Socially equitable energy system transitions

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ABSTRACT

The European transition to a net-zero economy by 2050 implies a wide range of changes which may adversely affect certain industrial sectors, communities, and regions. However, these impacts are entirely obscured by conventional least-cost analyses. Thus, this work compares the socio-economic impacts of various strategies to decarbonize the energy system by 2050 within the framework of the Sustainable Development Goals (SDGs). We demonstrate that transitions which protect domestic strategic assets and preserve key industrial sectors correspondingly deliver a socially equitable transition. Adopting a technology agnostic approach to decarbonising the European electricity system maximises the associated co-benefits, and potentially increases gross value added (GVA) to the economy by 50% relative to a business as usual scenario. This new way of thinking about the economic transition fundamentally reframes the discussion from one cost to one of opportunity.

The transformations needed to achieve the goals of the Paris Agreement require unprecedented rates of decarbonization, along with the interconnected technical, economic, social, and political changes that they entail[1–3]. This places unprecedented demands on national and sub-national political systems, and the social feasibility of such transformations is often questioned[4,5]

Over the last decades, principles of equity and justice have been shaping the debates around sustainable development and emission mitigation, especially in relation to the distribution of responsibilities and rights among nations[6–9]. The explicit recognition of equity as one of the principles of the United Nations Framework Convention on Climate Change (UNFCCC) has placed the concept of justice at the heart of negotiation leading to the 2015 agreement. Notions of equity are embedded in the Paris Agreement itself, which acknowledges the need for the transition to a low carbon society to be both fast and fair. More specifically, the Agreement states the need to account for "the imperative of a just transition of the workforce and the creation of decent work and quality jobs in accordance with nationally defined development priorities"[10].

The European Union has a history of pro-active environmental and energy policy, delivered via a range of initiatives. The 1992 Maastricht Treaty identified environmental protection as a key goal, alongside stable economic growth, with the subsequent 1997 White Paper[11] setting the target of 12% of renewable energy consumption[i] by 2010. By 2005, a comprehensive European Union energy policy was approved, with the 2009 Renewable Energy Directive (RED)[12] mandating that 20% of the energy used within the EU come from renewable sources[ii] and the 2012 Energy Efficiency Directive[13] mandating a reduction in final energy consumption to 1086 Mtoe[iii]. By 2019, the EU set a target of net zero emissions by 2050, and is currently supporting this goal via the European Green Deal[14]. However, at the time of writing, contemporary political and social challenges faced by various EU member states[15] bring the long-term challenge of climate mitigation action into sharp focus. As observed in major European coal-producing countries, fears of job losses, economic decline, and disruptive structural changes have fueled opposition to low carbon policies. It is hence becoming increasingly clear that, while Europe's energy transition puts into practice the values of sustainable development and stewardship of natural resources, it must also uphold two other key European values: fairness and solidarity.

To support its climate goals, the EU has recently incorporated climate action into its whole budget through the Multiannual Financial Framework (MFF), with a target of 25% of EU expenditure contributing to climate objectives. The next European MFF, with its envelope of almost €1.3 trillion, proposes several budget instruments (for example, the Cohesion Policy Funds and the European Social Fund Plus) which support a just transition. While these funds provide the means to underpin Europe's efforts to achieve a net zero carbon economy, both the size of the blueprint and the way to allocate the budget remain a major source of division among member states[16,17].

[i]also articulated as 22.1% of electricity consumption
[ii]wind power, solar power, hydroelectric power, ocean energy, geothermal energy, biomass and biofuels
[iii]Final energy consumption in EU-28 in 2017 was 1060 Mtoe

The discussion around European energy systems transition is often facilitated *via* various energy systems modelling exercises[18–22] , typically using cost metrics as the exclusive means of comparing low carbon scenarios. The results suggest that a cost-effective decarbonization European energy system can be achieved by transitioning on different pathways in terms of technology choice, spatial distribution of production capacity, and the degree of interconnection between different member states[23]. However, this exclusively technocratic view of the transition has left a remarkable paucity of analysis on the societal impacts of this transition[24,25] with negligible,if any, study on the potential for an equity based transition.

Thus, in order to identify technically feasible, financially viable and socially equitable transition pathways, the coupling of techno- and socio-economic perspectives is vital. Drivers such as socioeconomic development and the capabilities of individual member states, are judged to be particularly influential for implementing effective decarbonization strategies while averting the rise of social conflicts[26]. As such, detailed consideration of the country-specific natural resources, economic strengths, geopolitical perspectives, and levels of socioeconomic and technological readiness for energy transition is an imperative.[23,27,28].

To address this challenge, this work combines energy systems modelling and socioeconomic analysis and i) quantifies the varying socioeconomic costs of pursuing an exclusively cost-focused transition in a range of national contexts; and ii) investigates the potential of societal value as an orienting principle for shaping effective and progressive decarbonization trajectories. We then explore the synergies and trade-offs of alternative national energy transition pathways across energy-related sustainable development goals (SDGs) for selected EU countries.

