural tourism, the agroindustry, and a "silver economy" are recommended but may also face limitations. Based on these findings, the just transition of the Leonese energy sector can be partially achieved. Nevertheless, a complete just transition is overdue by three decades.

These conclusions have implications across multiple domains. The focus on systemic, quantitative modelling underscores its importance in engineering design, helping to optimise renewable energy systems in rural areas. These models can inform regulations, guiding policymakers in creating equitable transition policies that consider employment, land use, and social impacts. For energy systems, the emphasis on renewables highlights their potential for job creation. Energy planners can leverage this insight when making infrastructure decisions. Policymakers may consider the recommendation for upskilling and reskilling programmes, aligning workforce development with local transition needs. Financial decision-makers can assess the feasibility and impact of rural renewable projects, while environmental, social, and corporate governance criteria align with the principles of a just transition. Environmental considerations are crucial, as discussed, necessitating impact assessments. Lastly, the call for decentralised political solutions emphasises the importance of local governance in shaping energy transition policies for smaller regions.

CRediT authorship contribution statement

Pablo García-García: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Óscar Carpintero:** Funding acquisition, Project administration, Supervision, Writing – review & editing. **Luis Buendía:** Funding acquisition, Supervision, Writing – review & editing.

Declaration of competing interest

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

Data availability

Data have been taken from public databases that are referenced in the manuscript

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