System framework

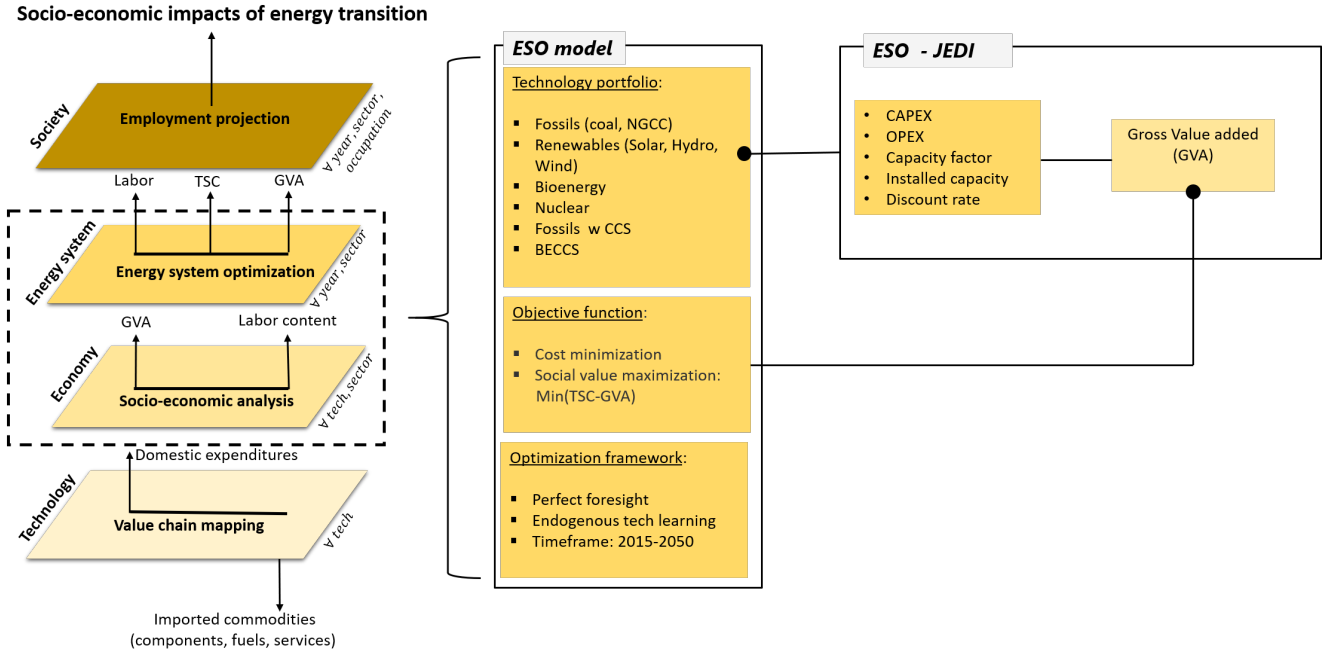


Figure 1. Analytical framework adopted in the study. Dashed lines indicates the link between ESO and JEDI models where the labor content and the Gross Value Added (GVA) of each technology in the different economic sectors, have been embedded in the optimization process

Following Markard[27], we define the energy transition as evolution in the electricity sector driven by climate mitigation goals that entail social, technical, and economic changes and that point to the inevitability of conflicts among actors. To quantify the societal impacts of energy transitions, a simultaneous analysis is hence required across four intertwined dimensions: energy technologies, economy, energy system, and ultimately society. Our framework operates across these levels (Figure 1) and combines an energy system optimization (ESO) framework[29–31] with a country-specific socioeconomic tool. ESO is an hybrid capacity expansion and unit commitment model built for planning power generation expansion. The model includes system-wide constraints to take into account grid-level requirements such as hourly electricity demand and renewables availability, reserve, inertia, and emissions target

requirements. It also incorporates technology-wise constraints for considering the key technical capabilities and limitations of each power generation and storage technology. As in a previous study on the employment impacts of low-carbon energy deployment[32], this work adopts the Job and Economic Development Impact (JEDI) model to measure the gross value added (GVA) and the direct employment associated with deployment of a portfolio of generation, energy storage, and interconnector technologies. The JEDI model adopts a series of national accounting tables derived from the socioeconomic STructural ANalysis database (STAN)[33], which contains yearly measures of GVA by economic activity, that is, the contribution of each industrial sector to the national gross domestic product (GDP). Importantly, our analysis distinguishes between energy technologies that are manufactured locally and thus create value for the national economy and those that are imported (see supplementary Tables S1 and S2 for more details). In this study, this framework is applied to the United Kingdom (UK), Spain, and Poland, which are countries where low-energy carbon deployment is technically achievable, but which have quite different patterns in terms of energy mix, socioeconomic structure, and mitigation ambitions. Table 1 summarizes the main socioeconomic and energy sector metrics that broadly illustrate the countries' readiness for the transition to a low carbon economy, with the UK and Poland falling, respectively, on the opposite ends of the spectrum. While the UK has set ambitious medium- and long-term climate mitigation targets[34,35] underpinned by economic and technological resources, Poland has one of the lowest GDPs per capita among EU countries. Moreover, owning to the economic-wide reliance on domestic coal, the emission factor for power generation in Poland is more than twice of that of the EU (Table 1); considering the modest decarbonization targets of the country's National Energy and Climate Plan (NECP), the dominance of coal seems unlikely to change in the near to medium term.

			EU28	**Poland**	**Spain**	**UK**
Energy transition	Import dependency[36]	Coal import (% demand)	49 %	5 %	91 %	89 %
		Gas import (% demand)	72 %	76 %	100 %	48 %
	Magnitude of effort[37]	Carbon Intensity[1] (kg_{CO_2}/MWh)	295.8	773.3	265.4	281.1
	Level of commitment[38]	2030 GHG emission reduction[1*]	National Energy Climate Plan (NECP)	No commitment	40 %	57 %
		2030 RES target[1]		27 %	74 %	over 50 %
		2050 GHG emission reduction*		No commitment	90 %	Net zero**
Socio-economic transition	Economic Development[39]	GDP per capita (2018 EUR,PPP)	34,902	31,647	40,371	45,643
	Social Development[40,41]	Social progress index	66.5	57.13	66.73	72.8
		Social protection expenditure (% GDP)	22.6	19.4	21.5	25.4

Table 1. Country-specific readiness for low carbon energy system transition. The indicators reflect the multidimensional nature of energy transition. The social progress index (SPI) includes a variety of social and environmental metrics to measure social progress as a complement to traditional measures of economic progress, such as GDP per capita. Comparing SPI to the level of government expenditure in social protection, shows a strong link between the two: current SPI in Poland is below EU average, which is reflected in the mild social protection government policies over the last years. [1] Specific to the power sector, * compared to 1990 levels, **economy-wide

Low carbon scenarios and objective functions

The GVA is a widely recognized macroeconomic variable that measures the contribution to the Gross Domestic Product (GDP) made by individual producers, industries or sectors in a country. The expression is profound as it consists of measuring the *value* that each industrial activity adds to the domestic economy. Since it descends directly from National Accounting frameworks, the GVA is widely used in energy investment planning to capture

regional economic impacts descending from energy projects roll-out. This is generally done by adopting Input-output (IO) models[42,43], based on the Leontief's production functions, that calculate *ex post* the economic gains deriving from specific industrial activities[44–46]. Whilst being able to take fully account of country-specific industrial inter-dependencies , IO models do not present a complete picture of the supply or of the demand side of the economy, in that they do not envision optimizing behaviour of economic agents faced with alternative courses of action. Importantly, choices about the proportions in which inputs, *e.g.* energy technologies, are to be combined in the production of a given output, *e.g.* power supply, are excluded from the analysis. As a result, IO models cannot be used to model impact on the supply side due to policy measures, *e.g.* a carbon tax, because there is no substitution among technology choices when relative prices change. To overcome these limitations, this study incorporates sector specific GVA values within the ESO optimization framework, which allow to identify low carbon deployment strategies that maximize social value in different economy archetypes. Moreover, in line with conventional energy systems modelling approaches, the analysis is subject to specific technology costs assumptions which are likely to produce uncertainties as the time-horizon lengthens. Notwithstanding this, our aim is to propose a novel method to bridge the gap between techno-economic and socio-economic approaches to energy transition, rather than a range of technology deployment futures.The remaining of the study contrasts two opposite approaches to energy transition: the conventional, least-cost and technology-focused approach, and a novel, technology agnostic and welfare-focused one. This is done by considering three different scenarios for decarbonizing electricity systems in the selected countries by 2050, described as below:

- Business As Usual (BAU): Here, existing policies, for example, the current carbon tax, and technology banning are maintained and all existing technologies, namely, nuclear, unabated fossil, and renewables and storage are deployed according to the historical build rates (see supplementary Table S3 and Figure S1) . No carbon target is imposed, and the system is developed purely to minimize the total system cost.

- All technologies (AllTech): all technologies are allowed to be deployed and the system expansion is planned to minimize the total system cost, subject to a target of net zero CO_2 emissions by 2050.

- Renewables and Storage (ReStor): as the European Green Deal aims at meeting the deep decarbonization target using predominantly renewable and storage technologies, we construct a scenario in which only renewables and storage technologies can be deployed. Technology build rates are accelerated to the nearest integer multiplier that can satisfy the system's requirements, that is, tripled for the UK and Spain and increased tenfold for Poland.

- Social Equity(EQ): this is similar to the AllTech scenario, but the system is designed to maximize the system's gross value added (GVA) during the transition as opposed to focusing exclusively on minimizing the total system cost. Here, we define maximum GVA as the value of GVA at which the marginal cost of increasing the GVA is equal to $€1/€_{GVA}$.

Least cost energy systems transition

Under the BAU scenario, the structure of the energy system remains broadly constant, changing primarily in response of retiring capacity and increasing demand: Renewable power and energy storage capacity are deployed in line with the imperative to deliver a least-cost energy system whilst ensuring security of supply. In this context, the overall capacity of thermal power plants (nuclear, coal, and gas) is essentially held constant, and CCS technologies are never deployed (Figure 2). In the UK, driven by a relatively higher carbon price, the share of renewables and storage progressively increases, leading to an additional 61.3 GW capacity installed by 2050, compared to the 19.5 and 9.8 GW of additional renewable capacity in Poland and Spain, respectively. Despite the imposition of the net zero emissions target, with associated implications for the cost of CO_2 emissions, the structure and size UK's electricity system in the period to 2050 remains relatively constant in both the BAU and AllTech scenarios: the installed capacity of renewables slightly increases, but the requirement for firm capacity in the system remains essentially constant. One key change is that, in the AllTech scenario, the majority of dispatchable thermal power is provided by combined cycle gas turbine (CCGT) with CCS (a combination of new-build and retro-fit). The capacity factor of unabated thermal power is greatly reduced, with residual emissions offset by the bioenergy with CCS (BECCS) capacity. Conversely, when power generation is provided exclusively by renewable power and energy storage (ReStor scenario), the grid capacity has to rapidly expand to meet demand while satisfying the net zero target by 8.1, 3.2, and 4.5 times the initial capacity for Poland, Spain, and the UK, respectively. Although offshore wind is relatively expensive, the technology will provide a major contribution to the systems under this scenario due to its higher

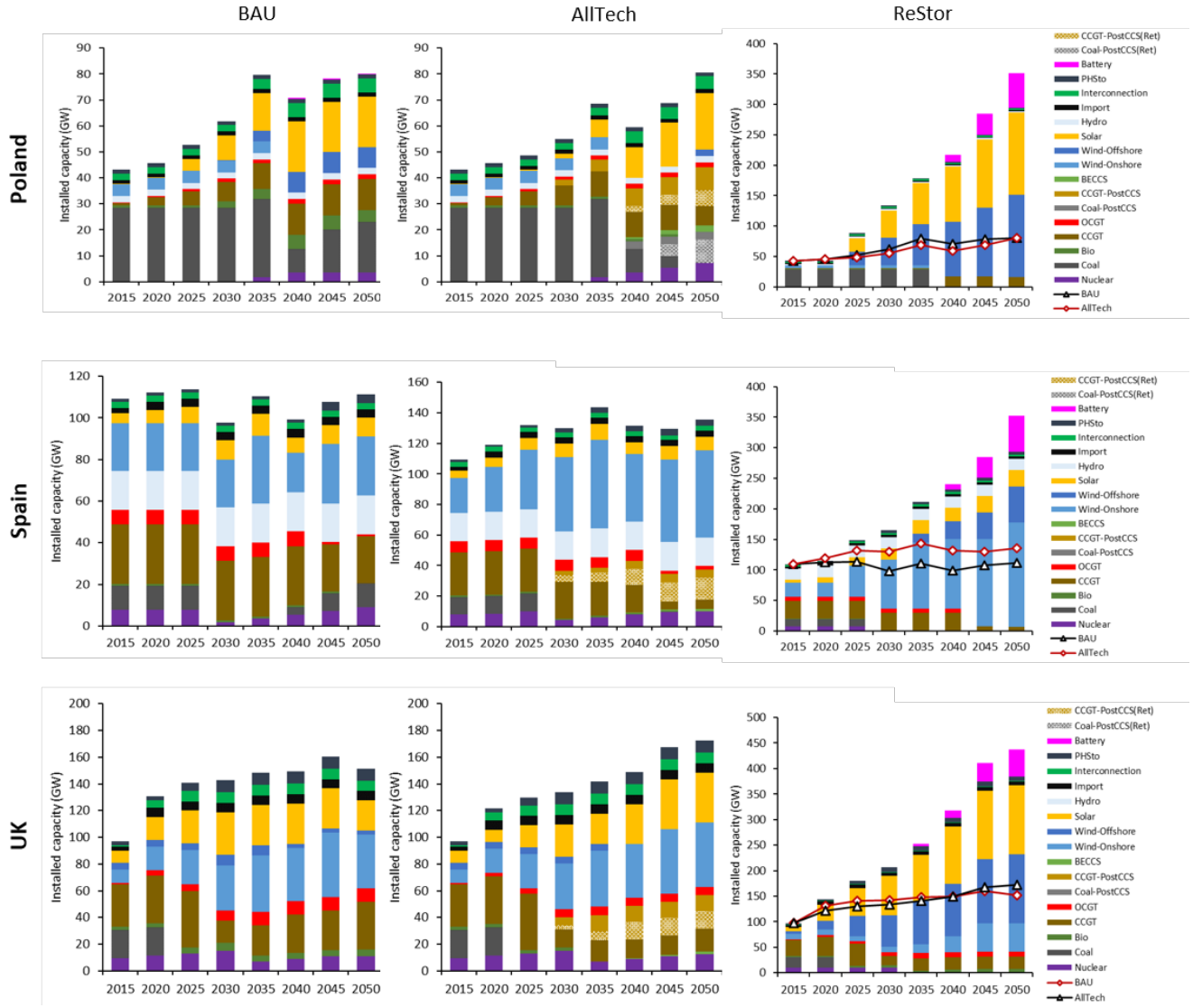


Figure 2. Least-cost energy system transition under different least cost scenarios. In all cases BAU scenarios project a growth in renewable capacity, mainly from solar PV and wind . Such trend is also observable in the All technologies scenario, where firm capacity is provided by Carbon Capture and Storage (CCS) instead of being served by unabated plants, delivering the carbon neutrality targets by 2050. Finally, meeting the power demand with renewable alone (ReStor), was observed to lead to a 3-fold (UK) to 6-fold (Poland) increase of installed capacity by 2050 relative the BAU or All Technologies scenarios (black and red marked lines in the figure). As a result, total system cost increases between 160% - 450% (in Spain and the UK, respectively). All acronyms are provided in the supplementary notes.

availability and reliability compared to onshore wind and solar photovoltaic (PV). Under the BAU scenario, the total system cost (TSC) for the UK, Poland, and Spain is €458 billion, €240 billion, and €287 billion, respectively. When the overall capacity of thermal power is maintained and the relative emissions are abated with CCS, the costs of achieving the net zero target is marginal, ranging from a 1% (Poland) to 11% (Spain) increase in the AllTech relative to the BAU scenario. For ReStor, total system cost increases between 160%- 450%. This is driven by the need to maintain security of supply which leads to the deployment of significant overcapacity in an attempt to minimise lost load. This notwithstanding, there remains significant potential for unserved demand, similarly to what was observed in previous work[47]. For industrial economies such as Spain and Poland, the impacts are less significant than in the service-based UK economy[30] (see supplementary Figure S2), although inadequate or unreliable power supply are perceived as important constraints on business activity, particularly in emerging economies like Poland[48] .

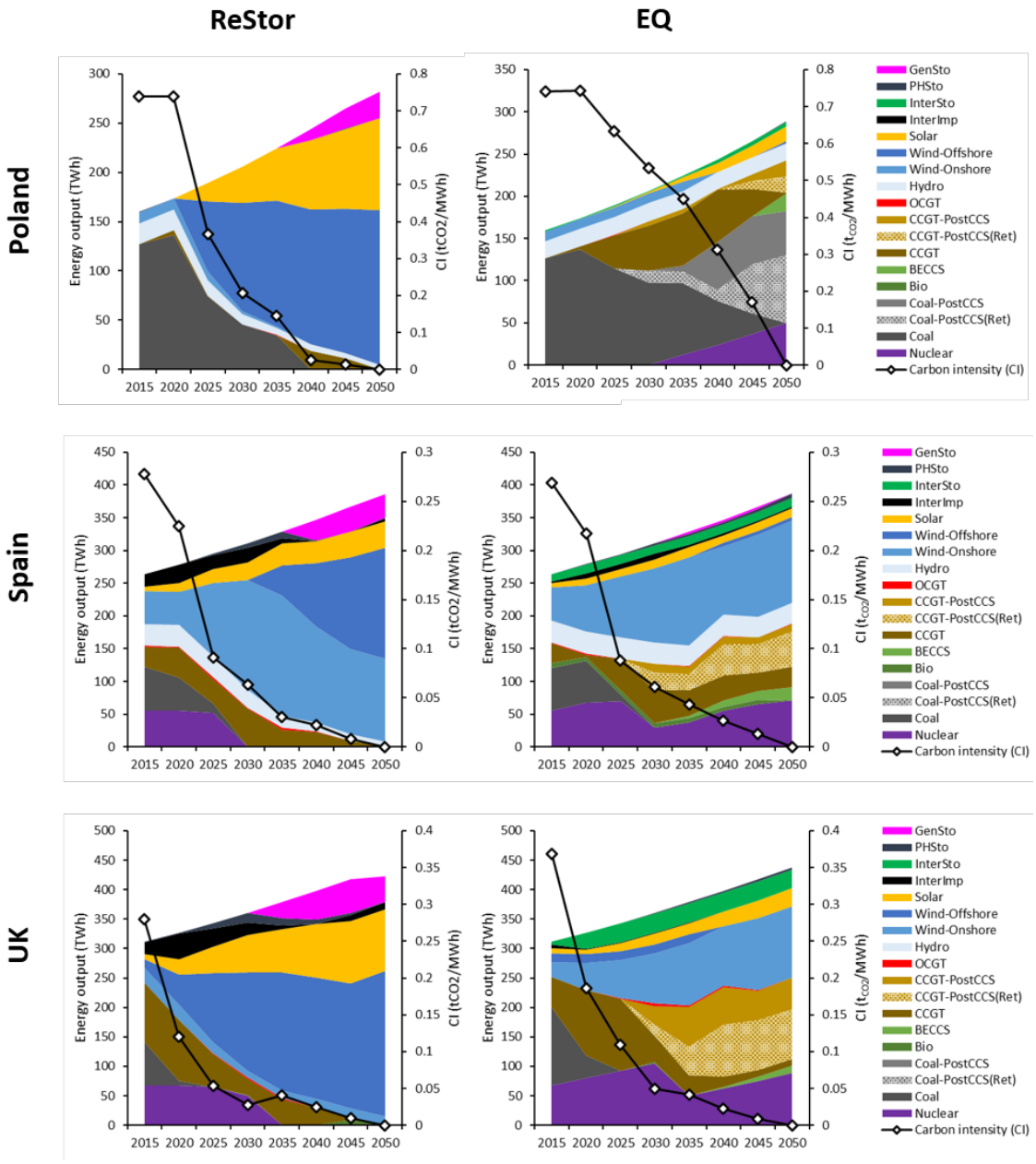


Figure 3. Annual energy generation mix for Poland, Spain and UK under renewable and storage (ReStor) and social value maximization (EQ) scenarios. In all countries, the ReStor scenario relies largely on wind to supply net-zero electricity. The EQ scenario favours the adoption of domestic energy assets: nuclear and indigenous biomass to reduce the reliance on gas imports in Spain, domestic coal coupled with CCS in Poland, and power generation from CCGT-CCS in the UK.

The left-hand side of Figure 3 presents the least cost energy generation mix in each country, under the ReStor scenario. In Poland, natural gas initially replaces coal, which is completely phased-out by 2035. with increasingly tighter carbon emission constraints, power generation from wind is rapidly expanded until it reaches a share 60% in the national energy generation mix in 2050. A similar trend is observed in Spain and in the UK, where nuclear and natural gas rapidly give way to renewable power especially from wind, producing more than 300 MWh and 260 MWh respectively. The social equity (EQ) scenario (Figure 3, right-hand side), favours a more diverse energy generation mix within each country with shares of local resources varying according to the services provided to the system. In

Poland abated coal supplies more than 50% of the power output, owing to the ramp-up of CCS which lenghtens the lifetime of existing plant and allows for new coal capacity addition. In Spain, nuclear provides more than 70 MWh of power output in 2050 in sharp contrast with what observed in the ReStor scenario. This, together with the adoption of indigenous biomass resources (with or without BECCS) allow to minimize the use of natural gas, which is entirely outsourced in the country, and to support the forestry sector which experience a 40% growth in GVA compared to the BAU. Compared to Spain, which gas reserves are negligible, UK can rely on domestic natural gas resources as well on local expertise in CCS projects. Hence, UK can utilize its CCGT-CCS capacity to provide firm, low-carbon capacity to the system while boosting its manufacture and mining sectors. Beside the overall preference for domestic resources, a common feature of all value maximization scenarios is the large deployment of CCS, emerging as both a least cost and socially valuable technology for a net zero energy transition. This is confirmed in Figure 4 , in which the cumulative changes in value added associated with each energy transition scenario is projected against the corresponding total system cost. Here, the AllTech and EQ scenarios, featuring a similar capacity expansion and both incorporating CCS to reach the 2050 zero-emission pledge, show comparable trends, especially for Poland and the UK . In these countries, the reliance on renewable energy alone to decarbonize the energy systems (ReStor) not only leads to a 200% to 600% fold increase in total system costs but also generates negative socio-economic impacts, as national strategic industries are replaced: domestic coal coupled with CCS in Poland, and thermal CCS plants in the UK. In Spain, however, the renewable capacity expansion leads to a 60% growth in value added by 2050 compared to BAU, as the country can rely on domestic industries for wind and solar PV manufacturing.

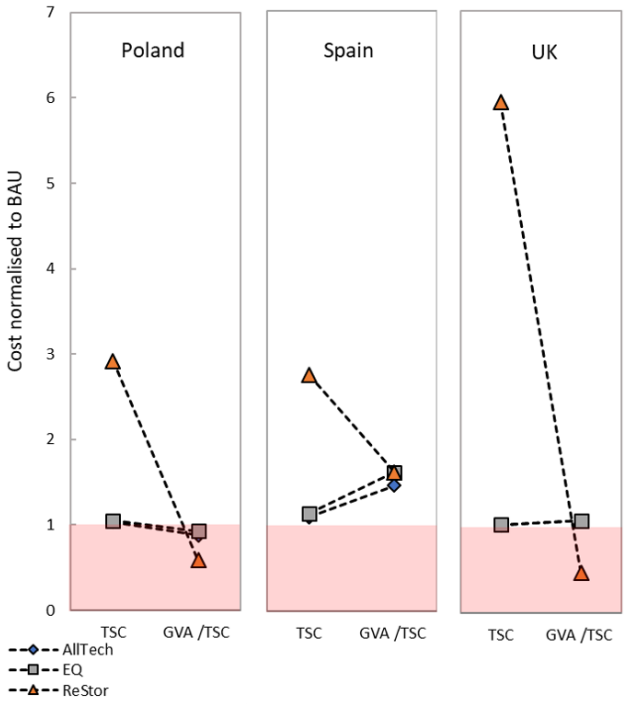


Figure 4. Total System Cost and associated Gross Value Added of the alternative energy transition scenarios in each country. When the full portfolio of technologies contributes to the energy system decarbonization, the least-cost (AllTech) and value maximization (EQ) scenarios show similar trends. The ReStor scenario generates negative socio-economic impacts especially in the UK, as the share of unmet demand in 2050 is higher than for the other countries.

Trade-offs across decarbonisation and non-climate objectives

Figures 5, 6 and 7 show the trade-offs between decarbonisation objectives and the societal goals defined by SDGs 8, 9, and 10, targeting work and economic growth, industrial innovation, and inequality. The previously identified net-zero scenarios for Poland, Spain and the UK, are compared against the following SDGs indicators: GVA to TSC ratio; employment growth (in the national economy and in the manufacturing sector); value added in the manufacturing sector (MVA); and shares of labour earnings in TSC (see SI for more details). As figure 5a reveals, any effort to

decarbonize the power sector in Poland leads to GVA losses, due to the diminishing role of domestic coal in the 2050 energy mix compared to the BAU scenario. Such trade-offs, which translate into 48% jobs reduction in the ReStor scenario, are lower in the EQ and AllTech scenarios, as the adoption of CCS allows for a grater utilization of abated coal for power production. As be observed from Figure 5b, showing the sectoral contributions to changes in local employment within each scenario, the job disruptions foreseen in the ReStor are unevenly distributed across the Polish economy. The mining sector bears the heaviest burden of the energy transition, while the manufacturing industry experiences 5% employment growth, resulting from the deployment of additional renewable capacity. However, these are primarily maintenance jobs associated with the routine operation of imported wind turbines and solar PV, increasing the exposure of the local labor market to to further disruption arising from greater automation[49]. Moreover, as illustrated in 5a the share of investment translating into compensation of employees is reduced by 50% in the ReStor scenario, as the energy transition is outsourced, economic valuable assets are being replaced and the demand for skilled workforce stagnates.

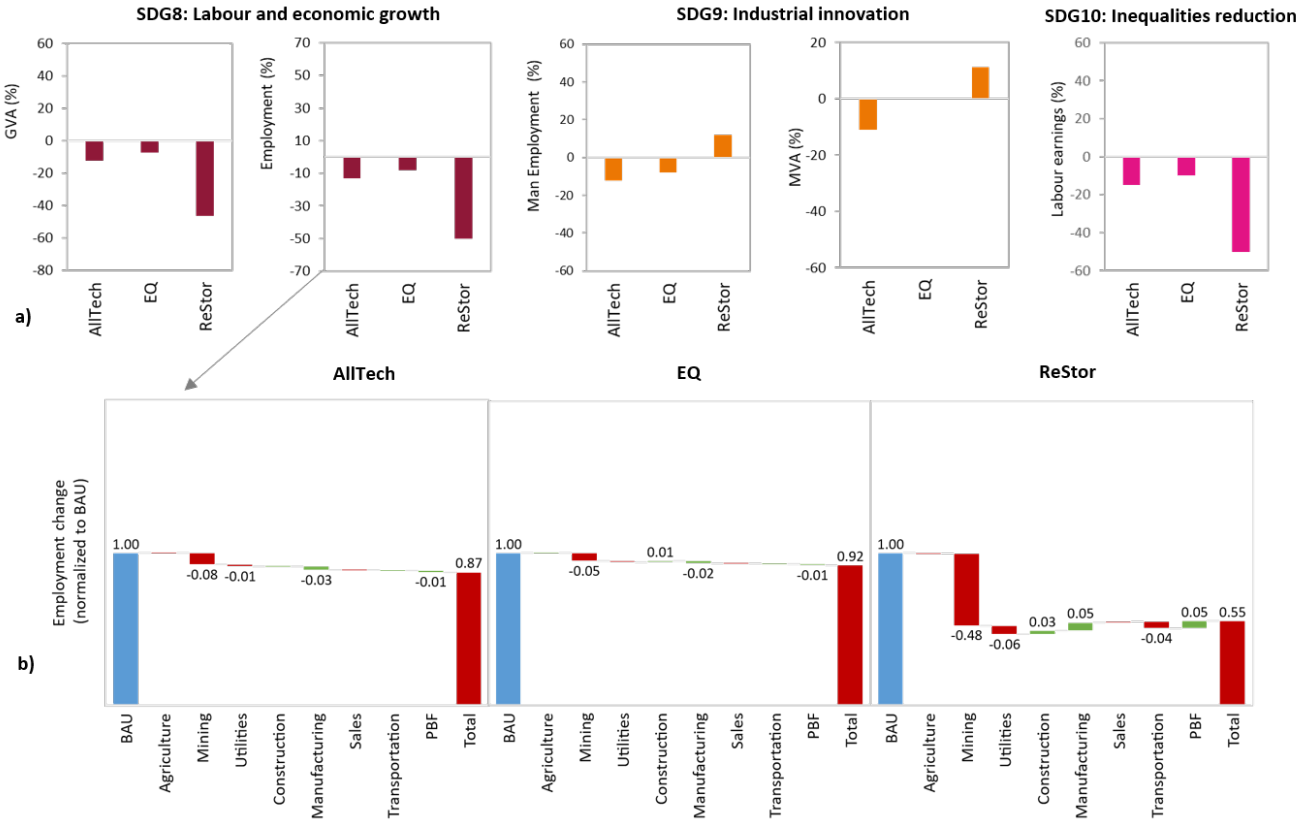


Figure 5. a) Socio-economic impacts of AllTech, EQ and ReStor scenarios across key SDGs indicators in Poland and b) sectoral contributions to changes in local employment. As the figure aims at showing trends in synergies and trade-offs of alternative pathways rather than an exact quantitative analysis, results are presented as changes relative to the country specific business as usual scenario (see supplementary materials for more details). Transitioning to net-zero leads to negative socio-economic impacts in all scenarios, as the country is highly relying on coal to fuel its economy. The ReStor scenario projects a 48% employment disruption in the mining sector and a modest growth in manufacturing jobs, associated with the maintenance of solar and wind facilities. Unevenly distributed job losses across the economy in this scenario, exacerbates the risk of stranded workers and labour conversion challenges, with gaps in income and status between different job categories.

In contrast to what observed for Poland, transitioning to a net-zero power system brings economic growth and employment opportunities in Spain, especially in the EQ scenario (figure 6) . The gains are quite evident in the manufacturing sector, which foresees a growth of 23-26% in employment and of around 40% in value added within each scenario, as the country can rely on domestic solar, wind and nuclear industries. In the EQ scenario, these benefits are perceived across all sectors of the economy, particularly in the agricultural sector, where the expansion of bioenergy and BECCS capacity translates into a 18% growth in cumulative employment by 2050. As a result,

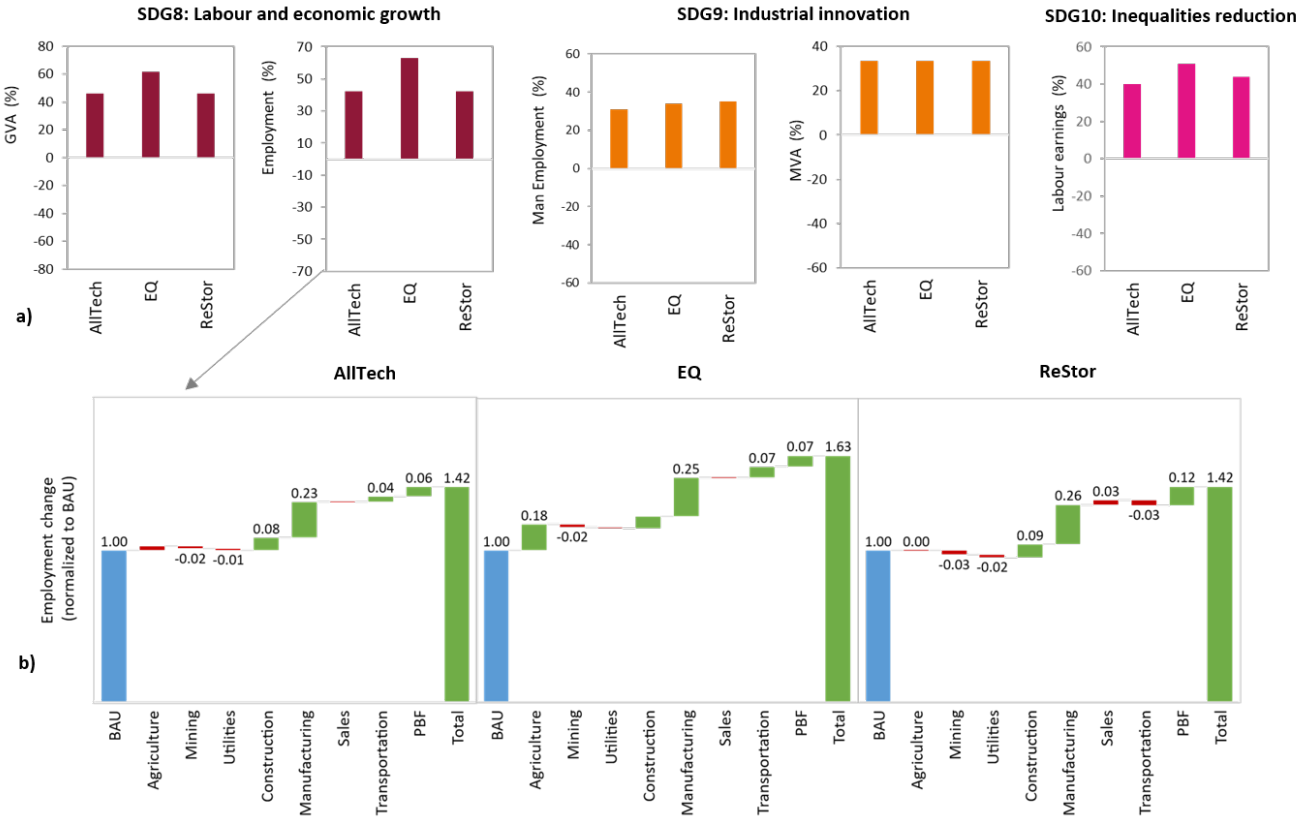


Figure 6. a) Socio-economic impacts of AllTech, EQ and ReStor scenarios across key SDGs indicators in Spain and b) sectoral contributions to changes in local employment. Here, all net-zero pathways project economic gains and employment growth, which are distributed across the different sectors of the economy in the case of EQ scenario, including in the agricultural sector. The manufacturing and professional, financial and business services (PFB) sectors benefit the most from the large expansion of wind projects in the ReStor scenario, although the benefits are counterbalanced with jobs disrupted from the phase-out of nuclear capacity.

high shares of low-carbon investments are retained in the economy in the form of employers salaries and benefits, e.g social security contributions and welfare services, as the country can lean on local industries (wind and solar in the ReStor, nuclear and bioenergy in the other scenarios), and on its domestic labor pool to conduct the energy transition.

As already observed in figure 4, the ReStor scenario falls behind on all indicators in the UK, with larger trade-offs observed in the manufacturing industry (figure 7). This is because, the 3-fold increase in installed capacity by 2050 required to meet the power demand from renewable energy sources alone, i) leads to higher investments having lower local value and ii) displaces local workers in CCGT plants. The socio-economic performance the AllTech and EQ scenarios show no considerable differences, as their technology deployment pathways are almost identical. Overall, both scenarios forecast mild additional co-benefits compared to the BAU: 7-8% growth in GVA and 5-7% growth in employment in the AllTech and EQ scenario respectively. Under the current carbon price floor, therefore, and assuming a rapid scale-up of the local CCS industry from 2030, the UK power system will "naturally" evolve into a socially equitable energy system, where welfare is maximized, and domestic assets are favoured.

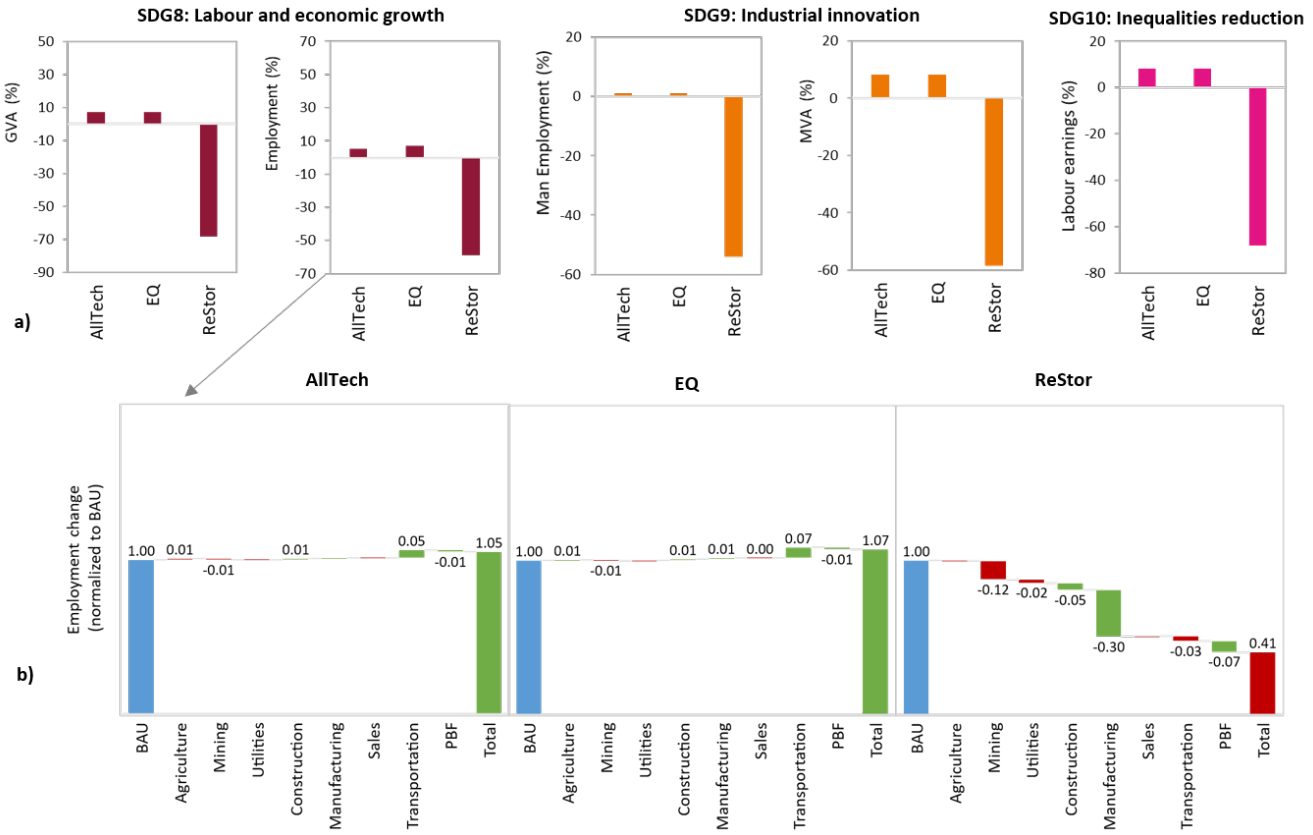


Figure 7. a) Socio-economic impacts of AllTech, EQ and ReStor scenarios across key SDGs indicators in the UK and b) sectoral contributions to changes in local employment. The AllTech and EQ scenarios perform almost the same, both featuring an increasing adoption of CCS-CCGT plants, leading to a 7-8% growth in GVA compared to the BAU. Negative socio-economic impacts are associated with the ReStor scenario, which shows considerably higher trade-offs than in the case of Spain and Poland. This is mainly associate with the overcapacity requirement foreseen for this scenario which increases the TSC, displaces locally manufactured CCGT-CCS capacity, and leads to negative employment balances.

Conclusions

To date, the scientific and policy debates around energy systems transition have mainly focused on the cost performances of energy technologies, either alone or in a comparative fashion. However, in any context, it seems apparent that there is no "one size fits all" solution, and that the relative costs and opportunities are unevenly distributed between countries. Moreover, depending on the transition pathway adopted, herein characterised by the BAU, AllTech, ReStor, and EQ archetypes, the size of the relative cost or opportunity will vary both quantitatively and qualitatively. Our results show that in all cases, a ReStor-type transition will be universally the costliest option, however, countries like Spain seem well-placed to benefit from the transition, regardless of the strategy they adopt. For UK-type countries, whilst the potential upside is more modest with the technology agnostic and equity-focused pathways, a value creation paradigm is still available. However, for other countries, such as Poland, the issue appears to be one of minimising the costs of transition by focusing on socially equitable solutions. It is in this context that broader equity concepts may need to be brought to bear, with an emphasis on regional solidarity. Conversely, cost-focused carbon mitigation strategies that neglect any social, geopolitical and macro-economic considerations, are likely to exacerbate labour market inequalities, as job losses are concentrated among specific socio-economic groups[50] and in some regions. Failing to address these national and region specific disparities will result in deeper social divisions, with adverse implications for growth, productivity, well-being, and social cohesion[49] .

Methods

The ESO-JEDI framework. A mathematical description of the JEDI tool can be found in the supplementary notes and is freely available for download at https://www.nrel.gov/analysis/jedi/international.html, country specific accounting tables are publicly available on the OECD STAN website (https://stats.oecd.org/). Data reference and additional methods on the socio-economic analysis used in this work are provided in the Supplementary Information. A mathematical description of the ESO power system model is available at[31] model assumptions, data references and additional methods specific to this work, are presented in detail in Supplementary Figs. S1-S3, Supplementary Tables S3. Main steps of the methodology are presented below.

Value chain mapping: The investment and operational cost data of 15 power generating and storage technologies are allocated across 36 industrial sectors, following the International Standard Industrial Classification (ISIC). Through value chain mapping, the capital and operational expenditures of energy projects are allocated to the main industrial sectors, considering only the technical component that are manufactured in the country of analysis and thus create value to the local economy. Main assumptions follow actual and historic data on global manufacturing trades (supplementary table S1, and S2). For instance, the large parts of solar PV supply chains is located in countries with strong demand, which generally follows attractive incentives: between 2011-2015, top exporters of solar PV cells and modules were in Asia (with China representing almost 30% of the global trade) and Germany. Accordingly, here we assumed that PV modules are manufactured outside the countries of analysis, and as such, the share of capital investments directed towards PV modules (around 30%) do not generate value for the national economy (and neither domestic jobs). The same rationale is used when considering different biomass feedstock types (municipal solid waste and woody residues) and origins (imported or domestic). Feedstock procurement activities for bioenergy plants adopting indigenous sources, are allocated to the domestic agricultural sector (or waste management sector, in the case of municipal waste). For imported biomass, only transportation activities (from seaport and inland ports to the bioenergy facilities) are assumed to generate economic value.

Socio-economic analysis: The Jobs and Economic Development Impacts (JEDI) model is an economic tool that estimates gross economic impacts from a portfolio of energy technology projects. The JEDI suite of models was first developed in 2004 by the National Renewable Energy Laboratory (NREL) to analyze low carbon (biomass, wind and solar PV) as well as conventional (coal and natural gas) energy projects in the United States. JEDI models have been used in many high-profile studies as well as in peer-reviewed journal articles[32,51,52]. In our work, we extend the JEDI suite of technologies according to the power generation mix described by ESO and we adapt the model to accommodate the industrial structure of Spain, Poland and the UK. The overall approach is to combine cost data of a specific energy project with country specific socio-economic indicators from the database for structural analysis (STAN). The STAN database is a comprehensive tool for analyzing industrial performance at a relatively detailed level of activity across countries. It includes annual measures of output, value added and its components, labor input, investment and capital stock, from 1970 onward, allowing to construct a wide range of indicators to focus on areas such as productivity growth, competitiveness and general structural change. STAN is primarily based on member countries annual national accounts, while data from the International Labour Organization[53]are adopted to estimate annual wages per sectors and industrial activities. The following indicators are extracted from STAN for

the calculation of direct impacts:

- %GVA$_i$ Value added share of production: this indicator shows the value added contributed by each sector i relative to total production. It provides an indication of the production structure of a given sector.
- %Labor$_i$ Labor share of value added: Amount of labor compensation within the value added created by a given industry. It is used to calculate the total earnings generated within a certain economic activity Wages: this indicator is used to calculate the number of jobs created by a given industry. For instance, if UK reported average annual earnings of € 10,000 per job in the agricultural industry in 2018, earnings of € 20,000 would support two jobs.

Value added and jobs created in each industry i are proportional to the output produced by technology t in that sector:

$$GVA_{i,t} = Output_{i,t} \times \%GVA_i$$

$$Jobs_{i,t} = \frac{\sum_t (Output_{i,t} \times \%Labor_i)}{Wages_i}$$

ESO: Electricity system optimisation framework (ESO) is a mixed integer linear program for electricity system unit commitment and expansion planning model. The model minimises total system cost, which includes capital and operation costs, of a power system subject to capacity expansion (initial capacity, build-rate, endogenous technology learning, etc.), system wide (for example electricity demand, system requirements and emissions targets), technology wise (grid services provision, flexibility, etc.), and integer scheduling constraints. The framework has been adopted in various peer reviewed studies[9, 29, 54] and several versions with distinct levels of spatial granularity, time horizon period, and formulation complexity (including endogenous technology learning capability). These features allows ESO framework to optimise capacity expansion planning or a power system that takes into account operational constraints on the technology level as well as system-wide requirements on the whole system level on hourly and annual basis from 2015 to 2050[29–31].

Originally, optimisation in ESO framework was conducted by means of total system cost minimisation. In this study, for EQ scenario, we modified the objective function to maximise the system's GVA up to an optimal point where the GVA increase is less than or equal the total system cost increase (*i.e.*, the marginal cost of increasing GVA is more than or equal to 1 €$_{GVA}$/€$_{TSC}$. This can be done by changing the objective function from pure TSC minimisation to net cost minimisation as shown below:

minimise $Obj = TSC - GVA$

SDGs indicators: The Inter-Agency and Expert Group on SDG Indicators endorsed a set of 230 individual indicators for monitoring the progress in achieving the SDGs . Since we are specifically interested in reconciling low carbon energy transition with the long-term objectives of social sustainability and economic growth, the proposed energy transition pathways are evaluated across SDGs 8 (work and economic growth), 9 (industrial innovation) and 10 (inequality reduction). Our choice of indicators is further constrained by the JEDI and ESO model structures and reported variables. For instance, since JEDI do not differentiate employment by income groups, our analysis could not account for indicators specifically targeting inequality and income disparities in the different segments of the population (e.g. indicators 10.1, and 10.2). To track the progress towards these goals, each indicator is defined as the variation (in % change) between baseline and selected technology deployment scenarios (supplementary table S4). Since it only selects some but not all targets linking economic development and social inclusion, the analysis does not intend to map the interaction between energy transition and the Sustainable Development Goals, but rather to provide a comparative framework for alternative technology deployment routes.

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Author contributions statement

N.MD. conceived the study with P.P., Y.P. performed ESO calculations, P.P. performed socio-economic calculations. All contributed to writing and reviewing the manuscript

Competing interests

The authors declares no competing interests.